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Effects of drip system uniformity on yield and quality of Chinese cabbage heads

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ABSTRACT

Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) production experiments with different system uniformities and field scales controlled by driplines were conducted in a solar heated greenhouse in 2009 and 2010. Three Christiansen uniformity coefficients (*CU* = 62, 81 and 96%) and two nitrogen application rates (150 and 300 kg/ha) were evaluated in 2009. In 2010, three *CU* values (57, 74, and 95%) and one nitrogen application rate (225 kg/ha) were tested. The uniformity of systems was established by randomly assembling segments of drip tubes with five different nominal emitter discharge rates (1.05, 1.4, 1.65, 2.3 and 2.6 L/h) along a dripline. For all of the system uniformities tested, the plant height, head height to diameter ratio, dry matter above ground and nitrogen uptake displayed high uniformity coefficients throughout the entire growing season. The effects of system uniformity and nitrogen application rate on the mean yield and quality indexes and their uniformities were insignificant. With the increasing of field scale controlled by one dripline, the uniformity of crop growth, yield and quality indexes demonstrated a decreasing tendency. 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, and their usage should consider the field scale controlled by dripline.

1. Introduction

Uniformity of water application is an important parameter in the design, maintenance and management of drip irrigation systems. The modeling of crop response to water application indicated that there was a dependent relationship between crop yield and irrigation uniformity and a more uniform application of water leads to a better distribution of nutrients in the soil and consequently a higher crop yield (Warrick and Gardner, 1983; Letey et al., 1984; Montovani et al., 1995; Li, 1998).

Several design and evaluation standards of drip irrigation uniformity have been developed in different countries (e.g., ASAE, 1988; Chinese Standard, 1995; ASABE, 2003). ASABE standard EP405.1 (ASABE, 2003) recommends a design emission uniformity (EU) of 70–95% depending on the source (point or line source), crop, emitter spacing and field slope. The Chinese standard SL103-1995 (Chinese Standard, 1995) suggests a design Christiansen uniformity coefficient (CU) of greater than 80%. However, many researchers have found that the uniformity of soil water from a non-uniform application could be improved over time due to lateral flow within the soil matrix and a redistribution of soil water, accumulated irrigation received and the development of the crop root system (Stern and Bresler, 1983; Perrens, 1984; Li and Kawano, 1996; Li, 1998; Chen et al., 2004). These results suggest that a uniformity criterion that is lower than the values recommended by current standards may be used.

Crop production is one measure of irrigation uniformity and efficiency (Solomon, 1984). Stern and Bresler (1983) showed that when soil properties were homogeneous, the redistribution of soil water after a non-uniform irrigation application caused corn (*Zea mays* L.) yield to be more uniform than the water applied. Mateos et al. (1997) indicated that there were no significant differences in cotton (*Gossypium hirsutum* L.) yield whether the sprinkler uniformity (Wilkox and Swailes' uniformity coefficients *WSUC*, $WSUC = 100(1 - CV)$ 100, *CV* is the coefficient of variability) was 80% or 52%. Li and Rao (2000) demonstrated that the uniformities of winter wheat (*Triticum aestivum* L.) yield were higher than those for water application and the yields seemed to be insensitive to spatial variation of applied water even though sprinkler uniformities varied from 57% to 89% during the irrigation season. The influence of sprinkler uniformity on crop yield observed in experiments is not as important as previous modeling results (Li, 1998). In a five-year study conducted in the Texas High Plains (Bordovsky and Porter, 2008), significant difference in cotton yield was not observed among subsurface drip irrigation treatments at flow variations (q_{var}) of 5%, 15% and 27%.

The experimental results mentioned above have indicated that the uniformity that is lower than the values recommended by

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current standards has a minor influence on crop yield. However, these studies were mainly focused on field crops. The production of vegetables in greenhouse has been increasing greatly in China, accounting for about 20% of total national vegetable production (Zhang, 2000). Drip irrigation is widely used in greenhouse vegetable production as it generates favorable environments for vegetable crop growth. Whether the results obtained from field crops can be applied to vegetable crops grown in greenhouse environments needs further research, since vegetable crops are normally more sensitive to water and nutrient deficits and no uniform precipitation was received to compensate for the nonuniform applied irrigation water during the growing season.

The objectives of this study were to determine the response of crop growth, yield and quality to nonuniform drip fertigation during the irrigation season of Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) in north China plain, and to provide recommendations for modifying the design criteria for microirrigation systems by conducting field experiments in a solar heated greenhouse.

2. Materials and methods

2.1. 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, and 40.1 m above sea level). The greenhouse was 50 m in length and 8 m wide. The soil was sandy loam (Fluvents, Entisols) with a bulk density of 1.44 g/cm^3, a field capacity of 0.33 cm^3/cm^3 and a permanent wilting point of 0.15 cm^3/cm^3 that was measured at 1.5 MPa suction using a centrifugal method. The region has 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.

Chinese cabbage was selected as the experimental crop. The experiments were conducted in the 2009 and 2010 growing seasons. 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. The initial NH_4-N and NO_3-N content for the 2009 and 2010 season are summarized in Table 1. The sum of the initial NO_3-N and NH_4-N content in a depth of 100 cm for the 2010 season (35.8 mg/kg) was similar to that of the 2009 season (35.2 mg/kg).

In the 2009 experiments, Chinese cabbage was seeded on August 12 at a row spacing of 40 cm. The cabbage plants were set at a fixed plant spacing of 60 cm along a row on September 8, and the harvest was conducted on November 15. In 2010, cabbages were seeded on August 11 at a row spacing of 40 cm. Plant setting was completed at a spacing of 60 cm in a row on September 9, and the cabbages were harvested on November 19.

The Christiansen uniformity coefficient (*CU*) (Chinese Standard, 1995) was used to quantify the uniformity of the emitter discharge rate, plant growth and nitrogen uptake, yield and quality indexes.

$$CU = 100 \times \left(1 - \frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{n\bar{x}}\right) \quad (1)$$

where x_i is the parameter being measured for uniformity, which was either emitter discharge rate (L/h), cabbage head height (cm), cabbage head height to diameter ratio, yield (kg/ha), nitrogen uptake (kg/ha) or quality indexes for the ith sample, $\bar{x}$ is the mean of x_i, and n is the number of samples.

In 2009, three designed *CU* levels of 60% (referred to as low uniformity, C1), 80% (referred to as medium uniformity, C2) and 95% (referred to as high uniformity, C3) and two levels of nitrogen application rates of 150 (N1) and 300 kg N/ha (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, including 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 possible lateral exchange of water between plots and allowed for access to each experimental plot. In 2010, three designed *CU* levels that were similar to those used in the 2009 experiments and one fertilizer application level of 225 kg N/ha (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, including C1N3, C2N3 and C3N3. The greenhouse was divided into 9 equal plots of 15.8 m × 2.4 m, and three replicates of each treatment were randomly distributed throughout the greenhouse (Fig. 1b). Such a plot dimension allowed us to use a field scale controlled by dripline differing from the scale used in the 2009 experiment.

2.2. Field installations

For each plot, a dripline was installed continuously along the median of two adjacent rows (Fig. 2a and b), and the two rows were irrigated by one dripline. As a result, the lateral length of the dripline was equal to 22.6 m and 49.8 m for the 2009 and 2010 experiments, respectively.

Low and medium designed *CU* values were obtained by randomly assembling segments of drip tubes with five different nominal discharge values of 1.05, 1.65, 2.6 L/h (Netafim Ltd., Tel Aviv, Israel), 1.4 L/h (Ruisheng-Yamit Ltd., Lanzhou, China), and 2.3 L/h (IrriGreen Ltd., Beijing, China) along the entire length of the line. However, a mean emitter discharge rate of 1.65 L/h at 0.1 MPa, which was similar to the mean emitter discharge for the high *CU* 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

Table 1
The initial water and NH_4-N and NO_3-N content for the entire experimental field prior to seeding during the 2009 and 2010 season.

Parameter	Depth (cm)	2009	2010
Water content (cm^3/cm^3)	0–20	0.26	0.23
	20–40	0.27	0.27
	40–60	0.27	0.29
	60–80	0.28	0.28
	80–100	0.30	0.28
	Average	0.28	0.27
NO_3-N (mg/kg)	0–20	55.8	39.7
	20–40	35.7	42.2
	40–60	35.8	26.1
	60–80	26.2	24.6
	80–100	17.0	20.4
	Average	34.1	30.6
NH_4-N (mg/kg)	0–20	1.5	5.4
	20–40	0.6	4.9
	40–60	1.0	5.3
	60–80	1.3	5.3
	80–100	1.3	5.2
	Average	1.1	5.2

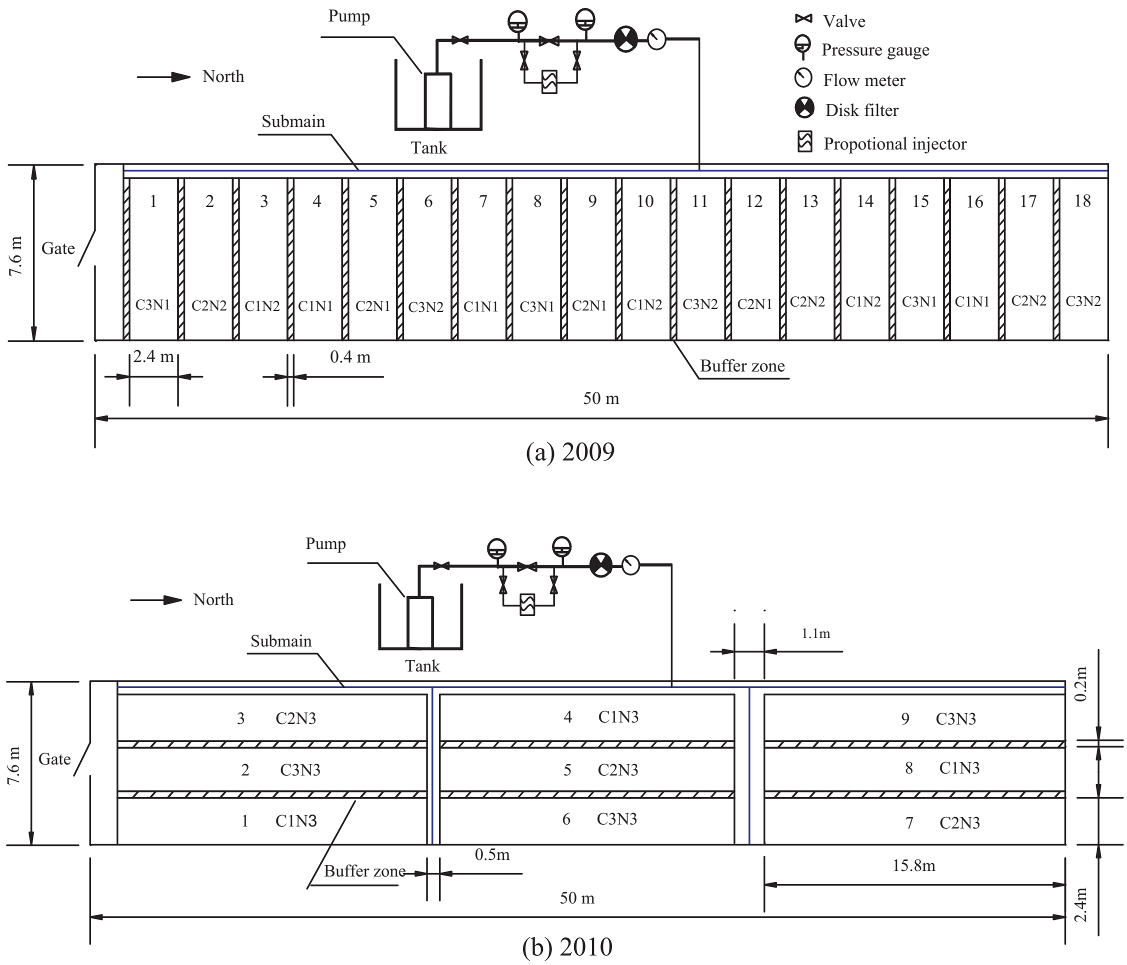

Fig. 1. Schematic of the randomly distributed experimental plots in the greenhouse for the 2009 and 2010 experiments.

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 *CU* treatments were measured prior to lateral installation by cans spaced at an interval of 0.8 (2009) and 1.2 m (2010) to confirm whether the *CU*s of the assembled laterals were comparable with the designed values. The variations of emitter discharge rates along dripline measured prior to the 2009 and 2010 installations are presented in Fig. 3 and the actual *CU*s of the

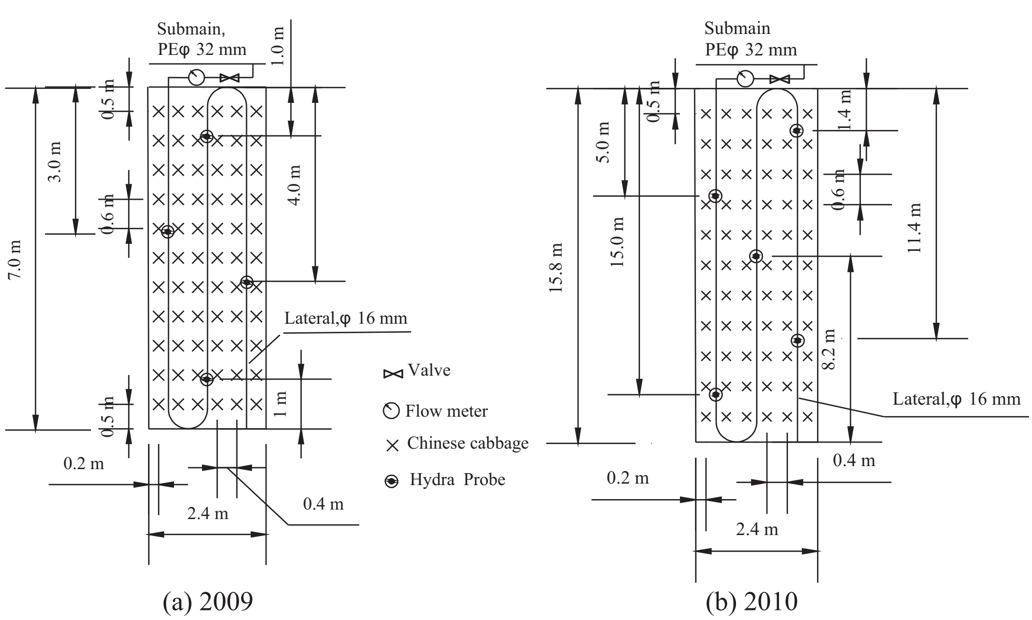

Fig. 2. Schematic of the lateral dripline and the location of Hydra Probe sensors within the experimental plots in 2009 and 2010.

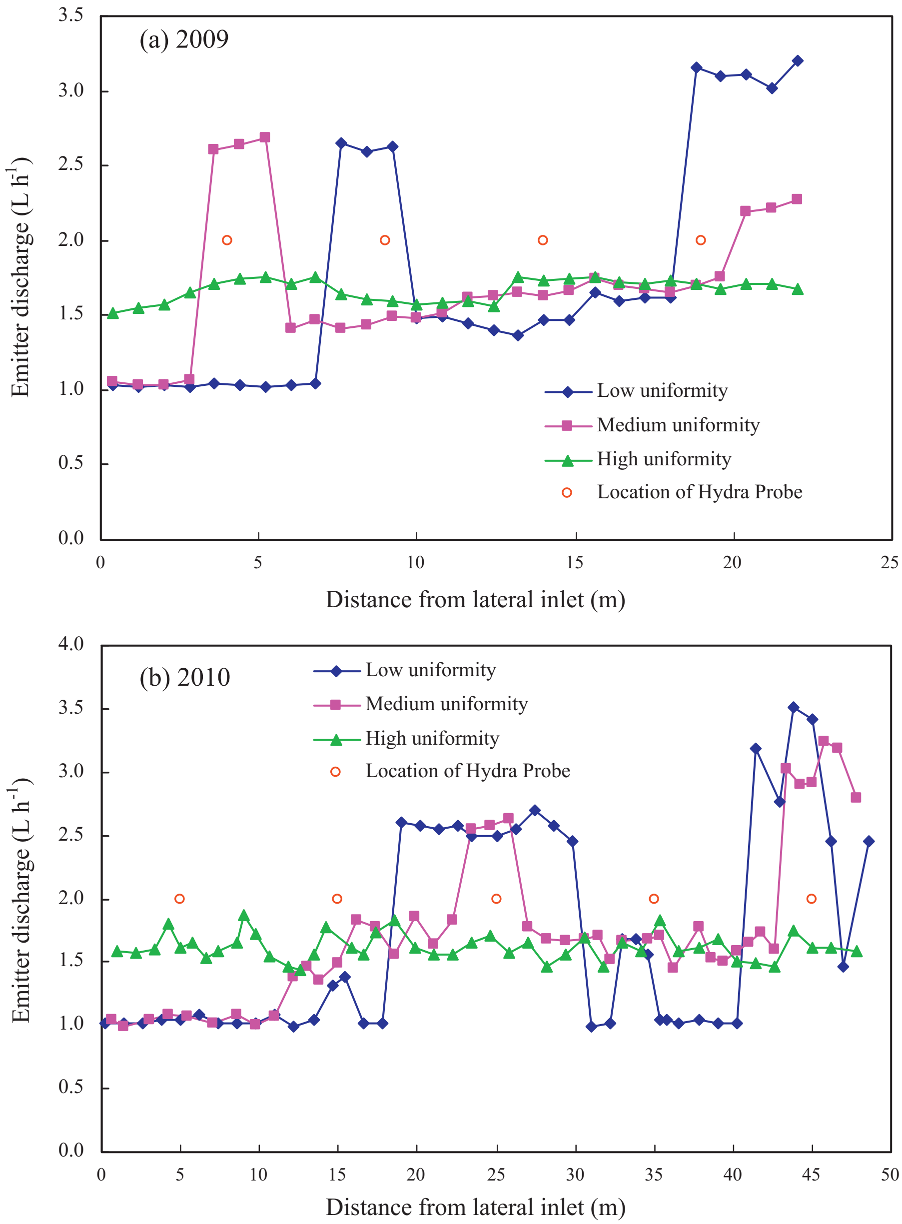

Fig. 3. Variations in emitter discharge rates measured along a dripline for the treatments of low, medium and high uniformity used in the 2009 and 2010 experiments.

2009 and 2010 experiments were 62, 81 and 96% and 57, 74 and 95%, respectively, while the designed values were 60, 80 and 95%.

A water-driven adjustable proportional pump (Model 2504, TEFEN Manufacture and Marketing Plastic Products, Nahsholim, Israel) and a pair of pressure gauges were installed ahead of the filter for fertigation (Fig. 1a and b). A type of multi-parameter capacitance (Frequency Domain Reflectometry, FDR) sensor (Hydra Probe, Stevens Water Monitoring Systems Inc., Oregon, USA), which has been documented as a low-cost instrument with acceptable measurement accuracy of soil water content (e.g., Kizito et al., 2008), was selected to monitor continuously the temporal and spatial variation of the soil water content within one plot of each treatment. Four sensors were installed within a plot for the 2009 experiments, while five sensors were used in 2010 (Fig. 2a and b). 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. The soil water content obtained from the sensor reading were used to represent the average water content within the root zone of Chinese cabbage. During the experiments, the data of soil water content were acquired by a data logger (DataTaker 80, Stevens Water Monitoring Systems Inc., Oregon, USA) at intervals of 15 min.

2.3. Irrigation and fertigation

Similar irrigation schedules were used for each treatment in 2009 and 2010. When the mean water content measured by 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 were applied over nine irrigation events during the 2009 season, while 145 mm of water was applied over seven irrigation events in 2010 (Fig. 4).

A readily soluble fertilizer of urea with 46% of nitrogen was used in 2009 and 2010. Twenty percent of the desired nitrogen content was broadcast prior to seeding, and the remaining fertilizer was

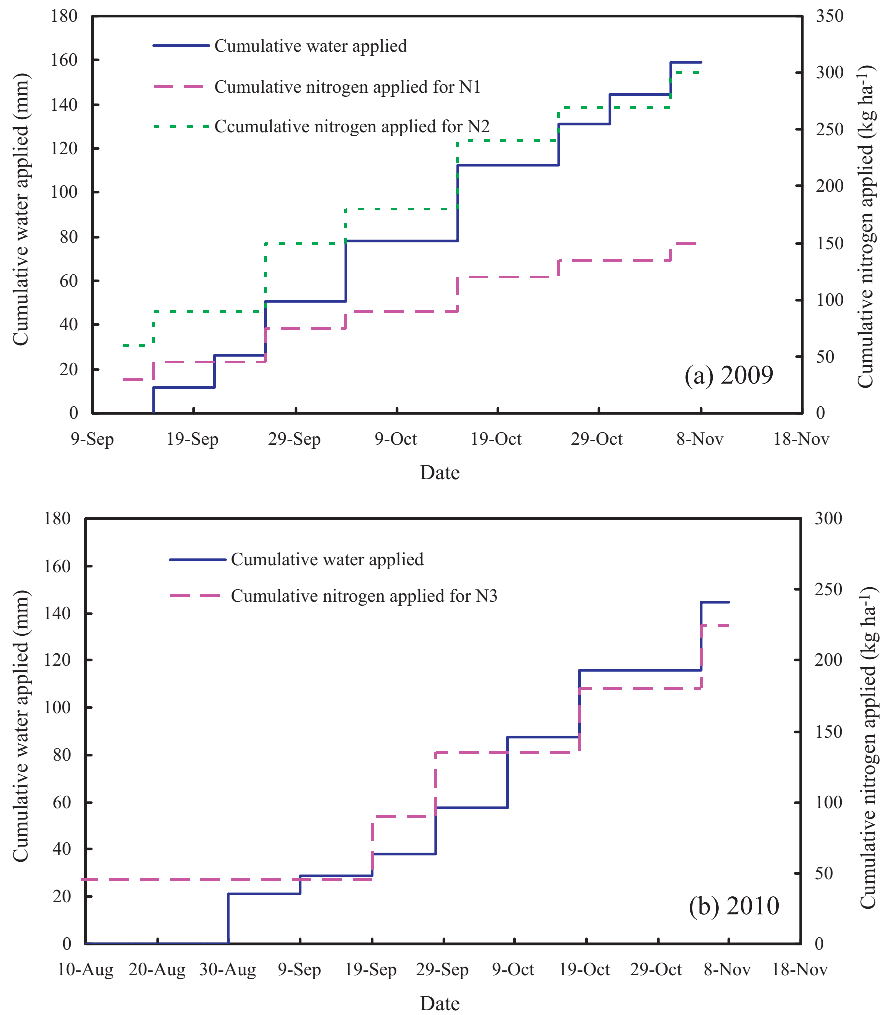

Fig. 4. Irrigation and fertigation schedules during the 2009 and 2010 seasons of Chinese cabbage.

applied in six different splits in 2009 and four equal splits in 2010 (Fig. 4).

2.4. Crop characteristics and statistical analysis

To investigate the effects of drip fertigation uniformity on crop growth, yield and quality, the plant height and head height to diameter ratio were measured every 10 days during the growing season; the dry matter above ground and nitrogen uptake were measured at the end of every growing stage. For plant height and head height to diameter ratio measurement, four equally spaced positions along the dripline in each plot were selected in 2009 and five positions were used in 2010. At each position, two plants of cabbage were marked and used for plant height and head height to diameter ratio measurement during the whole season. Dry matter measurement was sampled around the positions of plant height and head height to diameter ratio measurements, but one representative plant other than the two marked ones at each position was collected. Dry matter above ground was determined by drying at 105 °C to a constant weight. To obtain the total nitrogen content of each dry matter sample, 12 ml H_2SO_4–H_2O per gram of sample was used for digestion and the Kjeldahl nitrogen of the solution was measured by a Kjeldahl apparatus (Kjeltec 2300, Hilleroed, Denmark) (Persson and Wennerholm, 2008). Then the plant nitrogen uptake for each sample was determined by the product of the dry matter above ground and the total nitrogen content. Both the yield of Chinese cabbage heads and the total plant mass above ground were measured by weighing on harvest in 2010, while only the total above ground mass was measured in 2009. For each plot, the total plant mass above ground and yield were sampled every 1.8 m along the lateral. For each sample location, the average weight of a cabbage head was calculated as a mean of two heads weight chosen at two different rows. The quality of cabbage heads was measured at four equally spaced positions along the lateral in 2009 and at five equally spaced positions in 2010 for each plot. For each sample position, the average quality was determined from a mixing sample of three cabbage heads. The quality indexes, including concentration of vitamin C, total sugar, nitrate and crude fiber were measured in 2009 and the concentrations of vitamin C, total sugar, crude fiber and crude protein were measured in 2010. These measurements were conducted by the Vegetable Quality Supervision Testing Center, Ministry of Agriculture, China (Beijing). Vitamin C and total sugar were measured using a titrimetric method, crude fiber was measured using a lixiviation method and crude protein was measured using a kjeldahl determination (Lu, 2000). It was noted that the uniformity coefficient for quality indexes in 2009 was not computed because a mixed sample collected at the four positions in each plot was used for quality determination in order to reduce measurement cost.

The two-way analysis of variance was conducted to quantify whether the influence of each factor of the system uniformity coefficient and nitrogen application level on plant growth, nitrogen uptake, yield and quality was significant at a probability level of 0.05 for the data obtained in 2009 season. Similarly, one-way

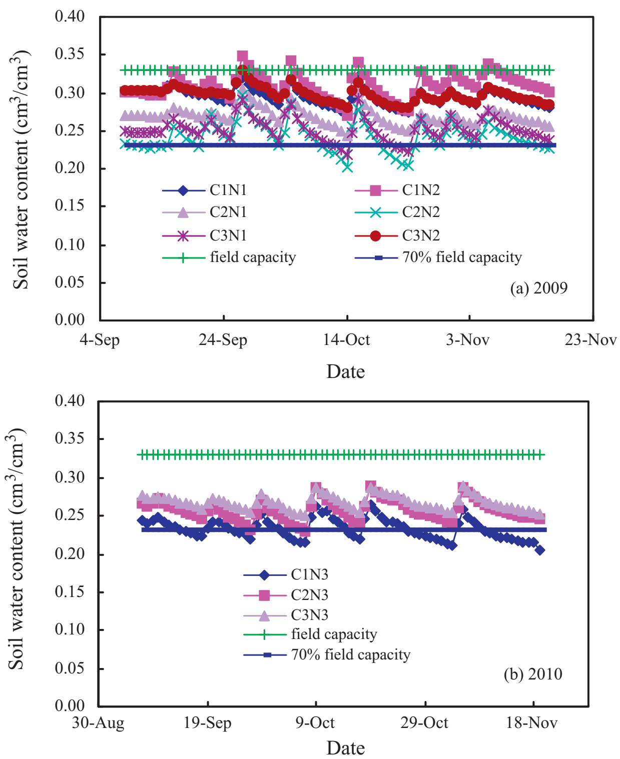

Fig. 5. The mean soil water content during the 2009 and 2010 seasons of Chinese cabbage.

analysis of variance was used to test the significance of the system uniformity effect for the data in 2010. The least significance difference (LSD) tests were also performed on all system uniformities and nitrogen application levels. These statistical tests were performed using the SAS software package, version 8.02 (SAS, 2001).

3. Results and discussion

3.1. The mean soil water content during the growing seasons

The average soil water content determined by the Hydra probe sensors buried at 15 cm depth for different drip fertigation uniformity treatments during the growing seasons of Chinese cabbage in 2009 and 2010 is shown in Fig. 5. For a given treatment, an increase of soil water content was observed after an irrigation event, and then it decreased gradually due to crop water consumption. During the whole growing season, soil water content varied mostly between 70% and 100% of the field capacity, although there were some differences among the treatments that might be caused by the difference of soil water content at seeding. This indicated that neither significant over irrigation nor water stress occurred during the whole growing season of Chinese cabbage in both 2009 and 2010 experiments.

3.2. Effects of drip system uniformity on crop growth

The Chinese cabbage height and its uniformity coefficient during two years of the experiments are shown in Fig. 6. The plant height increased gradually with time, while it decreased in the heading stage (starting from the end of October). The uniformity coefficient of plant height was 92–98% in 2009, and it was 94–99% in 2010. There was no statistically significant difference in Chinese cabbage head height to diameter ratio during two years of the experiments (Fig. 7). It basically kept constant value about 2.5 during the heading stage, and its uniformity coefficient was above 90%. The analysis of variance indicated that the drip system uniformity coefficient and fertilization amount had no significant effect on Chinese cabbage height, head height to diameter ratio and their uniformity coefficients.

3.3. Effects of drip system uniformity on above ground dry matter and nitrogen uptake

The above ground dry matter of Chinese cabbage and its uniformity coefficient during two years of the experiments are shown in Tables 2 and 3. The mean above ground dry matter increased greatly with time. Its uniformity coefficients for all treatments changed randomly during the growing season in 2009, while they tended to increase during the growing season in 2010. The analysis of variance indicated that the drip irrigation uniformity coefficient and fertilization amount had no significant effect on Chinese cabbage above ground dry matter and its uniformity coefficient.

The nitrogen uptake of Chinese cabbage and its uniformity coefficient during two years of the experiments are shown in Tables 4 and 5. The nitrogen uptake of Chinese cabbage increased as the plants grew. Although the fertilization amount had no significant effect on plant nitrogen uptake and its uniformity coefficient, the nitrogen uptake of high fertilization treatments (N2) was generally higher than that of low fertilization treatments (N1). For example, the average nitrogen uptake for C1N2 treatment was 10% higher than that of C1N1 treatment. An exception of the nitrogen uptake for C3N1 larger than the value for C3N2 was observed. This might be caused by the representativeness of the plants sampled. The drip irrigation uniformity had no significant effect on plant nitrogen uptake and its uniformity coefficient, while the nitrogen uptake uniformity coefficient was numerically higher in the high drip irrigation uniformity treatments in 2009. For example, the average nitrogen uptake uniformity coefficient over the two nitrogen levels increased from 76% to 82% when system uniformity increased from 62% (C1) to 96% (C3). For the 2010 experiments, however, the high, medium and low system uniformity treatments produced a similar nitrogen uptake uniformity coefficient of 77–78% in 2010.

3.4. Effects of drip system uniformity on cabbage head yield

The results obtained during two years of the experiments (Tables 6 and 7) showed that neither drip system uniformity nor fertilization level imposed a significant effect on Chinese cabbage yield. The total mass was 124.2–135.6 t/ha in 2009, and it was 125.6–128.5 t/ha in 2010. Compared with average yield, the deviation between maximum and minimum total plant mass was 8.8% and 2.3% in 2009 and 2010, respectively. The heads constituted 54–56% of the total plant mass in 2010. The uniformity coefficient of total plant mass was lower than that of heads yield. The average uniformity coefficient of total plant mass in 2009 (88%) was obviously larger than 82% in 2010. The residual water and nitrogen in the soil from the nonuniform water and fertilizer applications in 2009 may be a possible reason. There was no positive correlation between emitter discharge rate uniformity coefficient and yield uniformity coefficient. The yield uniformity coefficient of the C1 and C2 treatments was greater than their system uniformity coefficients.

3.5. Effects of drip system uniformity on cabbage head quality

The quality indexes of Chinese cabbage, including concentration of vitamin C, total sugar, crude fiber, nitrate and crude protein are shown in Tables 8 and 9 for the 2009 and 2010 experiments, respectively. There was no significant difference among the treatments

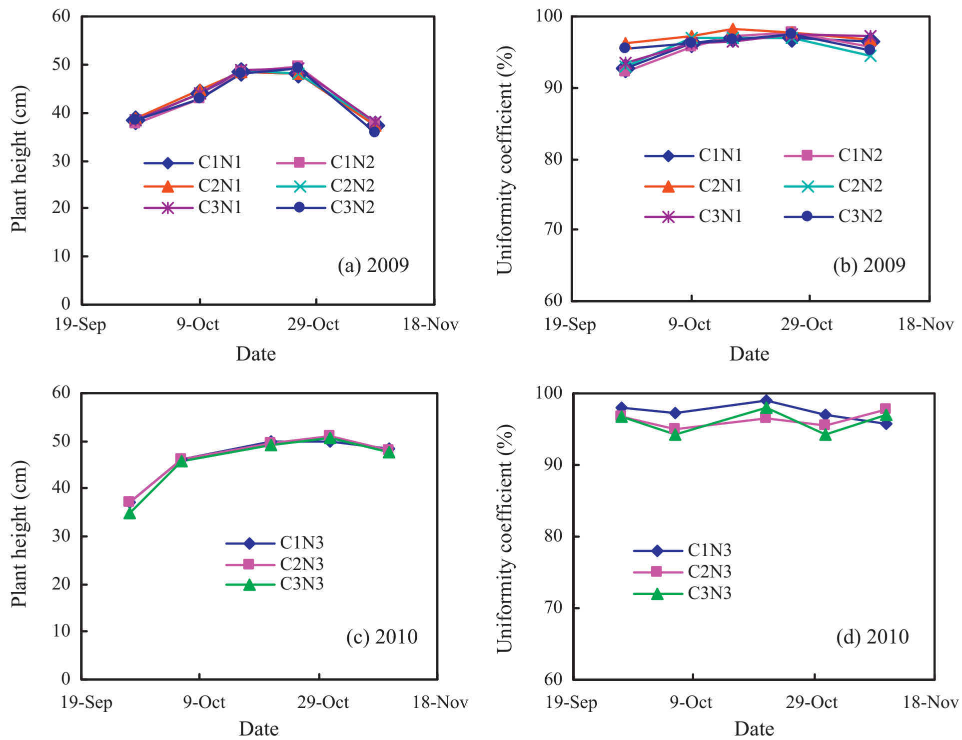

Fig. 6. Variations in mean and uniformity coefficient for plant height during the 2009 and 2010 seasons of Chinese cabbage.

with different system uniformities. Although the uniformity coefficients for quality indexes changed from 89% to 97% in 2010, the seasonal average uniformity coefficients for quality indexes among treatments were all above 93%.

The experimental results showed that the system uniformity and fertilization amount had no significant influence on Chinese cabbage growth, yield and quality when drip irrigation uniformity coefficients varied from 57% to 96%. An over fertilization might also

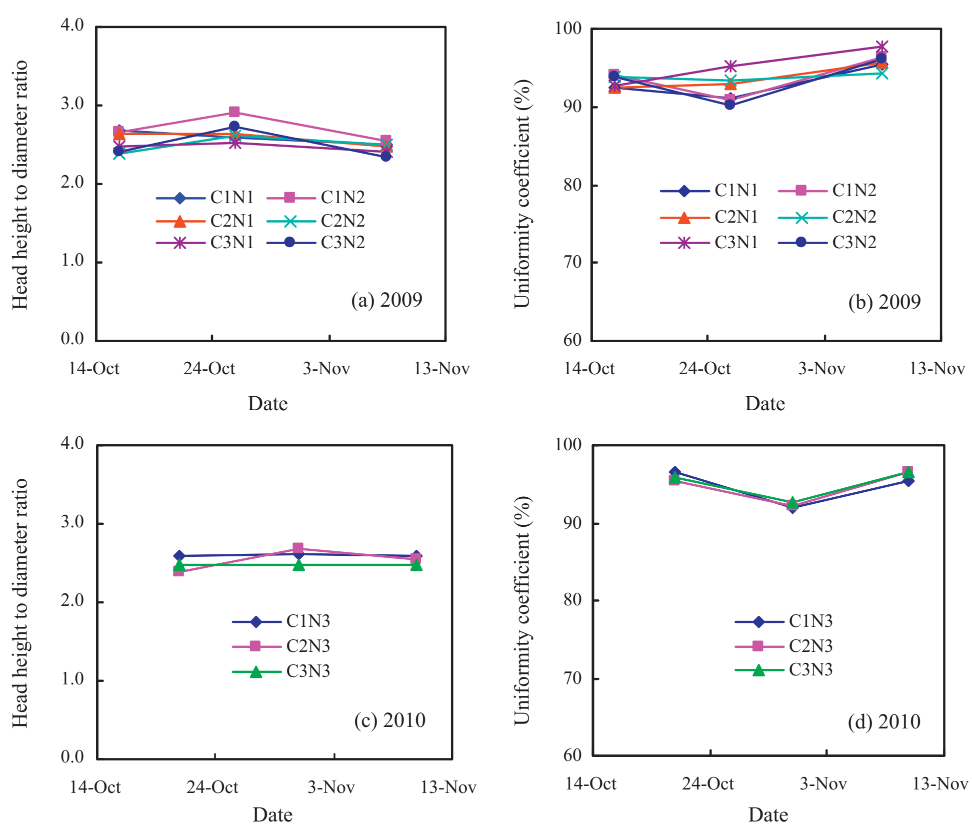

Fig. 7. Variations in mean and uniformity coefficient for head height to diameter ratio during the 2009 and 2010 seasons of Chinese cabbage.

Table 2
The mean and the uniformity coefficient *CU* for dry matter above ground of Chinese cabbage on different sample dates in 2009.

Parameter	Treatment	Date[a]			Seasonal average *CU*
		3 October	18 October	15 November	
Mean (kg/ha)	C1N1	1231.81 b[b]	3427.64 a	5158.16 ab	
	C2N1	1899.72 a	3508.06 a	4514.21 b	
	C3N1	1326.81 b	3058.75 a	6017.02 a	
	C1N2	1512.92 a	3428.19 a	5611.99 a	
	C2N2	1325.14 a	3637.64 a	5005.31 a	
	C3N2	1401.94 a	3347.78 a	4627.32 a	
	Two-way analysis of variance				
	System uniformity	NS ($P = 0.14$)	NS ($P = 0.21$)	NS ($P = 0.35$)	
	Nitrogen application rate	NS ($P = 0.51$)	NS ($P = 0.40$)	NS ($P = 0.70$)	
CU (%)	C1N1	71 b	77 b	85 a	78 a
	C2N1	74 ab	89 a	84 a	82 a
	C3N1	83 a	79 ab	83 a	82 a
	C1N2	73 a	81 a	66 b	73 a
	C2N2	74 a	82 a	81 ab	79 a
	C3N2	80 a	80 a	90 a	83 a
	Two-way analysis of variance				
	System uniformity	NS ($P = 0.19$)	NS ($P = 0.41$)	NS ($P = 0.13$)	NS ($P = 0.170$)
	Nitrogen application rate	NS ($P = 0.89$)	NS ($P = 0.87$)	NS ($P = 0.25$)	NS ($P = 0.499$)

[a] The final sampling date is the harvest date.
[b] The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

Table 3
The mean and the uniformity coefficient *CU* for dry matter above ground of Chinese cabbage on different sample dates in 2010.

Parameter	Treatments	Date[a]			Seasonal average *CU*
		2 October	25 October	19 November	
Mean (kg/ha)	C1N3	1645.53 a[b]	3945.80 a	5845.26 a	
	C2N3	1574.84 a	5002.75 a	5907.05 a	
	C3N3	2071.15 a	3946.25 a	5862.18 a	
	One-way analysis of variance				
	System uniformity	NS ($P = 0.483$)	NS ($P = 0.131$)	NS ($P = 0.993$)	
CU (%)	C1N3	71 a	76 a	89 a	79 a
	C2N3	74 a	73 a	85 a	77 a
	C3N3	63 a	83 a	84 a	77 a
	One-way analysis of variance				
	System uniformity	NS ($P = 0.730$)	NS ($P = 0.752$)	NS ($P = 0.221$)	NS ($P = 0.966$)

[a] The final sampling date is the harvest date.
[b] The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

Table 4
The mean and the uniformity coefficient *CU* for nitrogen uptake of Chinese cabbage on different sample dates in 2009.

Parameter	Treatment	Date[a]			Seasonal average *CU*
		3 October	18 October	15 November	
Mean (kg/ha)	C1N1	50.83 a[b]	137.58 a	193.64 ab	
	C2N1	76.95 b	140.23 a	164.45 b	
	C3N1	54.23 a	122.68 a	220.91 a	
	C1N2	63.18 a	142.89 a	197.74 a	
	C2N2	55.02 a	150.25 a	184.50 a	
	C3N2	58.37 a	132.10 a	178.68 a	
	Two-way analysis of variance				
	System uniformity	NS ($P = 0.15$)	NS ($P = 0.25$)	NS ($P = 0.40$)	
	Nitrogen application rate	NS ($P = 0.67$)	NS ($P = 0.35$)	NS ($P = 0.71$)	
CU (%)	C1N1	70 a	76 a	82 a	76 a
	C2N1	75 ab	86 a	84 a	82 a
	C3N1	81 b	79 a	80 a	80 a
	C1N2	75 a	80 a	70 a	75 a
	C2N2	76 a	83 a	78 a	79 a
	C3N2	80 a	81 a	91 b	84 a
	Two-way analysis of variance				
	System uniformity	NS ($P = 0.23$)	NS ($P = 0.39$)	NS ($P = 0.08$)	NS ($P = 0.100$)
	Nitrogen application rate	NS ($P = 0.67$)	NS ($P = 0.85$)	NS ($P = 0.40$)	NS ($P = 0.963$)

[a] The final sampling date is the harvest date.
[b] The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

Table 5
The mean and the uniformity coefficient CU for nitrogen uptake of Chinese cabbage on different sample dates in 2010.

Parameter	Treatment	Date[a]			Seasonal average *CU*
		2 October	25 October	19 November	
Mean (kg/ha)	C1N3	69.37 a[b]	158.08 a	236.47 a	
	C2N3	67.9 a	193.72 a	234.6 a	
	C3N3	88.31 a	155.96 a	235.71 a	
	One-way analysis of variance				
	System uniformity	NS ($P = 0.499$)	NS ($P = 0.270$)	NS ($P = 0.997$)	
CU (%)	C1N3	72 a	75 a	87 a	78 a
	C2N3	71 a	72 a	87 a	77 a
	C3N3	64 a	84 a	83 a	77 a
	One-way analysis of variance				
	System uniformity	NS ($P = 0.825$)	NS ($P = 0.678$)	NS ($P = 0.473$)	NS ($P = 0.984$)

[a] The final sampling date is the harvest date.
[b] The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

Table 6
Comparison of the mean and the uniformity coefficient *CU* between Chinese cabbage yield and emitter discharge rates in 2009.

	Treatment	Characteristic values		
		Mean (t/ha)	Maximum/minimum	*CU* (%)
Total plant mass	C1N1	129.8 a	1.22	87 a
	C2N1	128.2 a	1.43	87 a
	C3N1	132.2 a	1.29	90 a
	C1N2	128.4 ab	1.36	87 a
	C2N2	135.6 a	1.36	87 a
	C3N2	124.2 b	1.32	89 a
	Two-way analysis of variance			
	System uniformity	NS ($P = 0.32$)	–	NS ($P = 0.41$)
	Nitrogen application rate	NS ($P = 0.74$)	–	NS ($P = 0.79$)
Emitter discharge rate	C1N1	1.76	3.14	62
	C2N1	1.69	2.60	80
	C3N1	1.67	1.17	96
	C1N2	1.76	3.14	62
	C2N2	1.69	2.60	80
	C3N2	1.67	1.17	96

The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

Table 7
Comparison of the mean and the uniformity coefficient between Chinese cabbage yield and emitter discharge rates in 2010.

	Treatment	Characteristic values		
		Mean (t/ha)	Maximum/minimum	*CU* (%)
Total plant mass	C1N3	125.57 a	1.50	85 a
	C2N3	126.82 a	1.91	80 a
	C3N3	128.50 a	1.73	82 a
	One-way analysis of variance			
	System uniformity	NS ($P = 0.88$)	–	NS ($P = 0.29$)
Total yield of heads	C1N3	68.97 a	1.80	80 a
	C2N3	68.16 a	2.05	75 a
	C3N3	72.62 a	2.08	80 a
	One-way analysis of variance			
	System uniformity	NS ($P = 0.77$)	–	NS ($P = 0.394$)
Emitter discharge rate	C1N3	1.71	3.55	57
	C2N3	1.76	3.27	74
	C3N3	1.62	1.30	95

The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

produce an insignificant influence of system uniformity on crop growth. In this study, the monitoring of soil NO_3-N content indicated that the NO_3-N content varied from 22 to 80 mg/kg during the 2009 season and varied from 9 to 24 mg/kg in 2010 (Li et al., in press). These values were within the normal range of NO_3-N content for cabbage cultivation in the experimental region (Du et al., 2009). This confirmed that the insignificant influence of system uniformity was not caused by over fertilization. In addition, the relatively smaller emitter spacing along 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 insignificant influence of system uniformity on crop growth and product quality. The minor influence of sprinkler or drip uniformity on crop production was also reported by other researchers (Mateos et al., 1997; Li and Rao, 2000; Bordovsky and Porter, 2008). However, the average uniformity of dry matter above ground, nitrogen uptake and total plant mass in 2009 was 80, 79 and 88%, respectively, which was slightly higher than 78, 77, 82% in 2010. This difference might be partially resulted from the difference in field scale controlled by dripline used in the 2009 (22.6 m, Fig. 2a) and in

Table 8
The mean for quality indexes of Chinese cabbage on harvest in 2009.

Parameter	Treatment	Quality indexes			
		Vitamin C (mg/100 g)	Total sugar (%)	Nitrates (mg/kg)	Crude fiber (%)
Mean	C1N1	21.53 a	2.41 a	1030.00 a	11.07 a
	C2N1	21.73 a	2.45 a	924.67 a	11.57 a
	C3N1	20.57 a	2.30 a	1044.67 a	10.57 a
	C1N2	21.97 a	2.32 a	1143.67 a	10.06 a
	C2N2	20.40 a	2.41 a	1077.33 a	10.78 a
	C3N2	22.10 a	2.35 a	1013.00 a	11.07 a
	Two-way analysis of variance				
	System uniformity	NS ($P=0.57$)	NS ($P=0.73$)	NS ($P=0.61$)	NS ($P=0.50$)
	Nitrogen application rate	NS ($P=0.69$)	NS ($P=0.82$)	NS ($P=0.29$)	NS ($P=0.32$)

The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

Table 9
The mean and the uniformity coefficient CU for quality indexes of Chinese cabbage on harvest in 2010.

Parameter	Treatments	Quality indexes				Seasonal average *CU*
		Vitamin C (mg/100 g)	Total sugar (%)	Crude fiber (%)	Crude protein (%)	
Mean	C1N3	20.15 a	2.64 a	10.46 a	24.06 a	
	C2N3	21.18 a	2.49 b	10.20 ab	23.36 a	
	C3N3	20.8 a	2.50 b	9.75 b	23.48 a	
	One-way analysis of variance					
	System uniformity	NS ($P=0.72$)	NS ($P=0.06$)	NS ($P=0.08$)	NS ($P=0.82$)	
CU (%)	C1N3	95 a	95 a	91 a	95 a	94 a
	C2N3	89 a	92 a	92 a	97 a	93 a
	C3N3	92 a	93 a	92 a	94 a	93 a
	One-way analysis of variance					
	System uniformity	NS ($P=0.21$)	NS ($P=0.27$)	NS ($P=0.93$)	NS ($P=0.25$)	NS ($P=0.63$)

The values for a given nitrogen application rate followed by the same letter in the column are not significantly different at a probability level of 0.05.

the 2010 experiments (49.8 m, Fig. 2b). The research conducted by Hornbuckle et al. (2007) also indicated that the variation in emitter rates in a large scale, caused by a hole in the line causing water leakage, or a kinked, pinched or twisted line restricting water flow down the line, has a large effect on the performance of the wine grape vines which will in turn affect the yield and quality parameters associated with the vines.

4. Conclusions

The effects of system uniformity and nitrogen application rate on the crop growth, yield and quality were evaluated by applying drip irrigation to Chinese cabbage in a solar heated greenhouse during two growing seasons. The following conclusions were supported by the results of the present study:

1. A uniform distribution of Chinese cabbage growth, yield and quality was observed when the drip irrigation uniformity ranged from 57% to 96%. The uniformity of drip irrigation and the amount of applied nitrogen had an insignificant effect on the uniformity of Chinese cabbage growth, yield and quality at a significance level of 5%.
2. The average uniformity of dry matter above ground, nitrogen uptake, total plant mass and quality indexes showed a decreasing tendency with the increase of field scale controlled by dripline. Drip irrigation uniformities that are lower than the values recommended by the current standards can be used because they produced a uniform distribution of crop growth, yield and quality, while their usage should consider the field scale controlled by dripline.

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