THE EFFECTS OF DRIP IRRIGATION SYSTEM UNIFORMITY ON SOIL WATER AND NITROGEN DISTRIBUTIONS

J. Li, W. Zhao, J. Yin, H. Zhang, Y. Li, J. Wen

ABSTRACT. *The effects of drip irrigation system uniformity and nitrogen application rate on the distribution of water and nitrate in the soil were investigated through field experiments to modify the current design and evaluation standards for drip irrigation uniformity. The experiments were conducted in a solar-heated greenhouse in the 2009 and 2010 growing seasons of Chinese cabbage. Three statistical uniformity coefficients (Us = 55%, 73%, and 95%) and two nitrogen application rates (150 and 300 kg ha^{-1}) were evaluated in 2009. In 2010, three Us values (53%, 65%, and 94%) and one nitrogen application rate (225 kg ha^{-1}) were tested. The distribution of the soil water content and bulk electrical conductivity was monitored continuously with equally spaced frequency domain reflectometry (FDR) sensors located along a dripline. Gravimetric samples of soil for each plot were collected regularly to determine the distribution of nitrate. For all of the tested system uniformities, the soil water content displayed high uniformity coefficients throughout the entire growing season. The effects of system uniformity and nitrogen application rate on the seasonal mean water content and bulk electrical conductivity (EC_b) and on the seasonal mean uniformity of water content and bulk electrical conductivity were insignificant at a significance level of 0.05. The uniformity coefficient of the soil bulk electrical conductivity and nitrate content was substantially lower than that of the soil water content and was dependent on the uniformity of the initial salt and nutrient constituents in the soil. Moreover, the system uniformity and nitrogen application rate had an insignificant effect on the uniformity of the nitrate content. The results of this study showed that uniformity values that are lower than those recommended by the current standards can be used in drip irrigation systems if sufficient irrigation and fertigation events are conducted to approach a uniform distribution of water and nutrients in the soil.*

Keywords. *Chinese cabbage, FDR, Fertigation, Microirrigation, Nitrogen, Soil bulk electrical conductivity, Soil water content, Uniformity.*

Uniformity is an important parameter in the design and operation of microirrigation systems. A higher level of uniformity leads to a more uniform distribution of water and nutrients in the soil; however, the initial installation costs of systems with greater uniformity values are relatively high, although the long-term ownership costs might be less for higher-uniformity systems (Wilde et al., 2009). Several design and evaluation standards for drip irrigation uniformity have been developed in different countries (e.g., *ASAE Standards*, 1988, 2003; Chinese Standards, 1995). ASAE Standard EP405.1 (*ASAE Standards*, 2003) recommends a design emission uniformity (*EU*) of 70% to 95% depending on the source (point or line source), crop, emitter spacing, and field slope. Chinese National Standard SL103-1995 (Chinese Standards, 1995) suggests a design Christiansen uniformity coefficient (*CU*) of greater than 80%.

Several factors should be considered in determining the target uniformity criteria. A series of methods, including forward, backward, and finite element theory, have been presented in the literature to optimize hydraulic designs and to meet target uniformity values (e.g., Wu and Gitlin, 1973, 1974; Bralts and Segerlind, 1985; Kang, 1999). Design uniformity criteria have also been addressed from an economic point of view. Wu and Barragan (2000) simulated optimal design criteria by considering the economic return, cost of water, crop price, sensitivity of crop to deficit irrigation, environmental pollution, and irrigation schedule. In the aforementioned study, a linear water application function and a linear crop response model were assumed; however, the effect of nonuniform fertilizer applications on crop yield was not considered. The effect of fertilizer uniformity may be more obvious for microirrigation systems, through which many fertilizers are applied. In addition, experimental data that can be used to verify simulation results are relatively scarce. Nevertheless, in a five-year study conducted in the Texas High Plains (Bordovsky and Porter, 2008), significant differences in cotton yield and value were not observed among subsurface drip irrigation treatments at flow variations (q_{var}) of 5%, 15%, and 27%. In the aforementioned study, a base irrigation amount and 60% of the base irrigation amount were evaluated. This result suggests that a uniformity criterion that is lower than the val-

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ues recommended by current standards may be used. However, this result must be confirmed by conducting experiments on different crops and climatic conditions. Further research on the distribution of water and nitrogen in soil under a wide range of microirrigation uniformities would be beneficial for understanding the mechanism of the insignificant response of crop growth to drip irrigation nonuniformity.

The objectives of the present study were to investigate the effect of drip system uniformity on the distribution of water and nitrogen and to provide recommendations for modifying the design criteria for microirrigation systems by conducting field experiments in a solar-heated greenhouse in the absence of rainfall.

MATERIALS AND METHODS

EXPERIMENTAL DESIGN

Field experiments were conducted in a solar-heated greenhouse located at the Experimental Station of the National Center for Efficient Irrigation Engineering and Technology Research in Beijing (39°39' N, 116°15' E). The greenhouse was 50 m in length and 8 m wide. The experimental area undergoes a warm and semi-humid continental monsoon climate with an annual mean temperature of 11.6°C and an annual mean precipitation of 556 mm.

The particle size distribution of soil in the greenhouse, which was measured according to the laser method (Mastersizer 2000, Malvern Instruments, Ltd., Malvern, U.K.), is summarized in table 1, and the texture of the soil was classified as sandy loam. The bulk density measured by a 100 cm^3 ring, the field-measured saturated water content and field capacity, and soil water content at wilting point, measured at 1.5 MPa suction using a centrifugal method, are also presented in table 1.

Chinese cabbage (*Brassica pekinensis*, Beijing Xin No. 3), a moderately water- and nitrogen-sensitive vegetable, was selected as the experimental crop. The experiments were conducted in the 2009 and 2010 growing seasons. In the 2009 experiments, Chinese cabbage was seeded on 12 August at a row spacing of 40 cm. The cabbage plants were set at a fixed plant spacing of 60 cm along a row on 8 September, and the harvest was conducted on 15 November. In 2010, cabbages were seeded on 11 August at a row spacing of 40 cm. Plant setting was completed at a spacing of 60 cm in a row on 9 September, and the cabbages were harvested on 19 November.

In the 2009 experiments, two factors were considered: drip system uniformity and fertilizer application rate. As shown in equation 1, the statistical uniformity (*Us*) (*ASAE Standards*, 1988) was used to quantify the uniformity of the emitter discharge rate, soil water content, soil bulk electrical conductivity, or nitrate content in the soil:

$$Us = 100\left(1 - \frac{SD}{\bar{x}}\right) \tag{1}$$

where

$\bar{x}$ = average of x_i, $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

x_i = emitter discharge (L h^{-1}), soil water content (cm^3 cm^{-3}), soil bulk electrical conductivity (dS m^{-1}), or nitrate content in the soil (mg kg^{-1}) for the *i*th sample point

n = number of samples

SD = standard deviation of x_i.

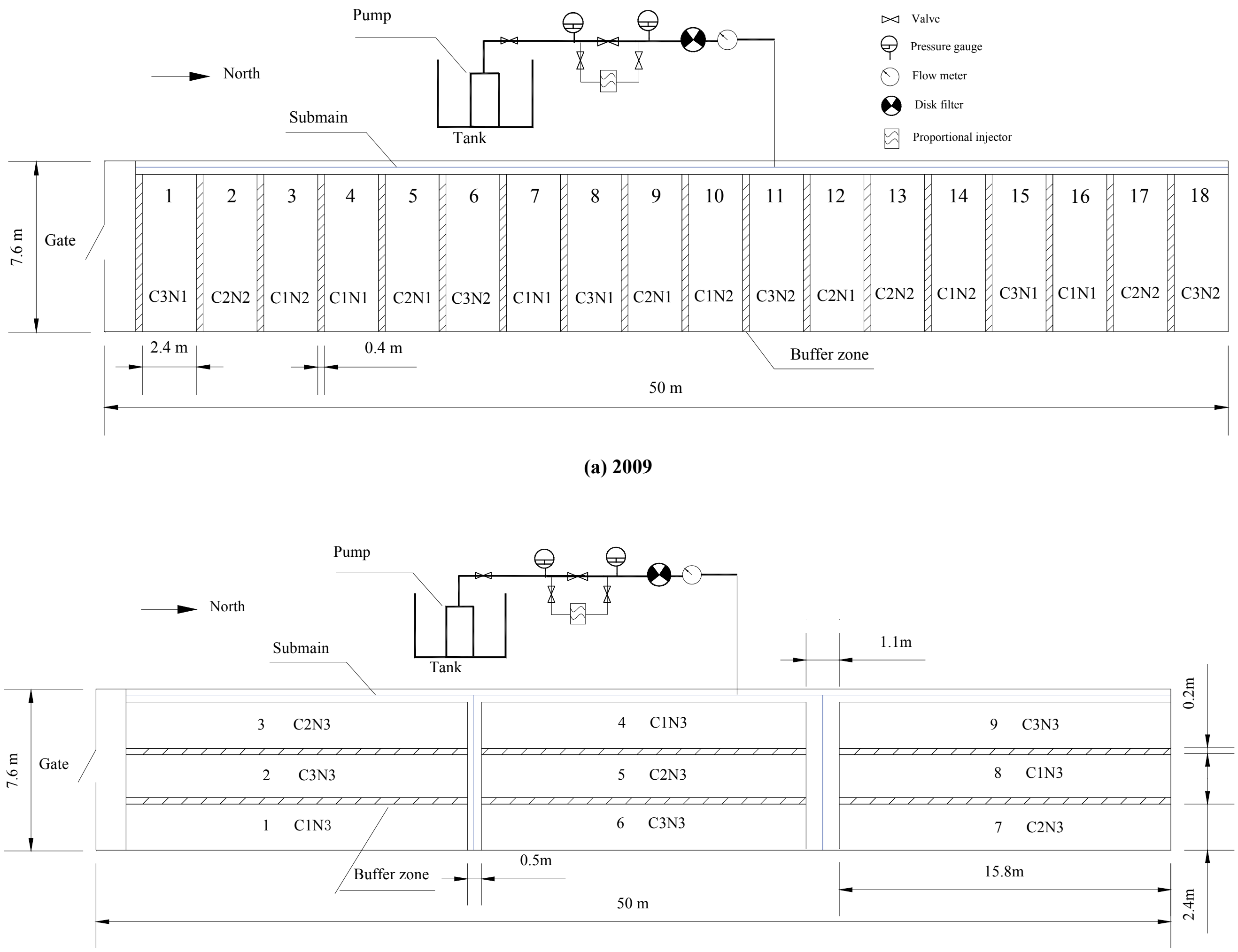
Three *Us* levels of unacceptable (<60%, referred to as low uniformity, C1), poor (65% to 75%, referred to as medium uniformity, C2), and excellent (95% to 100%, referred to as high uniformity, C3) according to the criterion recommended by the ASAE standard EP458 (*ASAE Standards*, 1988) and two levels of nitrogen application rates of 150 kg N ha^{-1} (N1) and 300 kg N ha^{-1} (N2) were evaluated in the experiments. The high nitrogen application rate approximated conventional nitrogen usage in the suburbs of Beijing. The experimental design resulted in six treatments: C1N1, C1N2, C2N1, C2N2, C3N1, and C3N2. Three replicates were conducted for each treatment. The greenhouse was divided into 18 equal plots of 7 m × 2.4 m, and the treatments were randomly distributed throughout the greenhouse (fig. 1a). A 40 cm buffer zone between adjacent plots reduced the likelihood of lateral exchange of water between plots and allowed for access to each experimental plot. In 2010, three *Us* levels that were similar to those used in the 2009 experiments and one fertilizer application level of 225 kg N ha^{-1} (N3) were evaluated because the rate of nitrogen application did not have a significant effect on crop growth in 2009. Thus, three treatments were conducted: C1N3, C2N3, and C3N3. The greenhouse was divided into nine equal plots of 15.8 m × 2.4 m, and three replicates of each treatment were randomly distributed throughout the greenhouse (fig. 1b).

FIELD INSTALLATIONS

For each plot, a dripline was installed continuously on the soil surface along the median of two adjacent rows (figs. 2a and 2b), and the two rows were irrigated by one dripline. As a result, the lateral length of the dripline was equal to 22.6 and 49.8 m for the 2009 and 2010 experiments, respectively. Low and medium *Us* values were obtained by randomly assembling segments of drip tubes with five different nominal discharge values (1.05, 1.4, 1.65, 2.3, and 2.6 L h^{-1} at 0.1 MPa) along the entire length of the line. However, a mean emitter discharge of 1.65 L h^{-1} at

Table 1. Particle size distribution, bulk density, saturated soil water content, field capacity, and soil water content at 1.5 MPa suction of the experimental soils.

Depth (cm)	Percentage for a Given Particle Size Range: 2.0 to 0.02 mm	<0.02 to 0.002 mm	<0.002 mm	Bulk Density (g cm^{-3})	Saturated Water Content (cm^3 cm^{-3})	Field Capacity (cm^3 cm^{-3})	Soil Water Content at 1.5 MPa
0-20	70.43	29.52	0.05	1.44	0.47	0.33	0.15
20-90	66.53	33.37	0.10	1.48	0.47	0.33	0.15



(b) 2010

Figure 1. Schematics of the randomly distributed experimental plots in the greenhouse for the (a) 2009 and (b) 2010 experiments.

0.1 MPa, which was similar to the mean emitter discharge for the high *Us* treatment, was maintained for the laterals. For a given uniformity, the number of emitters with different discharge rates was determined by the Monte Carlo method (Pei and Wang, 1998), assuming that the distribution of emitter discharges within a unit could be represented by a normal distribution function (Nakayama et al., 1979). The emitter spacing was 40 cm for all of the driplines.

The emitter flow rates of the three *Us* treatments were measured prior to lateral installation by cans spaced at an interval of 0.8 (2009) and 1.2 m (2010) to confirm that the *Us* values of the assembled laterals were comparable with the designed values. Resultantly, 28 emitters for each *Us* treatment were selected for discharge measurement in 2009 (n = 28 in eq. 1), and 44 emitters were measured in 2010 (n = 44). The variations of emitter discharge rates along the dripline measured prior to the 2009 and 2010 installations are presented in figure 3, and the actual *Us* values were 55%, 73%, and 95% for the 2009 experiments and 53%, 65%, and 94% for the 2010 experiments, while the designed values were <60%, 65% to 75%, and 95% to 100%.

Irrigation water with an electrical conductivity of 0.53 dS m^{-1} was supplied to a 2 m^3 tank from a tap supply system and was re-pressurized into the drip irrigation system by a pump with a capacity of 30 m^3 h^{-1} and a lift of 50 m. A disk filter (38.1 mm short filter, Arkal Filtration Systems, Kibbutz Bet Zera, Israel) with a mesh opening of 0.125 mm (No. 120 mesh) was installed at the head of the supply system. Moreover, a water-driven adjustable proportional pump (model 2504, Tefen, Beit-Dagan, Israel) and a pair of pressure gauges were installed ahead of the filter for fertigation (figs. 1a and 1b). A valve was installed at the beginning of the supply line to maintain a fixed inlet pressure of 0.10 MPa during irrigation, and a flowmeter was installed after the proportional pump to record the amount of water applied to the plot. An individual submain was used for all three replicates to fertilize each treatment separately.

The multi-parameter capacitance (frequency domain reflectometry, FDR) sensor has been documented as a low-cost instrument with acceptable measurement accuracy of soil water content and bulk electrical conductivity (e.g., Kizito et al., 2008). A type of capacitance sensor (Hydra Probe, Stevens Water Monitoring Systems, Inc., Portland, Ore.) was selected to monitor continuously the temporal and spatial variation of the soil water content, soil bulk

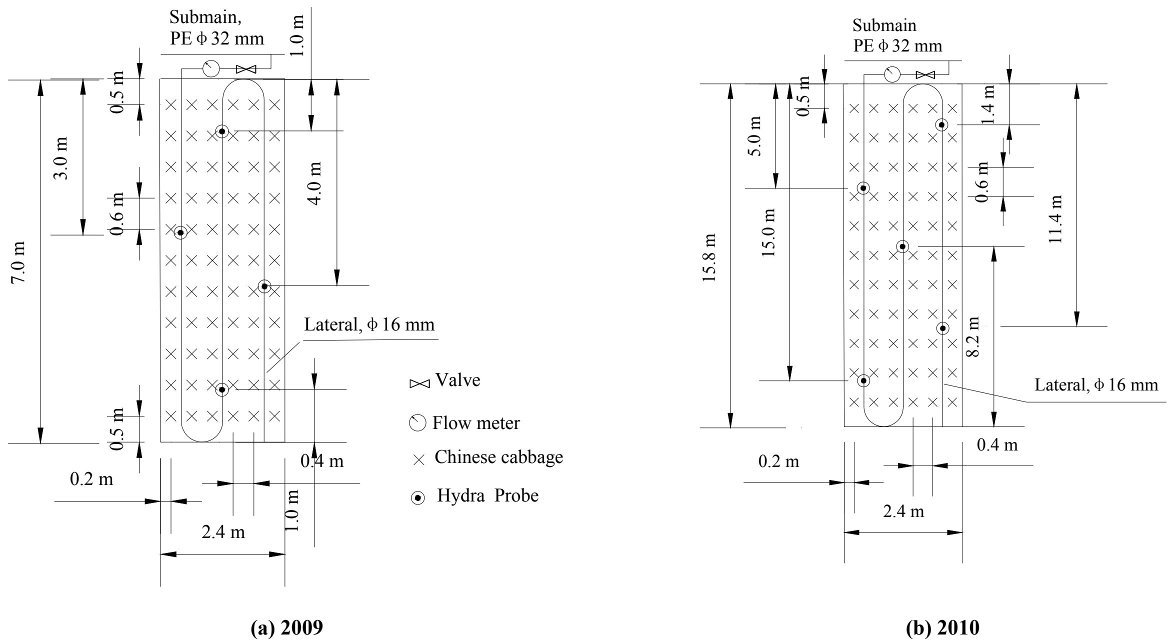


Figure 2. Schematic of lateral dripline and location of Hydra Probe sensors within an experimental plot in (a) 2009 and (b) 2010.

electrical conductivity (EC_b), and temperature within one plot of each treatment. Four sensors were installed within a plot for the 2009 experiments, while five sensors were used in 2010 (figs. 2a and 2b). In order to obtain the difference in water and EC_b caused by different emitter discharge rates, the sensors within a plot were positioned at a distance of 5 cm from the emitters having different nominal discharge rates but with approximately equal spacing (fig. 3). Each sensor was buried horizontally at a depth of 15 cm, which represented the average depth of the root zone of Chinese cabbage. The dynamics of nitrogen in the soil can be represented by the EC_b to some extent (Payero et al., 2006; Li and Li, 2009).

IRRIGATION AND FERTIGATION

Similar irrigation schedules were used for each treatment in 2009 and 2010. When the mean water content measured with the probes within the greenhouse approached 70% of field capacity, irrigation was applied to replenish the soil water to field capacity. In total, 159 mm of water was applied over eight irrigation events during the 2009 season, while 145 mm of water was applied over seven irrigation events in 2010 (fig. 4). Urea, a readily soluble nitrogen fertilizer, was used in 2009 and 2010. Twenty percent of the desired nitrogen content was broadcast prior to seeding, and the remaining fertilizer was applied in six different splits in 2009 and four equal splits in 2010 (fig. 4).

NITROGEN DISTRIBUTION IN THE SOIL

To obtain similar initial profiles in the different plots, 150 mm of water was applied to each plot by surface irrigation prior to seeding in both seasons to leach residual salts from the root zone. One day prior to seeding, gravimetric soil samples at depths of 0-20, 20-40, 40-60, 60-80, and 80-100 cm at nine locations within the greenhouse, each representing an approximately equal area, were collected using a 4 cm diameter auger to determine the initial soil water and nitrogen content. To investigate the influence of system uniformity and nitrogen application rate on the nitrate distribution, soil cores were collected at a distance of approximately 10 cm from the Hydra Probe sensors on selected dates one or two days after a fertigation event (29 September, 17 October, and 17 November in 2009; 21 October and 25 November in 2010). Soil cores in the plots without sensor installations were also sampled on the same dates at positions approximately similar to the plots with sensors buried. For each sample, 20 g of air-dried soil passing through a 2 mm sieve were extracted with 50 mL of 1 mol L^{-1} KCl, and the NH_4-N and NO_3-N content was determined using an Autoanalyzer III (Bran+Luebbe, Norderstedt, Germany) (Soil Science Society of China, 1999, pp. 156-158).

STATISTICAL TESTS

Two-way analysis of variance (ANOVA) with three replications was used to test if the system uniformity and nitrogen application rate had a significant effect on the mean and *Us* for soil nitrate content at a significance level of 0.05. As the Hydra Probe sensors were only installed in one plot of each treatment, a two-way ANOVA with one replication was applied to the 2009 Hydra Probe sensor data to test the significance of the system uniformity and nitrogen application rate on the seasonal mean value and seasonal mean *Us* for water content and electrical conductivity. No ANOVA was conducted for the 2010 Hydra Probe sensor data because only one factor (system uniformity) was considered in the experimental design. These statistical tests were performed using SAS (version 8.02, SAS Institute, Inc., Cary, N.C.).

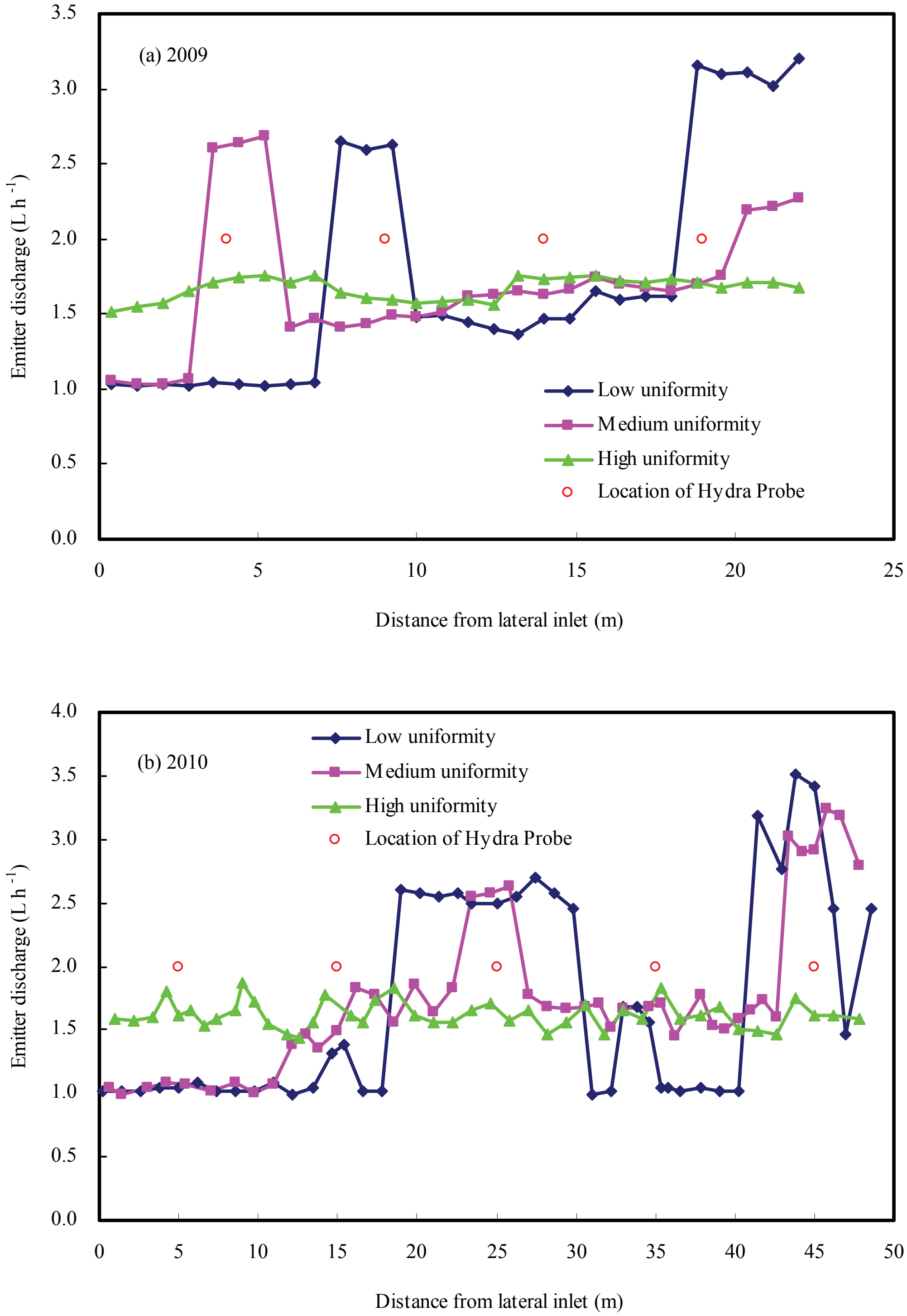


Figure 3. Variations in emitter discharge rates measured along a dripline for the low, medium, and high uniformity treatments in the (a) 2009 and (b) 2010 experiments.

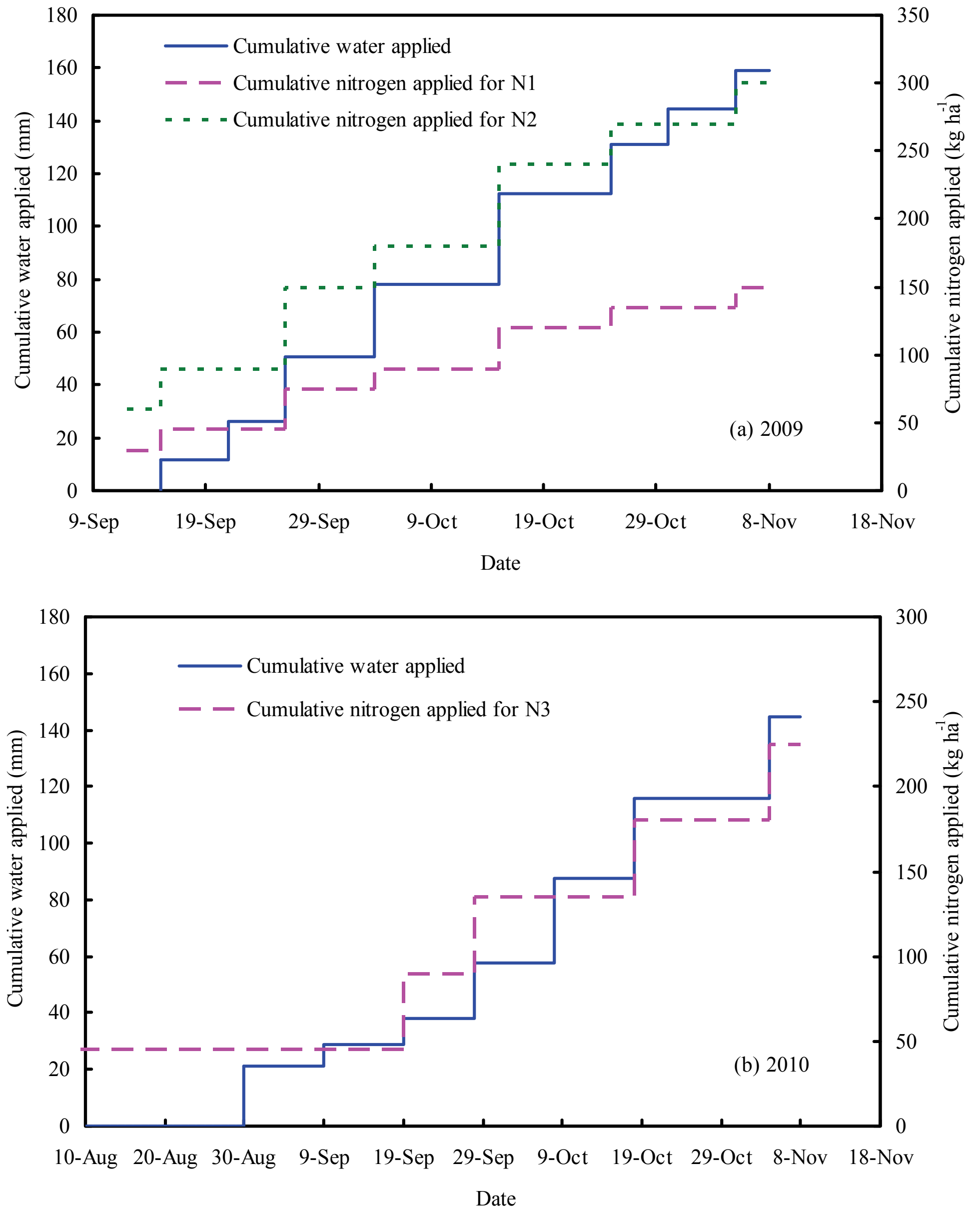


Figure 4. Irrigation and fertigation schedules during the (a) 2009 and (b) 2010 seasons.

RESULTS AND DISCUSSION

DYNAMICS OF WATER AND EC_b DURING A FERTIGATION EVENT

The variation in the mean and *Us* of the water content and soil bulk electrical conductivity (EC_b) during fertigation on 4 October 2009 for various treatments is illustrated in figure 5. Similar patterns were observed for the other fertigation events. For all of the treatments, the water content and EC_b increased continuously during fertigation. After the end of fertigation, the water content and EC_b decreased gradually as the uptake of water and nutrients by plants continued.

As indicated in figure 5, the dynamics of the *Us* of the water content and EC_b during fertigation was dependent on the relative magnitude of the fertigation *Us* and the *Us* of the water content and EC_b at the beginning of fertigation. When the drip fertigation *Us* was lower than the *Us* of the initial water content and EC_b, the uniformity of the water content and EC_b were reduced during fertigation. Otherwise, the water content and EC_b became more uniformly distributed as fertigation continued. For example, in the C1N1 (*Us* = 55%), C1N2 (*Us* = 55%), and C2N2 (*Us* = 73%) treatments, the uniformity of the water content and EC_b decreased during fertigation because the drip fertigation *Us* values were lower than the *Us* of the water content and EC_b at the beginning of fertigation (greater than 83%, figs. 5a, 5b, and 5d). Similar to C1N1, C1N2, and C2N2, the *Us* of the water content of the C2N1 treatment decreased during fertigation because the fertigation *Us* (73%) was lower than the *Us* of the initial water content (87%, fig. 5c). However, the *Us* of the EC_b increased from its initial value of 53% to 62% during fertigation because the fertigation *Us* (73%) was greater than the *Us* of the initial EC_b (53%). Because the fertigation *Us* of C3N1 and C3N2 (95%) was greater than the *Us* of the initial water content

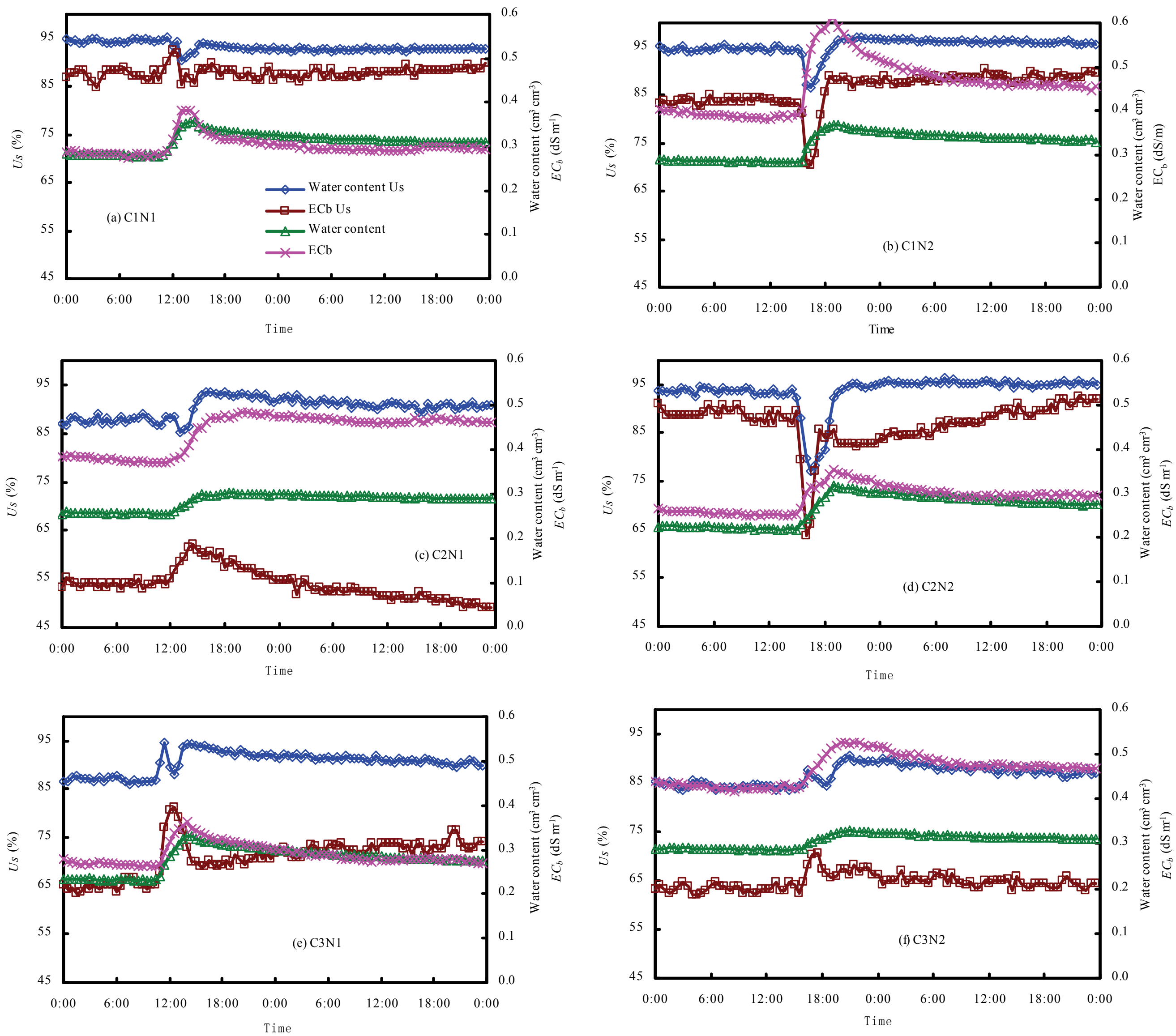


Figure 5. Mean and statistical uniformity (*Us*) of soil water content and bulk electrical conductivity at a depth of 15 cm during fertigation on 4 October 2009. For the N1 and N2 treatments, fertigation started at 9:00 and 13:55 and ended at 13:55 and 18:55, respectively.

and EC_b, a significant improvement in the distribution of the water content and EC_b was observed during fertigation (fig. 5f).

Figure 5 also shows that the effect of irrigation/fertigation on the spatial distribution of water and salts (nitrogen) in the root zone was nearly completed as water and fertilizer application ceased. That is, the *Us* values were close to the values at which they started within 24 h of irrigation/fertigation. The absolute difference in *Us* between the value at the beginning of the irrigation/fertigation event and the value at 24 h after the event ceased, averaged over all of the treatments, was within two percentage points for water content and within four percentage points for EC_b.

The variation in daily mean water content and EC_b and the variation in emitter discharge rate along a lateral are compared in figure 6 for different fertigation *Us* values for the selected fertigation on 4 October 2009 to illustrate the difference in water content and EC_b that resulted from different emitter discharge rates. For any system uniformity tested, neither water content nor EC_b followed the changes in emitter discharge rates. For the C1N2 treatment, for example, the emitters with discharge rates of 1.05, 2.59, 1.37, and 3.16 L h^{-1} (at a distance of about 3, 8, 13, and 18 m from the inlet) produced a daily mean water content of 0.30, 0.33, 0.30, and 0.31 and a daily mean EC_b of 0.47, 0.46, 0.39, and 0.49, respectively (fig. 6a). It can be seen in figure 6 that the daily mean water contents along the dripline for all of the treatments were near field capacity (0.33 cm^3 cm^{-3}, table 1), suggesting a primary convection movement of nitrate in solution. This was confirmed by the fact that a larger amount of fertigated nitrogen (N2) usually resulted in an expected greater daily mean EC_b than the N1 treatment for a given system uniformity.

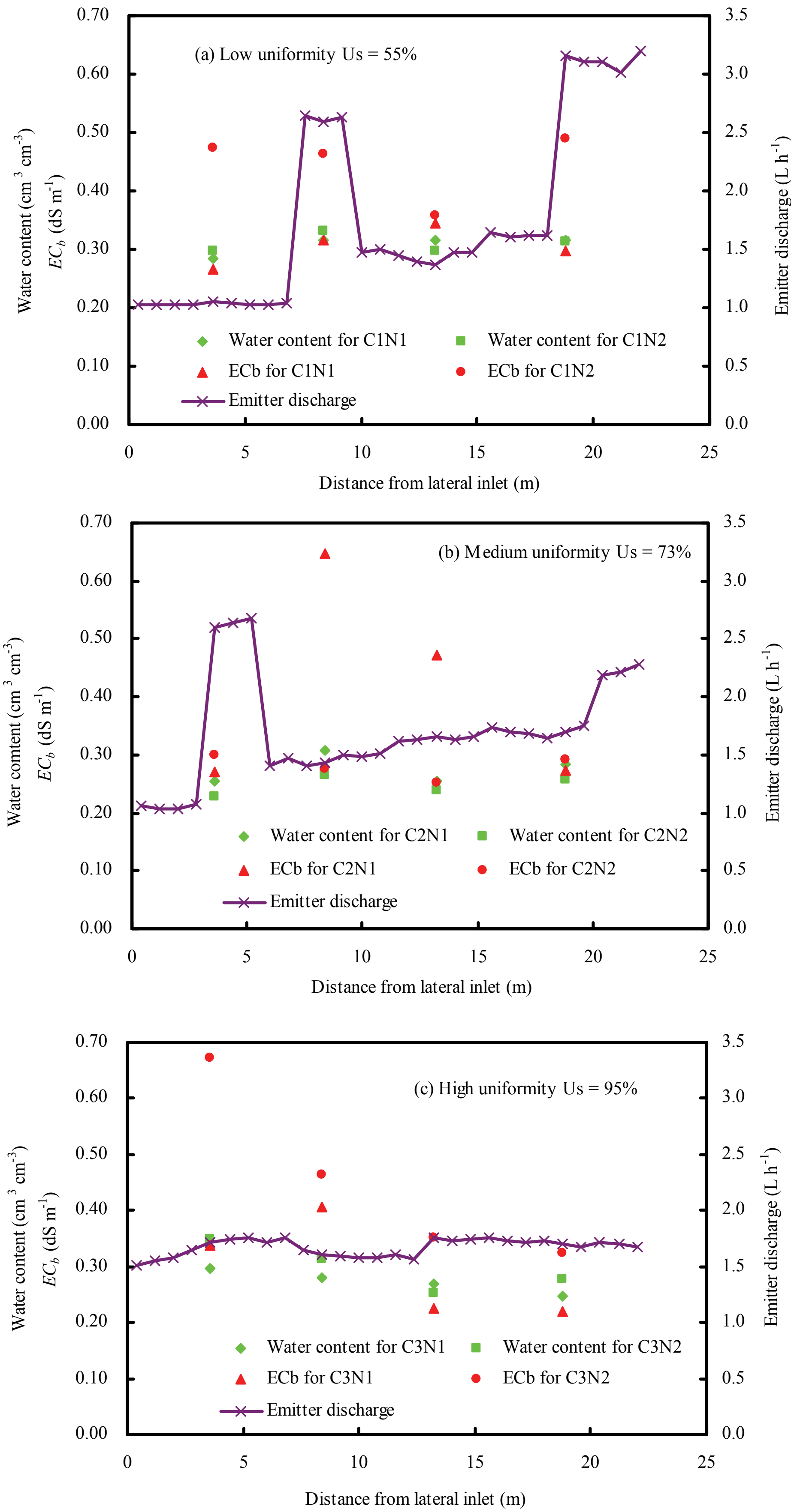


Figure 6. Comparison between the variations in water content and bulk electrical conductivity and the variations in emitter discharge rates along a dripline for fertigation on 4 October 2009 for the (a) low, (b) medium, and (c) high uniformity treatments.

Table 2. Mean, coefficient of variation (CV), and statistical uniformity (*Us*) of the initial water content, NH_4-N, and NO_3-N for the entire experimental field prior to seeding during the 2009 and 2010 seasons.

Depth	2009			2010		
(cm)	Mean	CV	*Us*	Mean	CV	*Us*
Water content (cm^3 cm^{-3})						
0-20	0.26	0.11	89	0.23	0.14	86
20-40	0.27	0.15	85	0.27	0.11	89
40-60	0.27	0.15	85	0.29	0.19	81
60-80	0.28	0.06	94	0.28	0.04	96
80-100	0.30	0.05	95	0.28	0.03	97
Average	0.28	0.06	94	0.27	0.09	91
NO_3-N (mg kg^{-1})						
0-20	55.8	0.75	25	39.7	1.03	-3
20-40	35.7	0.49	51	42.2	0.81	19
40-60	35.8	0.49	51	26.1	0.08	92
60-80	26.2	0.73	27	24.6	0.21	79
80-100	17.0	0.51	49	20.4	0.30	70
Average	34.1	0.59	41	30.6	0.49	51
NH_4-N (mg kg^{-1})						
0-20	1.5	0.54	46	5.4	0.25	75
20-40	0.6	0.55	45	4.9	0.30	70
40-60	1.0	0.65	35	5.3	0.37	63
60-80	1.3	0.76	24	5.3	0.12	88
80-100	1.3	0.38	62	5.2	0.18	82
Average	1.1	0.58	42	5.2	0.24	76

VARIATIONS IN UNIFORMITY OF WATER CONTENT AND EC_b DURING THE GROWING SEASON

The variation in the mean and *Us* of the water content and bulk electrical conductivity (EC_b) obtained from the Hydra Probe sensor measurements during the 2009 and 2010 seasons is illustrated in figures 7 and 8, respectively. The EC_b *Us* of the C2N1 treatment in 2009 was not included because one probe in the plot was out of order for EC_b measurement late in the season. For all of the treatments, soil water content usually fluctuated between 70% and 100% of the field capacity, increasing greatly following an irrigation event and then decreasing gradually due to crop water consumption. There were some differences in water content among the treatments. These might be mainly caused by the difference in soil water content at seeding. As indicated in figures 7a and 8a, the initial soil water content for all of the treatments demonstrated a coefficient of variation (CV) of 0.11 in 2009 and a CV of 0.06 in 2010. The gravimetric measurement of the initial soil content within 0-100 cm depth prior to seeding also indicated a comparable CV that ranged from 0.05 to 0.15 in 2009 and from 0.03 to 0.19 in 2010 (table 2). Soil bulk electrical conductivity (EC_b) showed a general decreasing trend during both seasons, although there was an increase following an irrigation/fertigation event. This suggests that the content of salt ions in the soil decreased due to irrigation leaching and plant uptake.

The *Us* of the water content fluctuated when an irrigation or fertigation event was conducted. A uniform water distribution in the soil was observed for most of the treatments in both seasons, and the *Us* ranged from 84% to 97% in 2009 and from 86% to 99% in 2010. However, an anomaly was observed in the *Us* of the C1N3 treatment in 2010, which ranged from 62% to 71% (fig. 8b). The nonuniform

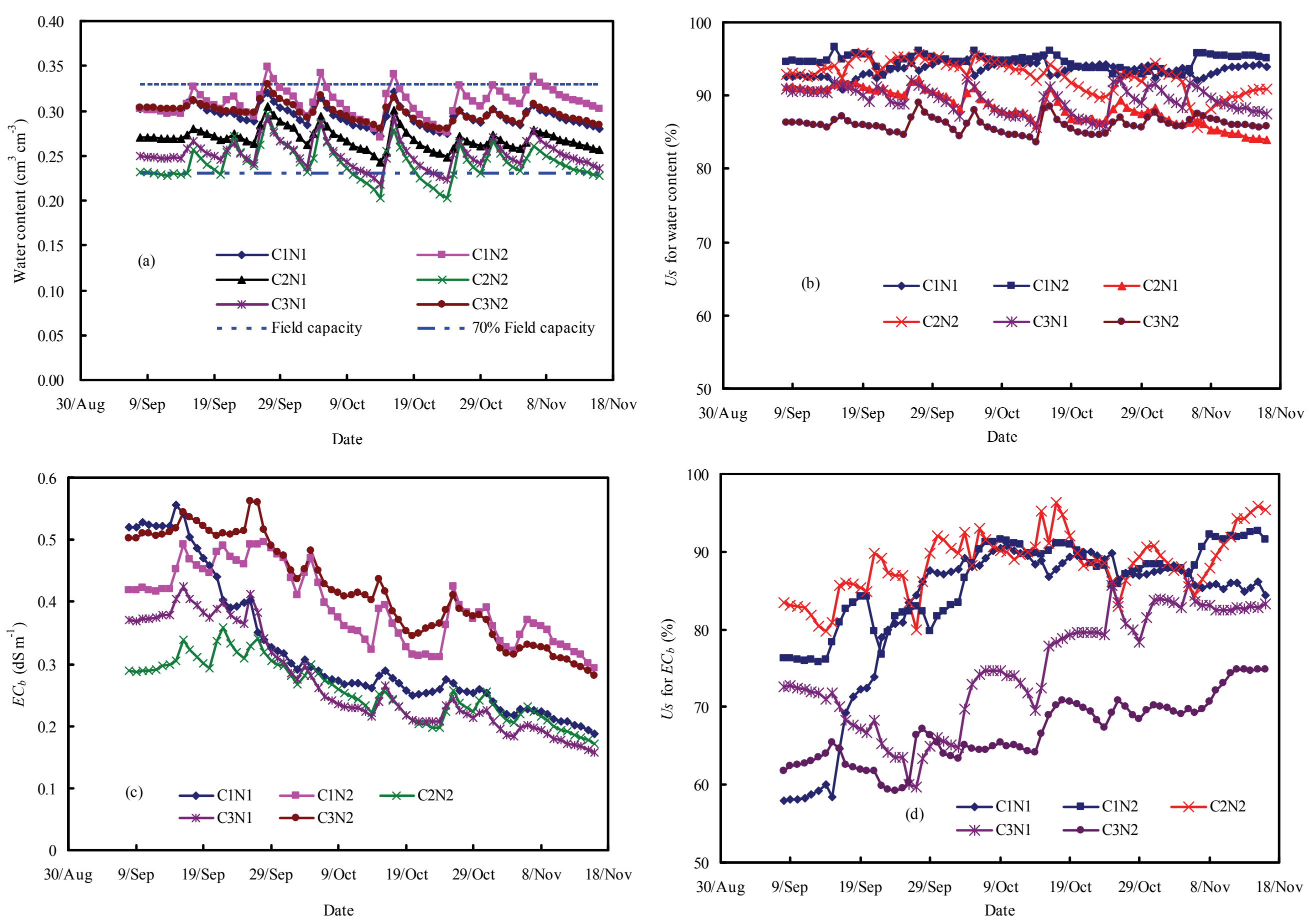


Figure 7. Mean and statistical uniformity (*Us*) of soil water content and bulk electrical conductivity (EC_b) during the 2009 growing season.

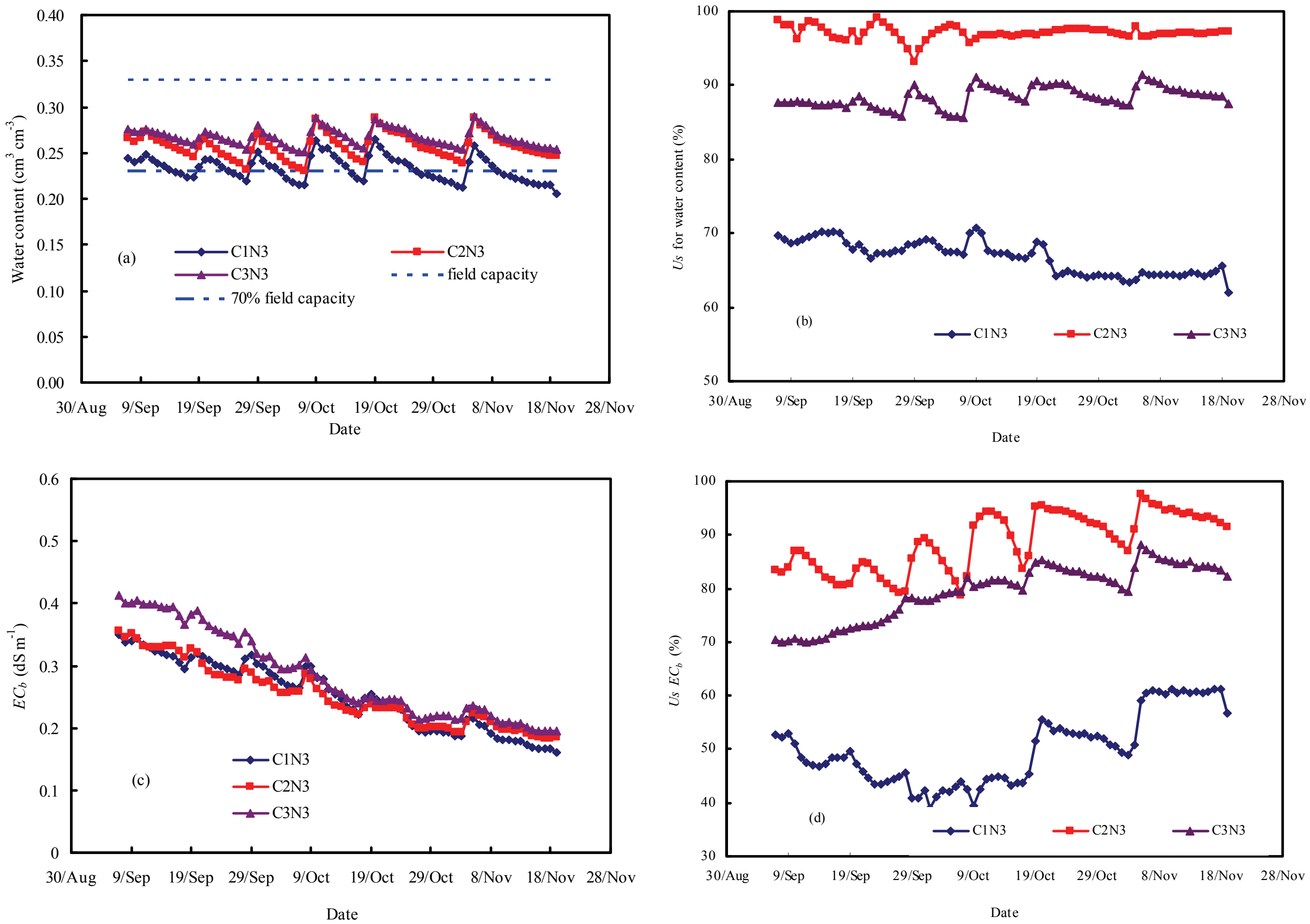


Figure 8. Mean and statistical uniformity (*Us*) of soil water content and bulk electrical conductivity (EC_b) during the 2010 growing season.

Table 3. Mean and statistical uniformity (*Us*) of initial soil water content and bulk electrical conductivity and seasonal mean values measured with the Hydra Probe sensors for each experimental plot during the 2009 and 2010 growing seasons.

Growing Season and Treatment		System Uniformity (*Us*, %)	Mean for Water Content (cm^3 cm^{-3}) Initial	Mean for Water Content Seasonal Mean	Mean for EC_b (dS m^{-1}) Initial	Mean for EC_b Seasonal Mean	*Us* for Water Content (%) Initial	*Us* for Water Content Seasonal Mean	*Us* for EC_b (%) Initial	*Us* for EC_b Seasonal Mean
2009	C1N1	55	0.30	0.29	0.52	0.32	93	93	58	82
	C1N2	55	0.30	0.31	0.42	0.39	95	95	76	86
	C2N1	73	0.27	0.27	0.37	0.38	91	88	73	NA[a]
	C2N2	73	0.23	0.24	0.29	0.26	93	93	84	88
	C3N1	95	0.25	0.25	0.37	0.27	91	89	73	75
	C3N2	95	0.30	0.30	0.50	0.42	83	86	62	67
	ANOVA[b]	System uniformity		NS (p = 0.45)		NS (p = 0.94)		NS (p = 0.28)		NS (p = 0.67)
		Nitrogen applied		NS (p = 0.63)		NS (p = 0.72)		NS (p = 0.63)		NS (p = 0.50)
2010	C1N3	53	0.24	0.23	0.35	0.25	70	67	53	50
	C2N3	65	0.27	0.26	0.36	0.25	99	97	84	89
	C3N3	94	0.28	0.27	0.41	0.25	88	88	70	79

[a] NA = not available.
[b] NS = not significant at a probability level of 0.05.

distribution of water in the C1N3 treatment may have been caused by the extremely low *Us* of the initial water content (70%) and the low drip system uniformity (53%) (table 3).

The *Us* of the water content was compared with that of the EC_b, and the results suggested that the EC_b *Us*, which ranged from 58% to 96% in 2009 and from 39% to 98% in 2010, was lower than the water content *Us*. As shown in figures 7d and 8d, the EC_b *Us* generally increased with an increase in the number of days after seeding, although a fluctuation might occur following an irrigation/fertigation event. For example, in 2009, the EC_b *Us* of the C1N1 treatment increased from 58% at the beginning of the season to 84% at the end of season, which suggests that the uniformity of the distribution of salts and nutrients in the soil increased as fertilizer was applied and plant uptake continued.

The results illustrated in figures 7d and 8d indicated that higher system uniformities did not always result in a more uniform distribution of EC_b during the irrigation season. For example, at a system *Us* of 55%, 73%, and 95%, the seasonal mean EC_b *Us* averaged over the two nitrogen application rates was 84%, 88%, and 71%, respectively (ta-

Table 4. Mean and uniformity coefficient of the soil nitrate nitrogen content measured on selected dates in the 2009 season.

Parameter	Date (2009)	Treatment	Depth (cm) 0-20	20-40	40-60	60-80
Mean (mg kg^{-1})	29 September	C1N1	46.8	39.4	38.6	37.5
		C1N2	63.2	42.6	35.1	24.6
		C2N1	55.4	42.7	46.0	48.3
		C2N2	48.6	25.1	25.0	21.9
		C3N1	35.3	38.8	40.2	36.9
		C3N2	59.3	43.3	40.0	42.9
	ANOVA[a]	System uniformity	NS (p = 0.74)	NS (p = 0.79)	NS (p = 0.92)	NS (p = 0.71)
		Nitrogen applied	NS (p = 0.19)	NS (p = 0.74)	NS (p = 0.39)	NS (p = 0.22
	17 October	C1N1	38.2	27.8	34.0	34.4
		C1N2	52.9	44.3	40.2	32.4
		C2N1	41.0	32.1	40.0	35.7
		C2N2	61.7	42.5	39.3	31.9
		C3N1	37.5	30.3	43.1	40.2
		C3N2	56.6	42.4	40.1	38.2
	ANOVA	System uniformity	NS (p = 0.59)	NS (p = 0.98)	NS (p = 0.86)	NS (p = 0.43)
		Nitrogen applied	(p = 0.002)**	(p = 0.02)*	NS (p = 0.75)	NS (p = 0.52)
	17 November	C1N1	28.1	23.6	29.8	33.5
		C1N2	59.6	30.9	32.0	26.7
		C2N1	57.3	32.2	40.6	30.2
		C2N2	57.5	30.3	40.4	44.2
		C3N1	37.2	35.3	27.3	28.6
		C3N2	79.6	46.8	54.4	39.9
	ANOVA	System uniformity	NS (p = 0.28)	NS (p = 0.19)	NS (p = 0.53)	NS (p = 0.42)
		Nitrogen applied	(p = 0.01)**	NS (p = 0.36)	NS (p = 0.25)	NS (p = 0.17)
Uniformity Coefficient (*Us*, %)	29 September	C1N1	58	62	74	56
		C1N2	62	58	53	62
		C2N1	54	58	56	46
		C2N2	67	54	51	61
		C3N1	60	43	47	50
		C3N2	65	57	59	56
	ANOVA	System uniformity	NS (p = 0.98)	NS (p = 0.81)	NS (p = 0.57)	NS (p = 0.84)
		Nitrogen applied	NS (p = 0.55)	NS (p = 0.86)	NS (p = 0.57)	NS (p = 0.33)
	17 October	C1N1	65	67	68	65
		C1N2	64	69	58	75
		C2N1	64	57	65	80
		C2N2	77	63	69	71
		C3N1	78	63	64	67
		C3N2	64	66	61	65
	ANOVA	System uniformity	NS (p = 0.73)	NS (p = 0.64)	NS (p = 0.80)	NS (p = 0.37)
		Nitrogen applied	NS (p = 0.93)	NS (p = 0.62)	NS (p = 0.65)	NS (p = 0.94)
	17 November	C1N1	63	68	59	48
		C1N2	37	62	58	67
		C2N1	46	45	56	59
		C2N2	48	45	27	52
		C3N1	74	48	36	59
		C3N2	71	67	-10[b]	57
	ANOVA	System uniformity	NS (p = 0.10)	NS (p =0.17)	NS (p = 0.07)	NS (p = 0.95)
		Nitrogen applied	NS (p = 0.38)	NS (p = 0.58)	NS (p = 0.11)	NS (p = 0.56)

[a] NS = not significant at a probability level of 0.05, * = significant at a probability level of 0.05, and ** = significant at a probability level of 0.01.
[b] Negative *Us* values indicate SD > mean (i.e., very nonuniform).

ble 3). Moreover, as indicated in table 3, the seasonal mean *Us* of the water content and EC_b was correlated to the *Us* of the initial water content and EC_b. A regression on the data presented in table 3 yielded the following equations:

$$\overline{Us}_w = 0.01Us + 1.1Us_{wi} - 7 \quad (r^2 = 0.980,\ SE = 2) \tag{2}$$

$$\overline{Us}_{EC} = -0.1Us + 0.9Us_{ECi} - 19 \quad (r^2 = 0.658,\ SE = 9) \tag{3}$$

where

$\overline{Us}_w$ = seasonal mean statistical uniformity of water content (%)

$\overline{Us}_{EC}$ = seasonal mean statistical uniformity of bulk electrical conductivity (%)

Us = statistical uniformity of drip irrigation system (%)

Us_{wi} = statistical uniformity of initial water content (%)

Us_{ECi} = statistical uniformity of initial bulk electrical conductivity (%)

r^2 = coefficient of determination

SE = standard error of the regression equation (%).

The coefficients for Us_{wi} and Us_{ECi} were considerably larger than the coefficients of drip system *Us* in equations 2 and 3, indicating that the distribution of the initial water content and bulk electrical conductivity had a stronger effect on the uniformity of water and nutrients in the soil than

Table 5. Mean and uniformity coefficient of the soil nitrate nitrogen content measured on selected dates in the 2010 season.

Parameter	Date (2010)	Treatment	Depth (cm) 0-20	20-40	40-60	60-80	80-100
Mean ($mg\ kg^{-1}$)	21 October	C1N3	18.8	12.4	22.3	23.8	22.3
		C2N3	18.3	13.7	21.8	21.9	19.7
		C3N3	19.3	13.3	22.6	23.5	20.5
	ANOVA[a]	System uniformity	NS (p = 0.90)	NS (p = 0.96)	NS (p = 0.99)	NS (p = 0.98)	NS (p = 0.84)
	25 November	C1N3	17.9	9.7	13.3	15.5	16.4
		C2N3	17.9	15.8	18.8	18.3	15.6
		C3N3	16.4	9.0	16.8	18.1	16.1
	ANOVA	System uniformity	NS (p = 0.94)	NS (p = 0.60)	NS (p = 0.79)	NS (p = 0.87)	NS (p = 0.96)
Us (%)	21 October	C1N3	46	50	46	40	47
		C2N3	70	38	49	38	42
		C3N3	59	38	36	37	39
	ANOVA	System uniformity	NS (p = 0.42)	NS (p = 0.66)	NS (p = 0.71)	NS (p = 0.99)	NS (p = 0.96)
	25 November	C1N3	21	-3[b]	3	13	37
		C2N3	56	35	49	41	42
		C3N3	50	46	29	28	41
	ANOVA	System uniformity	NS (p = 0.25)	NS (p = 0.18)	NS (p = 0.48)	NS (p = 0.84)	NS (p = 0.97)

[a] NS = not significant at a probability level of 0.05.

[b] Negative *Us* values indicate SD > mean (i.e., very nonuniform).

did the uniformity of water and fertilizer applied through the microirrigation system. The ANOVA (table 3) also indicated that the uniformity of the drip system and nitrogen application rate had an insignificant effect on the seasonal mean water content and EC_b and the seasonal mean uniformity of the water content and EC_b in 2009.

Distribution of Nitrogen in the Soil

The mean and coefficient of variation (CV) of the initial NH_4-N and NO_3-N content for the 2009 and 2010 seasons are summarized in table 2. The sum of the initial NO_3-N and NH_4-N contents at a depth of 100 cm for the 2010 season (35.8 $mg\ kg^{-1}$) was similar to that for the 2009 season (35.2 $mg\ kg^{-1}$). The variability in the initial NO_3-N and NH_4-N contents was lower in 2010 than in 2009. The content of NO_3-N and NH_4-N displayed moderate variability, with CV values ranging from 0.49 to 0.76 for the 2009 season and from 0.08 to 1.0 for the 2010 season (Hillel, 1980).

The mean and *Us* values of the soil NO_3-N content on selected dates in 2009 and 2010 are summarized in tables 4 and 5, respectively. As indicated in the tables, the NO_3-N content varied from 22 to 80 $mg\ kg^{-1}$ during the 2009 season and from 9 to 24 $mg\ kg^{-1}$ in 2010. These values were within the normal range of NO_3-N content for cabbage cultivation in the experimental region (Du et al., 2009). For a given system uniformity, treatment with a larger amount of nitrogen (N2) resulted in a significantly greater soil nitrate content in the 0-20 cm depth on the selected dates of 17 October and 17 November in 2009. The *Us* values for nitrate, which ranged from -10% to 80% in 2009 and from -3% to 70% in 2010, were substantially lower than those for water content and EC_b (figs. 7 and 8) due to the relatively low *Us* of the initial nitrate content (25% to 51% in 2009 and -3% to 92% in 2010, table 2). The ANOVA indicated that system uniformity and nitrogen application rate had an insignificant effect on the uniformity of nitrate in the soil for the 2009 and 2010 seasons at a significance level of 0.05. Examining the p-values of the system uniformity in table 4 reveals an increasing influence trend of system uniformity on the uniformity of nitrate as the cumulative number of fertigation events increased during the growing season of cabbage. For example, the p-value for the 0-20 cm (top) soil layer decreased from 0.98 on 29 September (when a total of two fertigation events had been conducted) to 0.10 on 17 November (when a total of six fertigation events had been conducted). This suggests that the nonuniformly applied water and fertilizer may have had a cumulative contribution to the nonuniformity of nitrate in the soil.

The results presented above were obtained by field experiments conducted in a greenhouse on a shallow-rooted crop in the absence of rainfall. That would make the effects of irrigation nonuniformity even more pronounced because a uniform rainfall event would reduce the nonuniformity of water and nitrogen in the soil. In addition, the relatively smaller emitter spacing along the dripline (40 cm) and lateral spacing (80 cm), being able to accelerate the lateral redistribution of water in the soil (Arbat et al., 2010), might be a contributor to the uniform distribution of water in the soil produced by a quite nonuniform water application. The spatial variability of soil water content (table 2) might also dampen the influence of nonuniform water application on the distribution of water in the soil.

Crop yield and quality of products are also important factors in determination of target uniformity of microirrigation systems. Measurements in the similar experiments indicated that drip system uniformity had an insignificant effect on the mean cabbage head yield and quality parameters (concentration of vitamin C, total sugar, crude fiber, crude protein, and nitrates) and their uniformities (Li et al., 2011). The possibility of using a target uniformity lower than the value recommended by the current standards (e.g., *ASAE Standards*, 2003; Chinese Standards, 1995) was strengthened by these results.

Summary and Conclusions

The effects of system uniformity and nitrogen application rate on the water content, bulk electrical conductivity, and nitrogen content of soil were quantitatively evaluated by applying drip irrigation and fertilizers to Chinese cabbage in a solar-heated greenhouse during two growing seasons. The following conclusions were supported by the results of the present study:

- A uniform distribution of water in the soil was observed when the drip system uniformity (*Us*) ranged between 53% and 95%. The uniformity of drip system and nitrogen application rate had an insignificant effect on the seasonal mean water content and EC_b and on the seasonal mean uniformity of the water content and EC_b.
- The soil bulk electrical conductivity showed a more nonuniform distribution than did the water content. The uniformity of the water content and EC_b during the irrigation season was correlated to their initial distribution, and the effect of system uniformity was insignificant at a significance level of 0.05.
- Drip system uniformity and nitrogen application rate had an insignificant effect on the uniformity of nitrate in the soil at a significance level of 0.05.
- Drip irrigation uniformities that are lower than the values recommended by the current standards might be used if sufficient irrigation and fertigation events are conducted to approach a uniform distribution of water and nutrients in the soil.

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