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Effects of deficit irrigation on yield and water use of greenhouse grown cucumber in the North China Plain

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Abstract

This study examines deficit irrigation on greenhouse grown cucumber in the North China Plain (NCP). The level of fulfillment of water requirements was used as a gauge to differentiate five border irrigation treatments. Fresh fruit yields were highly influenced by the total volume of irrigation water at every growth stage. The treatment with minimum irrigation water applied had the lowest productions. The mathematical functions that better fit for the production obtained with the water volume received were linearism, but the functions of evapotranspiration (ET) and yield were second-degree polynomials. The water use efficiency (WUE) and irrigation water use efficiency (IWUE) decreased with the increase of irrigation water applied from stem fruiting to the end, significantly since harvest of zenith fruits. But WUE and IWUE were ascending with the increase of irrigation water from cucumber field setting to first fruit ripening. Well irrigation along the whole cycle was a clearly advisable irrigation regime. On the other hand, the least advisable regimes were those that lead to deficiencies from harvest of the first fruit to the zenith fruits. But we strongly recommend actions be taken to limit the inefficient soil evaporation that resulted from higher temperature at the last growth stages in order to improve WUE and IWUE.

Keywords: Deficit irrigation; Greenhouse grown cucumber; Water use efficiency; Production function

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1. Introduction

Water is becoming one of the scarcest natural resources in North China Plain (NCP), one of the most important agricultural regions in China. Water shortage limits the economy development in the region, where there is no reliable surface water resources for irrigation. More than 80% of water resources have been exploited for irrigation (Liu and Wei, 1989; Zhang et al., 1999; Wang et al., 2001). The use of groundwater has caused the regional groundwater table to drop significantly and created many environmental problems (Liu and He, 1996; Wang et al., 2001). To cope with the water shortage, it is necessary to adopt water-saving agriculture countermeasures. Efficient use of water by irrigation is becoming increasingly important. Irrigation scheduling is very important to water saving. From previous studies, we have developed a fairly good knowledge of the influences that control irrigation regimes on grain crops and trees (Miller and Martin, 1987; Olufayo et al., 1996; Zhang et al., 1999, 2001; Oweis et al., 2000; Pandey et al., 2000; Motilva et al., 2000; Li et al., 2001; Fabeiro et al., 2001). But there is still a need to enhance the studies of deficit irrigation on vegetables. Although some papers dealt with water requirement of vegetables, most of them focused on the varieties (Chartzoulakis and Drosos, 1995; Mendezr, 1987; Mannini and Gallina, 1996) which could stand greater drought.

Cucumber is one of the most popular greenhouse vegetables in NCP. It needs more water than normal grain crops (Li et al., 2000) and local farmers relied on their experiences to irrigate cucumber. The rapid development of greenhouse vegetable planting over recent years would increase water scarcity in NCP. The purpose of this study is to demonstrate the effects of different irrigation levels on the yield, irrigation water use efficiency (IWUE) and water use efficiency (WUE) at different growth stages in unheated greenhouse grown cucumber and clarify cucumber irrigation schedule.

2. Materials and methods

The field experiment was conducted at Nanpi Agricultural Experimental Station, Chinese Academy of Sciences (38°06′N and 116°40′E and altitude 8 m above sea level), Hebei Province, China. The climate is warm temperate monsoon, with a cold-dry winter and a hot-humid summer. Average annual air temperature is 12.4 °C and average monthly lowest temperature is −6.1 °C. In winter vegetables must be planted in a greenhouse. The average annual groundwater table was 3 m and irrigated water resource was slightly saline groundwater (2–3 $g\,l^{-1}$), pumped from wells directly. Border irrigation was used for the experiment. Field trials cucumber seed variety was No3 winter, made in China. The greenhouse with silicon-magnesium bone was 30 m long, 4.5 m wide and unheated. Cucumber seeding, raised in culture medium-filled pots, was translated into the greenhouse in December.

Our deficit irrigation treatments were from 10 January to next 29 May, total 140 days since cucumber plant field setting. Based on cucumber appearance, we divided the whole experimental period into three stages namely S1, S2 and S3. S1 was the first stage from cucumber field setting to first fruit ripening, which was 10 January to 28 February. S2 was

Table 1
Design of deficit irrigation scheduling

Treatments	Design irrigation water amount per time (m^3 ha^{-1})	Intervals (days)	Total irrigated water amount (m^3 ha^{-1})
T1	300	18–20	2280
T2	300	10–12	3300
T3	300	5–6	4965
T4	300	3–5	6540
T5	300	2–3	6960

the second stage after harvest of the first fruit till the zenith fruits, which was 1 March to 12 April. S3 was from the harvest of zenith fruits to the end, which was 13 April to 29 May in our experiment.

Water meters were used to control the amount of irrigated water. Soil water content was measured at intervals of 0.1 m down to 1 m, using neutron probes (IH-II, Didcot, Wallingford, UK), once every 5 days during the growing stages; before start, end of stages and irrigation, the measurements were added once. Two access tubes were installed in each experiment plot. The neutron probes were calibrated against the soil water content determined gravimetrically at the experimental sites and readings were taken at 64 s. Evapotranspiration (ET) was calculated from the water balance equation: $ET = I + = \Delta SW + D$, where ET is the evapotranspiration (m^3), I the amount of irrigation water applied (m^3), ΔSW the soil water content changes (m^3), and D the deep water percolation. The amount of irrigation water was controlled, so, deep percolation was assumed to be zero.

The experiential field was divided into ten separated blocks. The experimental design was in random blocks with two repetitions for each of five water treatments tested. The treatments were devised according to cucumber's water requirement disciplinarian (Table 1).

The soil was calcaric fluisol (FAO, 1990) and the soil texture was light loam with bulk density of 1.35 g cm^{-3} in the top of 40 cm and 1.55 g cm^{-3} between 40 and 100 cm. And the soil field capacity and wilting point were 23–26% and 8–10% by volume, respectively.

WUE and IWUE were calculated as fresh fruit cucumber yield divided by ET and irrigation water applied volume, respectively. The herbicides and fertilizers were uniformly managed according to standard management practices.

3. Results and discussion

3.1. Responds of yield to water stress

Cucumbers have moderately deep roots and long taproots as well as shallow fibrous root systems but do not seem to be as extensive as others in this family. Most of the fibrous feeders are in the top 60 cm and the active roots are concentrated between 20 and 30 cm. And cucumber is a quick growing crop that produces a lot of succulent growth (Gao, 1994).

Table 2
Irrigation water applied (I, $m^3 ha^{-1}$) and fresh fruits yields (Y, $kg ha^{-1}$) of cucumber at different crop growth stages

Treatments	S1		S2		S3		Total	
	I	Y	I	Y	I	Y	I	Y
T1	937.5	2794.5	900.0	64417.5	600.0	70665.0	2437.5	137877.0
T2	969.0	2796.0	1275.0	72874.5	1200.0	86205.0	3444.0	161875.5
T3	1036.5	2952.0	1987.5	72922.5	2100.0	88702.5	5124.0	164577.0
T4	1056.0	4087.5	2190.0	81457.5	3300.0	90285.0	6546.0	175830.0
T5	1149.0	6180.0	2512.5	86262.0	3600.0	101557.5	7261.5	193999.5

The crop must be supplied with plenty of moisture for its vigorous growth. Irrigation is important for its plant and fruit growth. At different growing stages, different irrigation water amount was applied according to our design in this study (Table 2). Because our irrigation control was not so strict that irrigation data were not same with Table 1.

Cucumber response to irrigation deficit varied in different growth stages. The higher the amount of irrigation water applied, the higher fresh fruits of cucumber was obtained. Irrigation could increase the yield of fresh cucumber on every growing phase under greenhouse in NCP. The maximum and minimum total yields were 193999.5 $kg ha^{-1}$ and 137,877 $kg ha^{-1}$, respectively, under T5 and T1—the most and lowest irrigation water applied. With regard to fresh weight, the mathematical functions obtained depended on experimental data, showed the highly linear relationships between irrigation water amounts applied with yields at different phenomenal stages (Table 3). The initial yield required minimum irrigation of 797 $m^3 ha^{-1}$ in S1; however, after that, if there were no irrigation water applied any more, it would harvest 5.576 and 7.1167 $kg m^{-2}$ at S2 and S3, respectively, estimated from the intercept of the regression lines.

3.2. ET and the relationship with yield

Between 10 January and 28 February, cucumber smaller plant seedlings required less water and lower evaporation resulted from lower temperature at first, with the result that ET increased moderately. After the cucumber fruit appearance on stems, more cucumber plants blossomed and more fruits appeared. Plants needed more water to meet the needs of more succulent fruits and higher soil evaporation that resulted from higher temperature. So

Table 3
Linear model regression equations for fresh cucumber yield response to irrigation water applied[a]

Growth stages	Equation	R^2	Significance
S1	$Y = -12896.2 + 16.17928X$	0.8384	0.01
S2	$Y = 55760.1 + 11.747X$	0.8524	0.01
S3	$Y = 71167.06 + 7.55X$	0.7808	0.05
Whole growth period	$Y = 119619.1 + 9.51X$	0.8852	0.01

[a] Y is the fresh cucumber fruit yield ($kg ha^{-1}$), X the irrigated water applied ($m^3 ha^{-1}$).

Table 4
Average ET rate under different irrigation levels at different growing stages (mm per day)

Treatments	S1	S2	S3	Average
T1	2.0	2.6	1.5	2.0
T2	2.3	2.8	2.4	2.5
T3	2.7	4.3	4.2	3.3
T4	2.2	4.4	6.6	4.4
T5	3.2	4.6	7.0	4.9

water requirement increased dramatically. At S3, a number of cucumber plants waned and field yields were less but the temperature was higher and the cucumbers needed a greater quantity of water.

ET was equal to total crops' water consumption in greenhouse, decided by air temperature, crop varieties, soil texture, soil moisture and solar radiation etc. In order to clarify the effects of irrigation on ET, regression analysis was carried out. There was

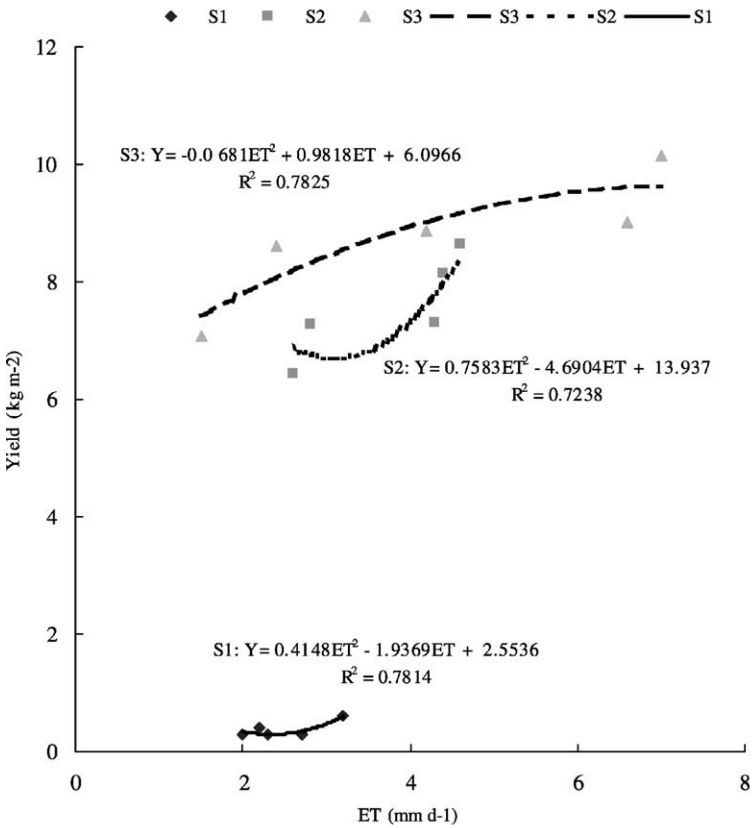
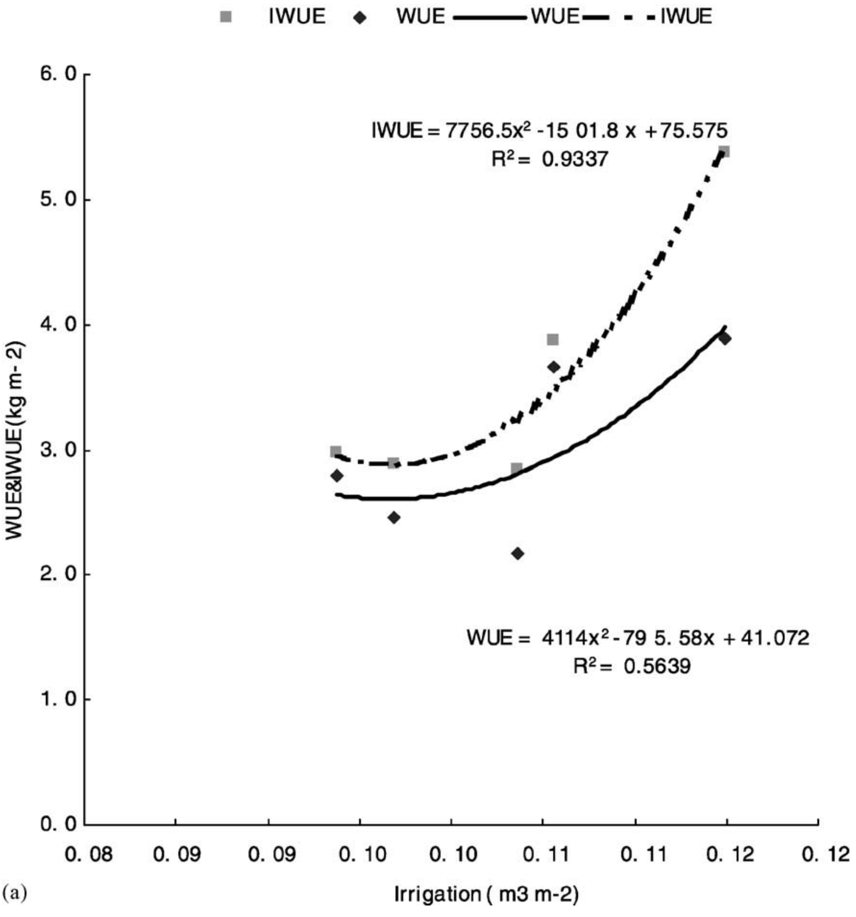


Fig. 1. The relationships between fresh cucumber yields and ET.

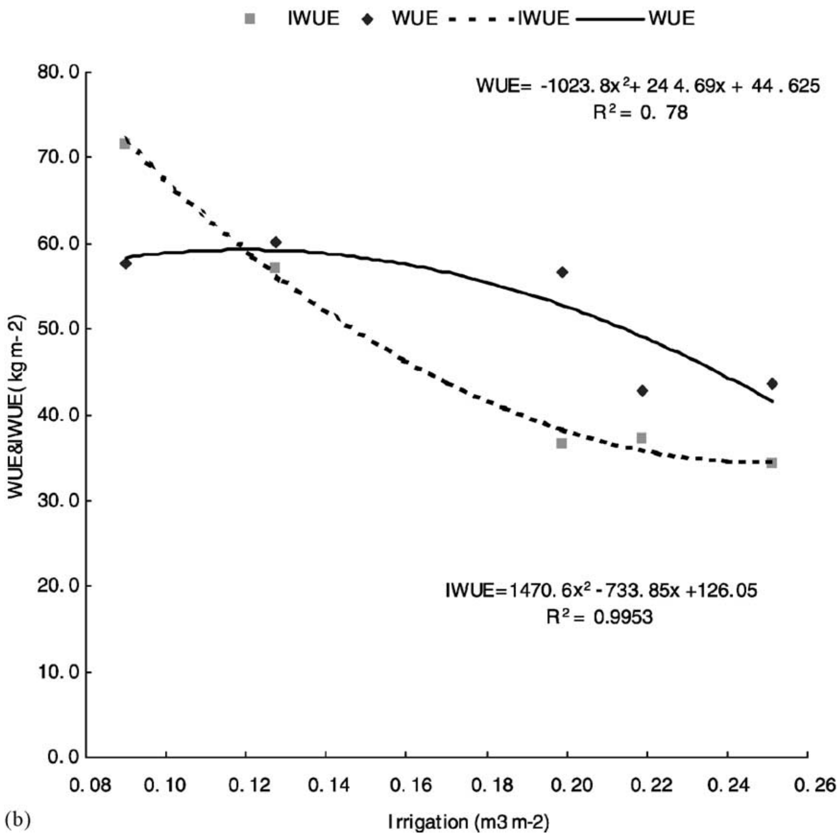
Table 5
WUE and IWUE at different growth stages under deficit irrigation

Treatments	S1		S2		S3		Average	
	IWUE	WUE	IWUE	WUE	IWUE	WUE	IWUE	WUE
T1	2.98	2.79	71.58	57.64	117.78	98.76	56.56	48.66
T2	2.89	2.46	57.16	60.13	71.84	74.93	47.00	46.28
T3	2.85	2.17	36.69	56.59	42.24	45.31	32.12	35.73
T4	3.87	3.66	37.20	42.86	27.36	28.98	26.86	28.67
T5	5.38	3.89	34.33	43.70	28.21	31.07	26.72	28.40



(a)

Fig. 2. The effects of irrigation on WUE and IWUE at S1 (a), S2 (b) and S3 (c).



(b)

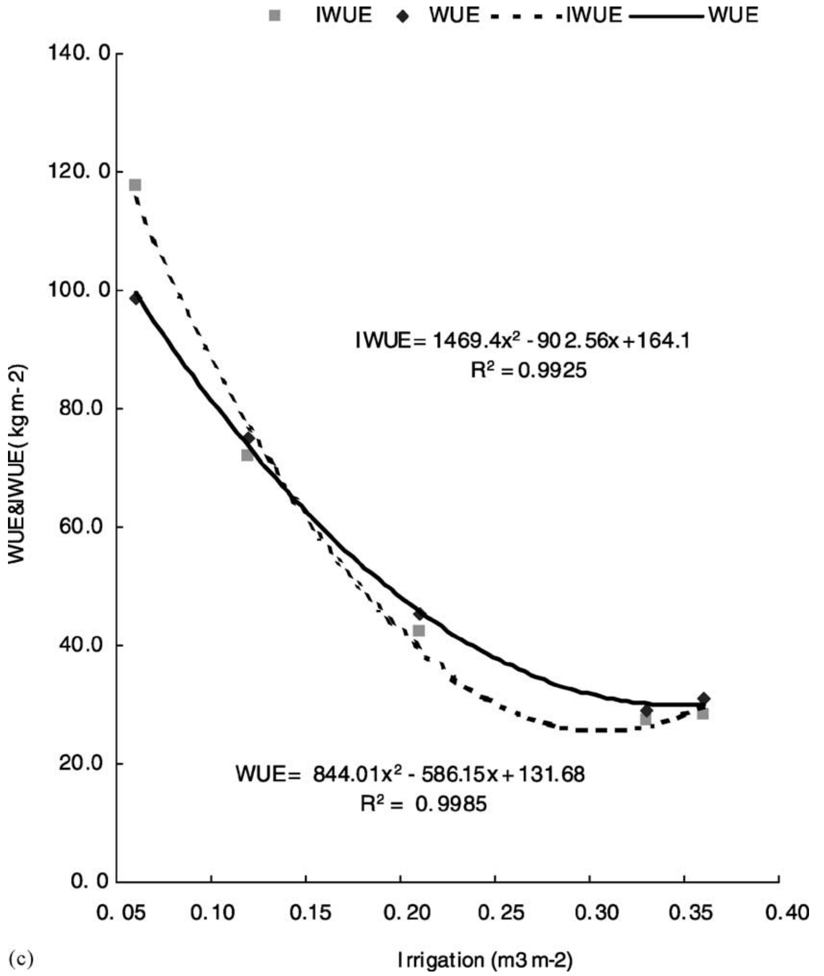
Fig. 2. (*Continued*)

high linear relationship irrigation water amount with ET at 0.001 significant levels as following:

$$\mathrm{ET} = 662.5 + 0.83I, \quad R^2 = 0.9879 \tag{1}$$

where ET is total water consumption ($\mathrm{m}^3\ \mathrm{ha}^{-1}$) and I the total irrigation water applied in growth period of cucumber ($\mathrm{m}^3\ \mathrm{ha}^{-1}$).

Among all treatments in our experiments, the maximum and minimum ET were obtained under T5 and T1 both at S3 (Table 4). But for deficit irrigation treatments T1, T2 and T3, their biggest ET were obtained at the growth stage S2. For T4 and T5, the biggest ET was at S3. The higher water consumption at S3 for high levels of irrigation treatments could be related to higher soil evaporation resulting from wetting soil surface a few times more. Regression equations fit for ET with fruit yields showed the same increase of ET would induce different improvement on cucumber fruit yields at different growing stages (Fig. 1); the most increase on yield would be produced at S2, therefore, S2 was the most water sensitive period for cucumber.



(c)

Fig. 2. (*Continued*).

3.3. WUE and IWUE

WUE ranged from 2.79 to 98.76 kg m^{-3} under deficit irrigation regime T1. The maximum WUE and IWUE appeared at S3 under T1, but minimum WUE and IWUE were at S1 under T3. Irrigation under T4 and T5 significantly increased WUE and IWUE at S1, but reverse at S2 and S3 perhaps due to higher evaporation. WUE and IWUE increased dramatically with the cucumber plants growth under T1, but they were not the same significant under T3, T4 and T5. The higher soil evaporation due to higher temperature would result in low WUE and IWUE under T4 and T5 at the last growing stage (Table 5).

Fig. 2 implied that irrigation could increase cucumber WUE and IWUE at S1 (Fig. 2(a)), but WUE and IWUE decreased with the increase of irrigation at S2 and S3 (Fig. 2(b) and (c), respectively), more significant at S3 due to higher evaporation. It was necessary to reduce evaporation and irrigation water amount at S3 in order to improve WUE and IWUE.

4. Conclusions

Cucumbers grown in irrigated greenhouses in the NCP showed good production responses. This paper enables us to infer that yield is considerably higher when cucumber receives a total quantity of water of 6500–7500 $m^3\,ha^{-1}$.

The experiment carried out did not enable us to know what response would have been if irrigation above 7500 $m^3\,ha^{-1}$, but the fresh yields did decrease when irrigation received only 2400 $m^3\,ha^{-1}$. These results showed that moderate irrigation was essential.

The analysis of water applied in each of crop's growth stages made it possible to classify their effects on the development of the yield. S2 was the most sensitive stage to water stress.

The WUE and IWUE found in this experiment showed that the most deficit irrigation strategies turn out to be the most efficient at S2 and S3 but, S1 was somewhat different which could only be accounted for the higher yields obtained.

When we attempted to select a strategic course of action recommendable for controlled deficit irrigation, we should point out that, with seasonal total volumes of water received ranging from 1500 to 2000 $m^3\,ha^{-1}$ for the last two stages, respectively, and 1000–1200 $m^3\,ha^{-1}$ at S1, we could obtain 8.0–8.5 kg m^{-2} at the last two growth stages and 5.0 kg m^{-2} at the first stage. And ET should be controlled to 2.2–2.5 mm per day for S1 and early phase of S2 and 4–5 mm per day from late phase of S2–S3, respectively. It is very important to limit soil inefficacy evaporation for irrigation water saving and WUE and IWUE improvement, mainly at the last growth stage.

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