Crop Yield as Affected by Uniformity of Sprinkler Irrigation System

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ABSTRACT
The effect of sprinkler uniformity on crop yield is a concern for system designers because it is an important consideration in selection of target uniformity for conventional systems. However, there is few field data on this subject. Field experiments were therefore conducted to observe the spatial variations of water in the soil and to study the response of crop growth and yield to nonuniform water application during the irrigation season of winter wheat in north China. Christiansen uniformity coefficients (CUC) were used in this article to quantify the uniformity of sprinkler water above and below canopy, soil water content, plant height, LAI, and crop yield. The results demonstrated that CUCs for water storage in the soil were always greater than 90% even though sprinkler uniformities varied from 57% to 89% during the irrigation season. Also, the uniformities of plant height, LAI, and crop yield were higher than those for water application and seem to be insensitive to spatial variation of applied water. The influence of sprinkler uniformity on crop yield is not as important as previous modeling. A reduced uniformity may not necessarily result in a lower yield.

KEYWORDS: Sprinkler irrigation; Uniformity; Winter wheat; Yield

INTRODUCTION
Sprinkler irrigation systems are characterized by some degree of nonuniformity in the application of water. Water application uniformity potentially affect crop yield and water use efficiency (WUE). Warrick and Gardner (1983) analyzed theoretically the effect of soil spatial variability and irrigation nonuniformity. Letey et al. (1984) did a similar analysis extended to crops with curvilinear yield functions. Montovani et al. (1995) simulated the effects on crop yield of sprinkler uniformity by using a linear crop water production function. Recently, Li (1998) presented a simulation model including the effect on crop yield of both sprinkler uniformity and water deficit. All of the modeling works showed that increasing irrigation nonuniformity decreases average yield.

The uniformity of sprinkler irrigation is usually quantified by the coefficient of uniformity proposed by Christiansen (Christiansen, 1942):

$$CUC = \left(1 - \frac{\sum_{i=1}^{N} |x_i - \overline{x}|}{N\overline{x}}\right) \times 100 \qquad (1)$$

where CUC is Christiansen uniformity coefficient; x_i is the ith water application depth; and $\sum_{i=1}^{N} |x_i - \overline{x}|$ is the sum of the absolute deviation from the mean, $\overline{x}$, of all N observations.

Such coefficients are good indicators to express the distribution of sprinkler water application on the ground surface, but seem to be insufficient to quantify the influence on crop yield, since they do not take into account some effects related to soil characteristics, spatial pattern of variation of the applied water in the soil, and the crop morphology. The uniformity coefficients are often determined from measurements with catch cans located above the canopy or on the bare soil. Our recent field experiments (Li and Rao, 1999) demonstrated that a winter wheat canopy tends to improve the uniformity when water flows through the canopy. Hart (1972) and Li and Kawano (1996) reported sprinkler water is more uniformly distributed in the soil than that measured on the ground surface for an individual irrigation event. The spatial distribution of nonuniform sprinkler water application in the soil was seldom monitored in a whole growing season (Stern and Bresler, 1983).

Modeling the effect of irrigation nonuniformity on yield has been widespread and productive. However, field data for validating models is very scarce. Ayars et al. (1990) and Ayars et al. (1991) studied sugar beet and cotton yield response to the uniformity of a linear-move sprinkler irrigation system that can generate different uniformities and scales of variation. These studies have shown important effects of the non-uniformity pattern on crop yield. However, Moteos (1997) reported that low irrigation uniformity does not imply yield reductions for cotton irrigated by a solid sprinkler system. The field experiments mentioned above were conducted on sugar beet and cotton but no study was conducted on winter wheat that is extensively grown in northern China.

The most common used sprinkler irrigation systems in China are solid and semi-permanent systems. In contrast with the variation in the amount of water applied by a linear-move irrigation machine, the configuration of solid or semi-permanent systems produce two-dimensional patterns with large scales of variation.

The objective of this study were to monitor the spatial variation in soil water under varying uniformities of water applied by a solid sprinkler system and to evaluate the importance of sprinkler uniformity to the crop yield of winter wheat.

MATERIALS AND METHODS

Experimental field

The experiments were conducted at the Experimental Station of Agrometeorology Institute, Chinese Academy of Agricultural Sciences in Beijing, China. An onsite automated weather station was installed 80 m from the experimental field to monitor wind speed and direction, air temperature, humidity and precipitation during the irrigation season. The soil was a clay loam with a bulk density of 1.4~1.5 g/cm^3 and a field capacity of 0.32 cm^3/cm^3. Winter wheat was sown on 10 October 1998 with row spacing of 30 cm and seeding rate of 112.5 kg/ha. Fertilization and pest and disease control followed the standard practices in this area. Irrigation treatment was initiated on 15 March 1999.

Two plots were used in the experiments (referred to as plot 1 and plot 2 below). Each plot was 15 m by 15 m in size, and sprinklers mounted on a 180-cm high riser were installed at each corner of the plot. The center 12-m by 12 m in each plot was selected as the observed area to avoid interference between adjacent plots. Flow rate for the sprinkler used was 0.8 m^3/h at a pressure of 300 kPa. Different sprinkler uniformities were obtained by varying pressure from 100 to 300 kPa. Four sprinklers applied water to an experimental plot using a rotation angle of approximately ninety degrees during an irrigation. For all the experiments, the average application rate ranged from 8 to 14 mm/h, and no surface runoff was found in the experiments.

Water measurements

The 12 m by 12 m observed area in each plot was divided into a grid of thirty-six 2 m by 2 m subplots. Catch cans of 112.8 mm diameter were placed at the center of each subplot on the ground surface to measure sprinkler water distribution below the canopy. Since the developing winter wheat canopy has a potential to affect the distribution of sprinkler water, catch cans were also located above the canopy. The cans with the same size as those on the ground surface were arranged in a 3 m by 3 m grid. The top of the cans above the canopy was 85 cm above the ground surface. The water collected in both above and below the canopy cans was measured 10 min after the designed amount of water was applied.

Crop Measurement

To investigate the effects of sprinkler uniformity on crop growth, the leaf area and plant height for each 2 m by 2 m subplot were measured periodically. Plant samples were collected on 28 March, 16 April, 26 April, and 22 May 1999. Five plants were used for each subplot. The leaf area was measured from five leaves in each sample by an area meter, then the leaf area per unit leaf mass (specific leaf area) was determined. The LAI was computed as the product of specific leaf area and the total leaf mass divided by the sample area. Christiansen uniformity coefficients for LAI and plant height were also calculated by using of Eq. 1. One square meter of winter wheat for each subplot was harvested on June 19 and the dry grain yield was recorded. The yield at the position of ground can was represented by the yield of 1 m^2 sample.

Irrigation

Soil water contents from 30 to 100 cm depth were measured weekly by a neutron probe with intervals of 10 cm but the contents at top 30 cm were measured by a TDR. Nine access tubes were installed in a 4 m by 4 m grid for each plot. TDR sample was about 10 cm around the access tube. Irrigation was applied when average soil water content within top 40-cm layer depleted to 70% of field capacity (about 40 mm depletion). A total of seven irrigation events were applied between 15 March to June 16, 1999. Irrigation and precipitation dates, amounts and the average wind speed during each irrigation are summarized in Table 1.

Table 1 Summary of applied depth above the canopy (AW), sprinkler discharge efficiency(E), average wind speed at 2 m during irrigation (V_w), date of each of the seven irrigation events and precipitation during irrigation season

Plot 1				Plot 2				Precipitation	
Irrigation date	AW (mm)	V_w (m/s)	E (%)	Irrigation date	AW (mm)	V_w (m/s)	E (%)	Date	Depth (mm)
Mar 19	24.6	1.73	90	Mar 19	21.3	1.73	87	Apr 11	6.0
Apr 06	33.2	1.58	75	Apr 07	37.8	1.90	72	Apr 12	15.0
Apr 24	21.2	1.35	90	Apr 24	15.2	1.35	68	Apr 19	5.4
Apr 25	15.2	4.52	75	Apr 25	16.4	1.52	74	May 18	11.8
May 12	20.0	1.07	75	May 12	19.0	1.07	71	May 24	8.8
May 13	18.7	1.16	84	May 13	17.2	1.16	77	May 31	15.0
May 31	36.4	1.36	82	Jun 04	27.8	1.20	78		
Total	169.0				155.0				

Discharge efficiency (E), defined as the ratio of water collected by catch cans above the canopy to water discharged by sprinklers, is also given in Table 1 for each irrigation event. The value of efficiency was affected by environmental factors and sprinkler pressure, ranging from 68% to 90%.

RESULTS AND ANALYSIS

Spatial Variation of Water in the Soil during Irrigation Season

Figure 1 illustrates the variation of Christiansen uniformity coefficients of water storage within 50-cm and 100-cm depth from the soil surface during irrigation season for both plots. The coefficients of water storage within 50-cm and 100-cm depth were always greater than 90% for both plots although the uniformity coefficients of sprinkler water application varied from 67% to 89% for plot 1 and from 57% to 84% for plot 2 during irrigation season. This is due to the fact that a winter wheat canopy improved the uniformity when water flows through the canopy (Li and Rao, 1999) and that sprinkler water was redistributed laterally and vertically in the soil (Hart, 1972 and Li and Kawano, 1995).

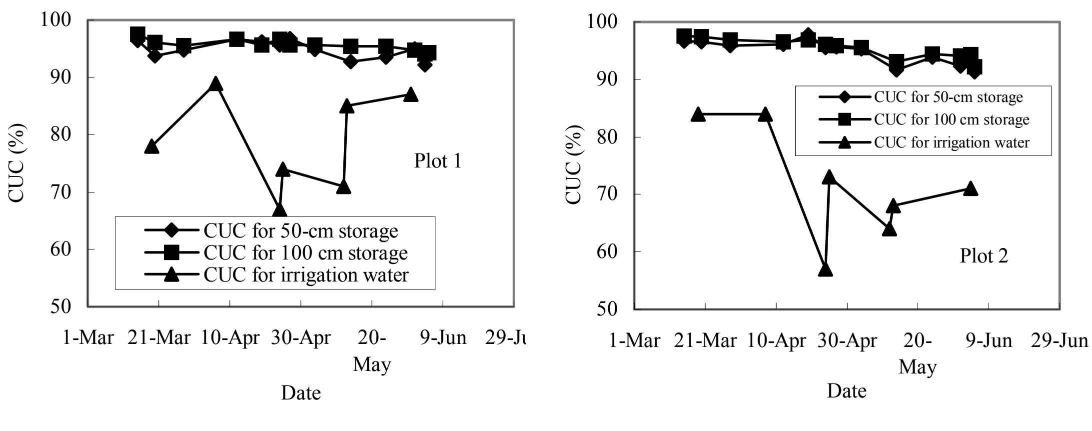

Figure 1 Variations of Christiansen uniformity coefficients for water storages within 50-cm and 100-cm depth from the soil surface during irrigation season

Crop Growth as Affected by Nonuniformity of Water Application

Table 2 presents Christiansen uniformity coefficients for plant height and leaf area index (LAI). The coefficients for both plant height and LAI generally increased with plant's growing and the coefficients for plant height were always larger than those for LAI.

Table 2 Summary of mean plant heights and leaf area index (LAI) averaged across all measured subplots

Date	Plot 1						Plot 2					
	LAI			Plant height (cm)			LAI			Plant height (cm)		
	Mean	CV*	CUC (%)	Mean	CV	CUC (%)	Mean	CV	CUC (%)	Mean	CV	CUC (%)
Mar 28	1.69	0.20	86	--	--	--	1.77	0.19	85	--	--	--
Apr 16	3.87	0.20	85	38.7	0.06	95	4.06	0.17	87	41.4	0.07	95
Apr 25	7.70	0.09	93	54.8	0.04	96	7.79	0.07	95	57.5	0.05	97
May 22	6.34	0.09	95	70.3	0.03	98	6.72	0.07	93	70.7	0.03	98

*CV = standard deviation/mean

Christiansen uniformity coefficients for LAI increments between March 28 and April 25 (△LAI) were compared with the coefficients for water application depth below canopy during this period and the results are summarized in Table 3. Table 3 indicates that CUCs for LAI increments are larger than water application uniformities.

Table 3 Christiansen uniformity coefficients for LAI increments and water application depths below canopy between March 28 and April 25, 1999 for both plots

	CUC for △LAI (Apr 25 – Mar 28) (%)	CUC for water application depths (%)		
		Sum of Mar 19, Apr 6 or 7 and Apr 24	Sum of Apr 6 and Apr 24	Apr 6
Plot 1	91	87	87	89
Plot 2	91	88	86	84

Figure 2 demonstrates the relationship between yield and water depth at collector location on the ground surface for both plots. A regression of yields on irrigation depths led to the following two equations:

$$Y = 0.008D + 6.1 \qquad (r^2 = 0.06, n = 36) \text{ for plot 1} \qquad (2)$$

$$Y = 0.003D + 6.7 \qquad (r^2 = 0.01, n = 36) \text{ for plot 2} \qquad (3)$$

where Y is yield (t/ha), and D is water application depth (mm).

The considerable low correlation coefficients of Eqs. 1 and 2 may suggest that crop yield give no response due to the water applied by irrigation.

Table 4 summarizes CUCs for grain yields and for cumulative water depths both above and below canopy during irrigation season. The average value of individual CUCs for both plots is also given in the table. Two points are worth to be noted in Table 4. First, grain yields were more uniformly distributed than cumulative water depths above and below canopy. Secondly, higher sprinkler uniformity produced a higher yield, but the increase of yield with uniformity was insignificant. For instance, an 11% increase in CUC (from 72% to 80%) resulted in a 1.3% increase in yield. This increased yield is considerably less than a previous modeling increase of 8.4% (Li, 1998).

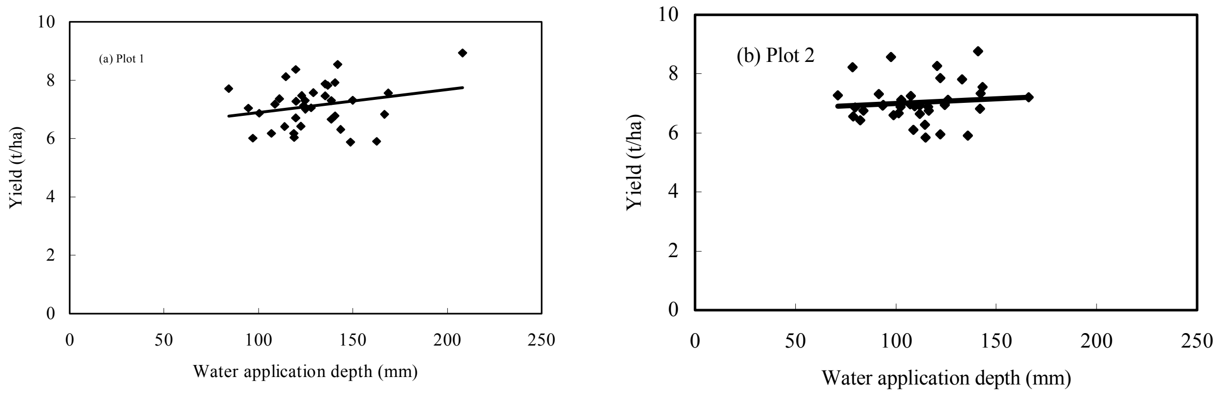

Figure 2 Crop yield as a function of irrigation depth at catch-can location below canopy

Table 4 Christiansen uniformity coefficients for crop yield and cumulative water depths below and above canopy as well as averaging of individual irrigation CUCs during irrigation season for plots 1 and 2

Treatment	CUC above canopy (%)		CUC below canopy (%)		CUC for yield (%)	Yield (t/ha)
	Average	Cumulative	Average	Cumulative		
Plot 1	80	86	81	89	92	8.55
Plot 2	72	81	76	88	93	8.44

Field experiments to study the effects of sprinkler uniformity on crop yield are labor consuming compared with experiments on sprinklers hydraulic performances. To reduce the amount of field experiments, we divided the experimental plot into several groups and each group includes at least twelve 2 m by 2 m grids. Mean and CUC for cumulative depth, and mean crop yield for each group were calculated from the experimental data. The relationship between crop yield and CUC below canopy are presented in Figure 3 for the data having approximate equal irrigation depth (120~140 mm for plot 1 and 100~120 mm for plot 2).

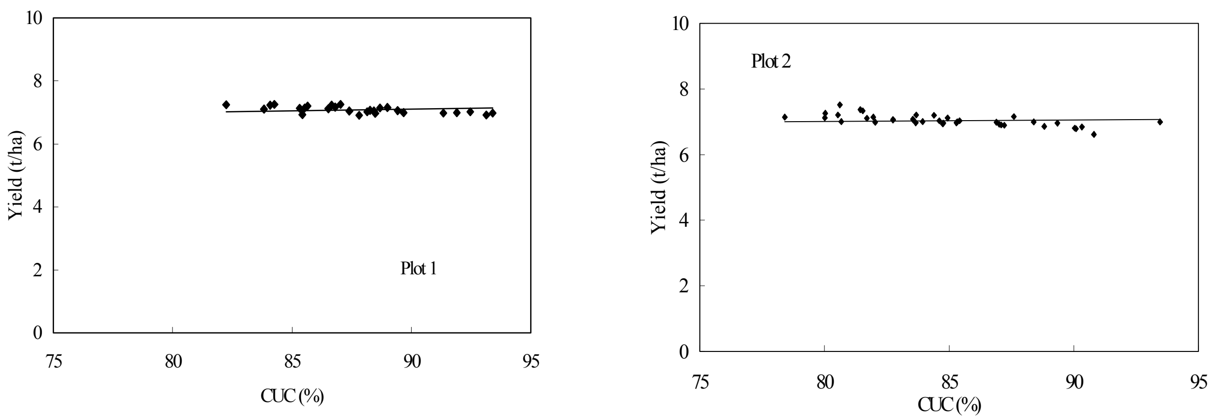

Figure 3 The relationship between crop yield and CUC below canopy for plots 1 and 2

A correlation between crop yield and CUC for the data illustrated in Figure 3 gave the following equations:

$$Y = 6.1 + 0.011CUC \quad \text{for plot 1} \quad (4)$$

$$Y = 6.7 + 0.004CUC \quad \text{for plot 2} \quad (5)$$

Again, one can find from Figure 3 and Eqs. 4 and 5 that sprinkler uniformity has little effect on crop yield for both plots. Through field experiments, Mateos et al. (1997) also demonstrated sprinkler irrigation uniformity has a lower impact on crop performance than expected from simulation studies. The insignificant effect on crop yield of sprinkler uniformity could be explained from the following aspects. Sprinkler water becomes more uniform when water flows through a winter wheat canopy (Li and Rao, 1999). The uniformity for cumulative irrigation depth is always larger than individual CUCs (Li and Rao, 1999). Canopy interception and redistribution of sprinkler water in the soil resulted in a considerably uniform spatial distribution during the irrigation season. In addition, there was 148 mm of precipitation in the growing season of 1998 to 1999, which can be considered as uniform. All of the facts mentioned above reduced the negative influence of sprinkler nonuniformity on crop yield.

SUMMARY AND CONCLUSIONS

Field experiments were conducted to observe spatial variations of water in the soil during a growing season of winter wheat under varying uniformities of sprinkler irrigation and to study the effects of uniformity on crop growth. The following conclusions were supported by this study:

- Christiansen uniformity coefficients of water in the soil were always larger than 90% although the uniformity coefficients of water application varied in a wide range, from 57% to 89% during the irrigation season.
- The spatial variations of plant height and leaf area index (LAI) under nonuniform water application were small and insensitive to the spatial variation of water application.
- The influence of sprinkler uniformity on winter wheat yield is less important than that reported from previous modeling results. A lower uniformity may not mean a lower winter wheat yield for the regions where there is about 150 mm of precipitation during growing season. This conclusion is significant for the design of sprinkler irrigation system.

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REFERENCES

Ayars, J. E., R. B. Hutmacher, G. J. Hoffman, J. Letey, J. Ben-Asher, and K. H. Solomon. 1990. Response of sugar beet to non-uniform irrigation. Irrigation Science 11: 101-109.

Ayars, J. E., R. B. Hutmacher, S. S. Vail, R. A. Schoneman. 1991. Cotton response to

nonuniform and varying depths of irrigation. Agricultural Water Management 19: 151-166.
Christiansen, J. E. 1941. The uniformity of application of water by sprinkler systems. Agricultural Engineering 22: 89-92.
Hart, W. E. 1972. Subsurface distribution of nonuniformly applied surface waters. Transactions of the ASAE 15: 656-661, 666.
Letey, J., Vaux, H. J., and E. Feinerman. 1984. Optimum crop water application as affected uniformity of water infiltration. Agronomy Journal 76: 435-441.
Li, J. 1998. Modeling crop yield as affected by uniformity of sprinkler irrigation system. Agricultural Water Management 38: 135-146.
Li, J. and H. Kawano. 1996. The areal distribution of soil moisture under sprinkler irrigation. Agricultural Water Management 32: 29-36.
Li, J. and M. Rao. 2000. Sprinkler water distributions as affected by winter wheat canopy. Irrigation Science 20: 29-35.
Montovani, E. C., F. J. Villalobos, F. Orgaz and E. Fereres. 1995. Modeling the effects of sprinkler irrigation uniformity on crop yield. Agricultural Water Management 27: 243-257.
Moteos L., E. C. Montovani, and F. J. Villalobos. 1997. Cotton response to non-uniformity of conventional sprinkler irrigation. Irrigation Science 17: 47-52.
Stern, J. and E. Bresler. 1972. Nonuniform sprinkler irrigation and crop yield. Irrigation Science 4: 17-29.
Warrick, A. W. and W. R. Gardner. 1983. Crop yield as affected by spatial variation of soil and irrigation. Water Resources Research 19: 181-186.