Yield, Nitrogen Uptake and Nitrogen Leaching of Sensor-Based Fertigation-Cultured Tomato in a Shallow Groundwater Region: Effect of Shallow Groundwater on Tomato Irrigation

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Abstract

Fertigation with surface drip has been introduced and broadly applied for vegetable cultivation in the Eastern China, which presents high precipitation and always has shallow groundwater. To estimate the influence of high groundwater level on the tomato nitrogen (N) and water use efficiency and develop new sensor-based fertigation technology, experiments were executed in plastic greenhouse in the experimental farm of Yangzhou University located in the suburban of Yangzhou city during 2016-2017 growing seasons using a block randomization with three replications. Three N dosages and 4 watering treatments were carried out in this experiment. The data indicated that irrigation threshold of -35 kPa was optimum to get the maximum production of tomato. In this treatment, the value of estimated plant evapotranspiration (ETc) was much higher than total applied water volume, suggesting high groundwater table had a significant contribution on the tomato ETc and a sensor-based irrigation strategy should be more accurate than the simulated ETc irrigation method to calculate the water demand under this condition. In addition, our results indicated that high groundwater level had a positive effect to alleviating N leaching. Finally, we can conclude that fertigation technology enhanced the N use efficiency (NUE) and water use efficiency (WUE) and three fourths of the calculated N dosage (according to a traditional nutrient equation) was sufficient to optimize tomato yield.

Keywords: high groundwater table, irrigation threshold, nitrogen use efficiency, tomato, water use efficiency

1. Introduction

The middle and lower reaches of Changjiang River in China range from 111° to 123° east longitude and 27° to 34° north latitude, covering an area of about 200,000 km². In this region, the elevation is 5 m to 100 m (mostly below 50 m), the annual precipitation is 1000 to 1400 mm and the mean annual temperature is 14 to 18 °C (http://www.cma.gov.cn/). As a result, the water table of this region always remains at a high level. Due to its warm and humid climate, the middle and lower reaches of Changjiang River is one of the most important regions for vegetable production in China. Un-heated plastic greehouse is the most popular facility for vegetable production in this region. Annual thermophilous vegetables, such as solanaceous crops, beans and cucurbits, are always delayed-cultured in the autumn or accelerating-cultured in the spring in these walk-in plastic greenhouses. According to the official data, in 2013 there were about 1.7 million hectares of un-heated plastic greenhouse in China, among which about 0.44 million hectares were located in the middle and lower reaches of Changjiang River (Ministry of Agriculture of China, 2014).

Tomato is one of the most popular vegetables grown in these walk-in greenhouses in the middle and lower reaches of Changjiang River because of their delicious taste and high nutritional value. Tomato is a long season crop with high water and nitrogen (N) requirements and tomato yield is sensitive to the deficiency of soil water and N (He, Q. Chen, Jiang, X. P. Chen, & Zhang, 2007; Wang & Xing, 2017). On the other hand, growers always apply excessively irrigation water and high N rates to minimize risk of yield reductions due to water and N limitations, which usually cause serious water and N loss. Therefore, the irrigation and fertilization strategy should be carefully managed to minimize the water and N leaching without yield reduction. The response of tomato nitrogen use efficiency (NUE), water use efficiency (WUE) and yield to different irrigation and fertilization programs has been studied detailedly in different regions of the world in the past decades (Du, H. X.

Cao, Liu, Gu, & Y. X. Cao, 2017; Hou et al., 2017; X. L. Li, Liu, G. T. Li, Lin, & Jensen, 2010; Wang & Xing, 2016; Zotarelli, Scholberg, Dukes, Muñozcarpena, & Icerman, 2009). The optimal schedule varied among different reports, depending on the cultivation methods, the soil properties and the climate conditions.

Recently, owing to the growing labor cost and the rising attention of the agricultural source pollution, fertigation with surface drip and plastic mulch culture has been commonly used in this region. In addition, the sensor-based automatic irrigation system has gradually been applied to realize the precision irrigation and further reduce the labor cost. However, little study about fertilization and irrigation management has been conducted for these new vegetable production systems. On the other hand, researches about the nitrogen and water management of tomato were always conducted in the semi-arid or arid areas (Du et al., 2017; He et al., 2007). Unlike these semi-arid or arid regions, the middle and lower reaches of Changjiang River has plenty of rainfall and high groundwater level. According to our measurements, the depth of groundwater table is easily to be found less than 1 m in vegetable greenhouses at different sites in this area. It was reported that the shallow groundwater always has a considerable contribution to the total crop water requirement (Han, Zhao, Šimůnek, & Feng, 2015; Liu, Pereira, & Fernando, 2006; Ramos, Simionesei, Jauch, Almeida, & Neves, 2017; Wu, Liu, Paredes, Duan, & Pereira, 2015). Therefore, the management of fertilization and irrigation of vegetable crops should be different widely between arid and humid regions. However, up to date little research has focused on the water and N application strategies in shallow water table regions.

The purpose of this study is to investigate the response of tomato yield, dry matter, N uptake and N leaching to different fertilization and irrigation programs and collect data to improve the sensor-based fertigation technology for plastic walk-in greenhouse tomato cultivation in the middle and lower reaches of Changjiang River.

2. Materials and Methods

2.1 Experimental Site and Soil Properties

During spring-summer seasons in 2016 and 2017, the experiment was carried out at a vegetable farm (32°68′82″N, 119°59′10″E) in Yangzhou, Jiangsu Province, a typical region of the middle and lower reaches of Changjiang River. The year-round average temperature at the experimental site is 16.2 °C. The average annual rainfall is approximately 1021 mm, of which about 225 rainfall occurs in the spring (from March 1 to May 30) and 480 mm in the summer (from June 1 to August 31). Average annual evaporation is 937.7 mm (from the free water surface). Silt loam represents the main soil texture at the experiment region. The chemical and physical characteristics of the soil was shown in Table 1.

Table 1. Physical and chemical characteristics of the 0-30 cm depth of the experimental soil

Properties	2016	2017
Clay (%)	22	23
Loam (%)	56	57
Sand (%)	22	20
Bulk density (g cm^{-1})	1.41	1.40
Field capacity (%)	26.9	25.7
Field capacity (mm)	113.9	107.9
Wilting Point (%)	14.7	14.2
Wilting Point (mm)	62.8	60.2
pH	6.4	6.4
Organic matter content (%)	1.97	2.00
Salinity (dS m^{-1})	0.39	0.40
Total nitrogen (g kg^{-1})	1.05	1.05
Available nitrogen (mg kg^{-1})	108.4	112.3
Available phosphorous (P_2O_5 mg kg^{-1})	20.7	22.9
Available potassium (K_2O mg kg^{-1})	136.2	147.3

2.2 Crop Management and Treatments

The experiments were executed in the typical un-heated plastic greenhouses. These walk-in tunnels for experiment were 50 m long, 8 m wide, 2.3 m high and oriented south-north, which are typical in the middle and

lower reaches of Changjiang River. The tunnel frame was covered with polyethylene film (0.06 mm) during the whole period the experiment. In 2016 and 2017, Tomato seedlings at 7-leaf stage were transplanted in these greenhouses at March 1. Dairy manure 45 m^3 ha^{-1} (containing 32.84 kg N, 64.92 kg P_2O_5 and 80.42 kg K_2O) was mixed in the soil (20 cm) during bedding. The transparent plastic mulch and the drip irrigation system were equipped before transplanting. The vent was closed during raining and the ventilation was executed everyday according to the humid and temperature inside the greenhouse. Disease and pest control was carried out if necessary. All side shoots of tomato plants were mechanically removed. Fruits were harvested everyday when they met the market standard. The last harvest date was at July 3 in 2016 and July 7 in 2017. The distance between plants and rows was demonstrated in the Figure 1.
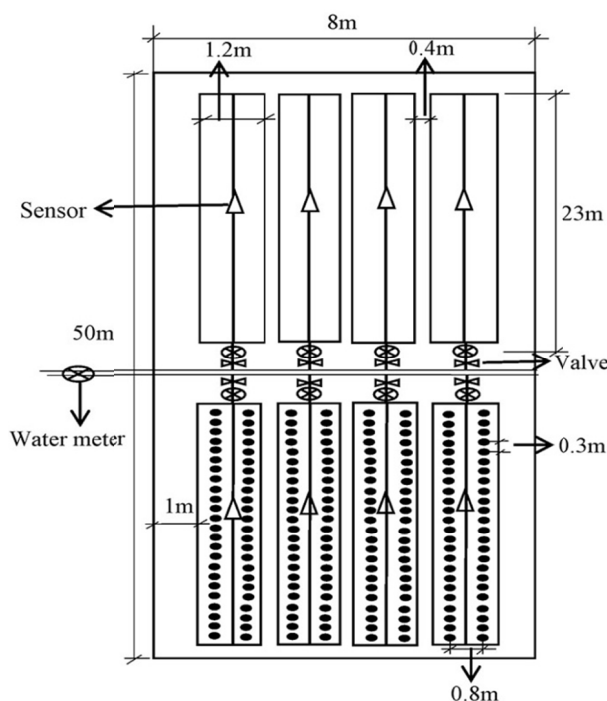

Figure 1. Schematic layout of the plots, fertigation arrangement, sensor irrigation system and the distance of plants and rows in greenhouses

Three N rates and 4 irrigation water schedules (totally 12 treatments) were arranged in this experiment (Tables 2 and 3). The N_R (chemical N recommended) was calculated according to the soil nutrient balance, in which the expected tomato yield was 100 tons ha^{-1}, the soil available NUE is 45%, the organic fertilizer NUE is 20%, and the chemical fertilizer NUE is 50%, according to local experiences. Therefore, 3 N rates were calculated as N1 = 0.5 N_R, N2 = 0.75 N_R and N3 = N_R. The exact dosage of chemical fertilizers was list in Table 2. Potassium sulfate, calcium superphosphate and urea were used as chemical fertilizers to provide potassium, phosphorus and N, respectively. Urea and potassium sulfate were dissolved and applied by the fertigation system during plant growth. To meet the plant need, twenty percent urea was used from 0 to 40 days after transplanting, forty percent urea and forty percent potassium sulfate were used from the 40 to 80 days after transplanting, and forty percent urea and sixty percent potassium sulfate were used from 80 days after planting to the end, according to N and potassium assimilating patterns of tomato plants (data from previous local experiments, unpublished). In each irrigation event, the dosage of urea and potassium sulfate solution were used averagely according to the total amount and irrigation time in each growth stage. The calcium superphosphate was mixed in the soil when bedding as a base fertilizer.

Table 2. Applications of chemical fertilizer in the experiments

Year	N (kg ha^{-1})	P$_2$O$_5$ (kg ha^{-1})	K$_2$O (kg ha^{-1})
2016	187.86	176.77	467.88
	281.81		
	375.72		
2017	180.61	149.47	480.02
	270.92		
	361.22		

Table 3. Applications of irrigation in the experiments

Year	Treatment	Irrigation times*	Irrigation water dosage (mm)*
2016	-50 to -35 kPa	22	207
	-35 to -20 kPa	28	258
	-20 to -5 kPa	34	319
	-50 to -5 kPa	10	268
2017	-50 to -35 kPa	23	246
	-35 to -20 kPa	29	310
	-20 to -5 kPa	35	375
	-50 to -5 kPa	11	321

Note. * Irrigation times and irrigation water dosages include the 45 mm water applied at the first day and the same amount water at the second day after transplanting, respectively.

A sensor based irrigation system was applied in this experiment. Four irrigation schedules were set up as: -50 to -35 kPa, -35 to -20 kPa, -20 to -5 kPa, and -50 to -5 kPa. Prior to the beginning of the irrigation treatments, plants were applied with 45 mm water at the first day and the same water amount at the second day after transplanting for a better plant establishment. The exact values of irrigation time and dosage of the treatments were list in Table 3. The last irrigation was at June 25 in 2016 and June 29 in 2017, respectively.

In this experiment, each greenhouse contained 4 plots, as shown in Figure 1. Thus, each replicate included 3 tunnels. The experiment included 3 replicates and totally need 9 tunnels per year. To block the cross movement of N and water, in the same tunnel, plots were segregated with PVC plates (depth of 0.5 m). The fertigation system was controlled independently to allow us conducting the randomized block factorial experimental design.

2.3 Measurements

Soil samples (0 to 30 cm) were taken for parameter analysis listed in Table 1, according to Lu (1999). The groundwater level was monitored by water table sensors (YKKT-1E, Xian Xingyi Yibiao Technology CO., LTD, China), one sensor per greenhouse. A weather station (NHQXZ601, Wuhan Zhongke Nenghui Technology Development CO., LTD, China) was equipped in one of the experiment greenhouses to collect weather data for ET$_0$ estimation. The rainfall data was collected by another weather station set up outside the greenhouses. Flow meters were used to control the irrigation water dosage of each treatment (one flow meter per plot).

Total fruit weights harvested from each plot were record (transformed into kg ha^{-1}). After the last harvest, 5 plants in each replicated plot were selected randomly to measure the dry weight of roots, fruits, stems and leaves (including the harvested fruits and pruned side shoots). The dry matter of different organs was assayed by drying samples at 65 °C to a constant weight and total dry weight was evaluated as the sum dry matter of all organs. The N contains of roots, fruits, stems and leave were measured by the micro Kjeldahl protocol of digestion and titration individually (Bremner & Mulvane, 1982). The total N uptake was estimated using the dry matter and the N concentration of each tissue. Before planting, 3 self-made lysimeters were inbuilt in each plot with their collection surface at 30 cm depth to collect N leaching. The soil solution collected in each lysimeter was aspirated using a syringe with a long hose (Figure 2). Water samples were sampled every 5 days from lysimeters. The receiver of the lysimeter is large enough to avoid the overbrimming. Total N quantities of the leachates in lysimeters were assayed using a continuous flow analyzer (Futura, Alliance, France). Nitrogen leaching (kg ha^{-1})

of each treatment was estimated as the ratio of one hectare to the collecting surface area of 3 lysimeters times the total N leaching in the lysimeters. In this experiment, water use efficiency (WUE) was evaluated as fruit yield divided by total irrigated water (kg mm^{-1}), and the N use efficiency (NUE) was defined as fruit yield divided by total chemical N application (kg kg^{-1}).
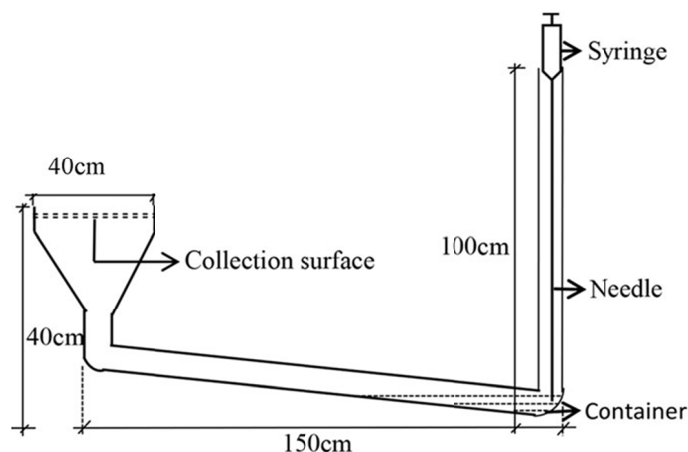
Figure 2. Diagrammatic drawing of the self-made lysimeter used in the experiment

2.4 Statistical Analysis

Two-way ANOVAs were performed to determine significances among experimental years, irrigation programs and N dosages with SPSS Statistics 18. The significance of treatment effects and their interactions was estimated using the F-test, and the least significant difference (LSD) were used to comparing means at the 0.05 level.

3. Results

3.1 Precipitation and Underground Water Level

Daily rainfall and the groundwater table level in the experimental greenhouse were observed. As shown in Figure 3, the precipitation during the experiment stage was 592.1 mm in 2016 and 274.9 mm in 2017. In both years, about half of rainfall occurred in June (forty-nine percent in 2016 and forty-six percent in 2017 during the cropping period). The depth of water table ranged from 11 to 78 cm in 2016 and 12 to 83 cm in 2017. In an addition, a closely relationship between the rainfall and the depth of groundwater table was observed, although the ventilation opening of greenhouses was closed when raining.
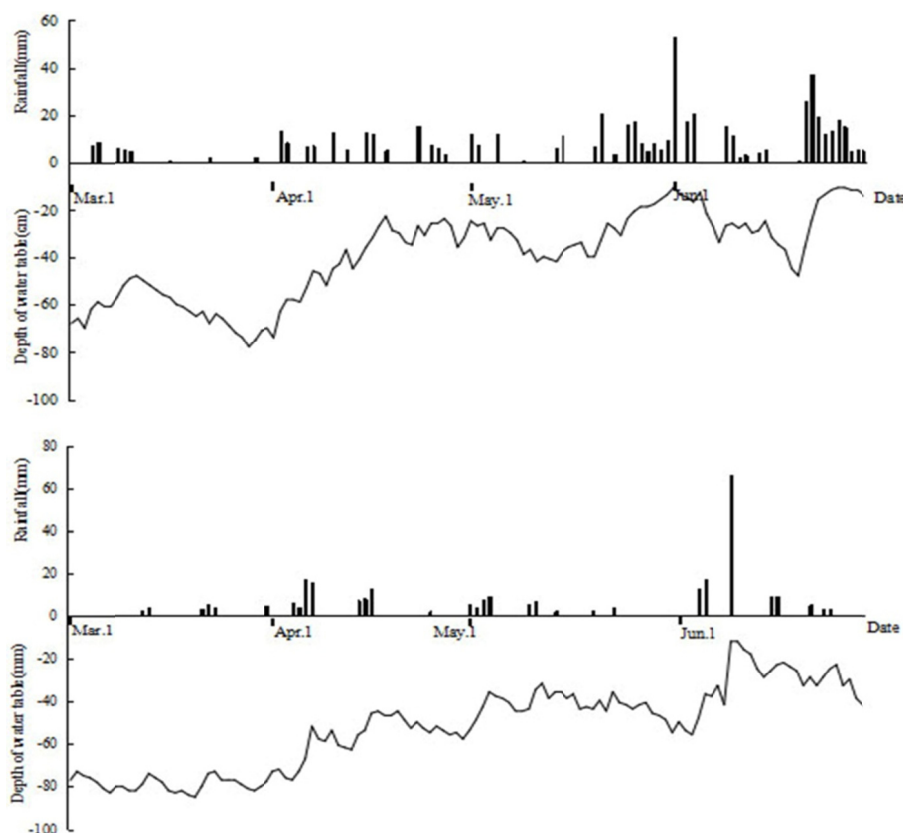
Figure 3. Daily data of rainfall and depth of groundwater table in 2016 and 2017 during plant growth

3.2 Tomato Yield

As shown in Table 4, tomato yield ranged from 64.3 (N1 -50 kPa to -35 kPa, 2017) to 126.5 tons ha^{-1} (N2 -35 to -20 kPa, 2017) over 2 study years. Basically, the response of tomato yields to different N rates could be summarized as N3 > N2 > N1 each year. However, a significant irrigation × N interaction on tomato yield was observed. In -50 to -35 kPa and -35 to -20 kPa treatments, there was no remarkable difference between N2 and N3, while in -20 to -5 kPa and -50 to -5 kPa, tomato yield of N3 was remarkably higher than that of N2. The response of tomato yield to different irrigation treatments also revealed an irrigation × N interaction effect. In N1, the tomato yield of different irrigation treatments was -35 to -20 kPa > -50 to -5 kPa > -20 to -5 kPa > -50 to -35 kPa. While in N2 and N3, it was -35 to -20 kPa > -20 to -5 kPa > -50 to -5 kPa > -50 to -35 kPa. In addition, statistical analysis of the experimental results suggested there were significant differences in the yields between two experimental years (2016 < 2017). Statistically, the (N2, -35 to -20 kPa) combination was the optimal treatment to achieve the highest tomato yield in the experimental condition.

Table 4. Tomato yield under different N × irrigation combinations in 2016 and 2017 (tons ha^{-1})

Treatment	2016				2017[NS]			
	N1	N2	N3	Average	N1	N2	N3	Average
-50 to -35 kPa	67.3 g	87.8 e	90.1 de	81.7 C	64.3 h	89.3 f	92.6 ef	80.1 C
-35 to -20 kPa	94.6 cd	121.9 a	120.0 a	112.2 A	97.8 d	126.5 a	121.5 b	115.3 A
-20 to -5 kPa	78.7 f	109.4 b	123.6 a	103.9 AB	80.2 g	111.4 c	119.3 b	103.6 AB
-50 to -5 kPa	86.2 e	98.5 c	110.8 b	98.5 B	88.7 f	96.3d e	111.2 c	98.7 B
Average	81.7 B	104.4 A	111.1 A	99.1	82.8 B	105.9 A	111.2 A	99.4

Note. Values with different lower case letters in the N × irrigation combinations (totally 12 treatments each year) are significantly different at the 0.05 level. Values with different upper case letters in the same average column or the same average row each year are also significantly different at the 0.05 level. The same definitions apply to Tables 5-9. [NS] indicate no significant difference between 2016 and 2017 at the 0.05 level. The same definitions apply to Tables 5-7.

3.3 Dry Matter

Similar to the response of fresh yield, the tomato dry matter of N2 and N3 was markedly higher than that of N1, while there was no remarkable difference of plant dry matter between N2 and N3. The similar irrigation× N interaction on tomato dry matter was also observed, *i.e.*, In N1, the plant dry matter of different irrigation treatments was -35 to -20 kPa > -50 to -5 kPa > -20 to -5 kPa > -50 to -35 kPa. While in N2 and N3, it was -35 to -20 kPa > -20 to -5 kPa > -50 to -5 kPa > -50 to -35 kPa. There was no significant difference of plant dry matter data between 2016 and 2017.

Table 5. Tomato total dry matter under different N × irrigation combinations in 2016 and 2017 (tons ha^{-1})

Treatment	2016				2017[NS]			
	N1	N2	N3	Average	N1	N2	N3	Average
-50 to -35 kPa	7.0 i	10.9 fg	10.4 g	9.4 B	6.4 f	10.9 cd	11.7 c	9.67 C
-35 to -20 kPa	11.9 ef	16.1 ab	15.1 bc	14.4 A	12.0 c	16.2 a	15.5 ab	14.6 A
-20 to -5 kPa	9.3 h	13.8 d	16.6 a	13.2 A	9.5 e	14.8 b	15.9 a	13.4 AB
-50 to -5 kPa	10.1 gh	12.5 e	14.0 cd	12.2 A	10.3 de	11.6 c	14.8 b	12.2 B
Average	9.6 B	13.3 A	14.0 A	12.3	9.6 B	13.4 A	14.5 A	12.5

3.4 N Uptake

In all 4 irrigation treatments, the plant N uptake increased with the increase of N dosage from N1 to N3. A similar irrigation × N interaction was also observed in terms of N uptake, In N1 treatments, the order of N uptake amount was -35 to -20 kPa > -50 to -5 kPa > -20 to -5 kPa > -50 to -35 kPa. While in N2 and N3, it was -35 to -20 kPa > -20 to -5 kPa > -50 to -5 kPa > -50 to -35 kPa. The impact of experimental year on the N accumulation was also significant (2016 < 2017). In -50 to -35 kPa and -35 to -20 kPa, comparing with N2, N3 improved the plant N accumulation, but had no beneficial effect on tomato yield, suggesting a luxury N consumption happened in N3 in these conditions.

Table 6. Nitrogen uptake under different N × irrigation combinations in 2016 and 2017 (kg ha^{-1})

Treatment	2016				2017[NS]			
	N1	N2	N3	Average	N1	N2	N3	Average
-50to-35kPa	143.6 i	227.0 fg	248.3 ef	206.3 C	131.5 h	219.0 f	242.3 df	197.6 C
-35to-20kPa	252.3 e	369.1 a	384.5 a	335.3 A	269.2 c	372.6 a	382.5 a	341.4 A
-20to-5kPa	185.4 h	308.8 bc	312.9 b	269.0 B	190.5 g	311.9 b	305.6 b	269.3 B
-50to-5kPa	213.6 g	263.0 de	284.5 cd	253.7 B	224.6 f	262.2 cd	278.1 c	255.0 B
Average	198.7 B	292.0 A	307.6 A	266.1	204.0 B	291.4 A	302.1 A	265.8

3.5 N Leaching

The response of N leaching to different N and irrigation combinations was specific. As shown in Table 7, the leached N remarkabely increased with the increase of the amount of N fertilizer and irrigation water used (N3 > N2 > N1, -20 to -5 kPa > -50 to -5 kPa > -35 to -20 kPa > -50 to -35 kPa. There was no significant difference of N leaching data between 2016 and 2017. The N leaching seasonal evolution of combination N2 -50 to -5 kPa and N2 -35 to -20 kPa in 2016 was list in Figure 4. Basically, the N leaching amount revealed a downtrend during the crop season. Other combinations also showed similar tend (data not shown). The results also indicated that the large amount of irrigation water at the first two days after transplanting result in severe N leakage.

Table 7. Nitrogen leaching under different N × irrigation combinations in 2016 and 2017 (kg ha^{-1})

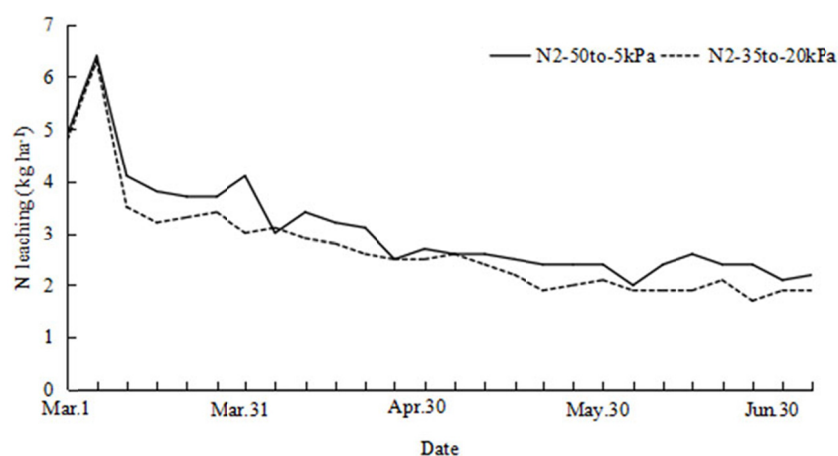| Treatment	2016				2017[NS]			
	N1	N2	N3	Average	N1	N2	N3	Average
-50 to -35 kPa	31.6 i	57.3 fg	78.6 d	55.8 D	29.3 j	58.4 g	81.5 de	56.4 C
-35 to -20 kPa	43.2 h	70.4 e	94.3 c	69.3 C	41.6 i	72.3 f	96.7 b	70.2 B
-20 to -5 kPa	59.4 f	89.2 c	121.7 a	90.1 A	55.3 g	88.6 c	119.3 a	87.7 A
-50 to -5 kPa	51.3 g	79.6 d	103.7 b	78.2 B	48.2 h	76.4 ef	100.2 b	74.9 B
Average	46.4 C	74.1 B	99.6 A	73.4	43.6 C	73.9 B	99.4 A	72.3

Figure 4. The N leaching seasonal evolution of combination N2 -50 to -5 kPa and N2-35 kPa to -20 kPa in 2016

3.6 WUE of Different Treatments

Basically, in three N treatments, the WUE data followed the pattern N3 > N2 > N1. However, in -50 to -35 kPa and -35 to -20 kPa treatments, there was no significant difference of WUE between N2 and N3. The WUE difference between N2 and N3 was mostly found in -20 to -5 kPa and -50 to -5 kPa treatments. Among 4 irrigation treatments, the order of WUE was -35 to -20 kPa > -50 kPa to -35 kPa > -50 kPa to -5 kPa > -20 kPa to -5 kPa. In addition, the WUE of 2016 was significantly higher than that of 2017, mostly due to the lower irrigation volume of water applied in 2016 than in 2017.

Table 8. Water use efficiency (WUE) under different N × irrigation combinations in 2016 and 2017 (kg m^{-3})

Treatment	2016				2017*			
	N1	N2	N3	Average	N1	N2	N3	Average
-50 to -35 kPa	32.5 fg	42.4 bc	43.5 b	39.5 B	26.1 g	36.3 cd	37.6 bc	33.3 AB
-35 to -20 kPa	36.7 e	47.3 a	46.5 a	43.5 A	31.6 e	40.8 a	39.2 ab	37.2 A
-20 to -5 kPa	24.7 h	34.3 f	38.8 d	32.6 C	21.4 h	29.7 f	31.8 e	27.6 C
-50 to -5 kPa	32.2 g	36.8 de	41.3 c	36.8 B	27.6 g	30.0 ef	34.6 d	30.7 BC
Average	31.5 B	40.2 A	42.5 A	38.1	26.7 B	34.2 A	35.8 A	32.3

Note. * indicate the significantly difference between 2016 and 2017 at the 0.05 level. The same definitions apply to Table 9.

3.7 NUE of Different Different N × Irrigation Combinations

As shown in Table 9, the NUE increased significantly with the decreased N fertilizer rate in both years. Among 4 irrigation programs, the optimal NUE was observed in -35 kPa to -20 kPa and the lowest NUE was in -50 kPa to -35 kPa, indicating water deficiency retarded N uptake in this occasion. In N1 treatment, the NUE of -50 kPa to -5 kPa was higher than that of -20 kPa to -5 kPa, while in N2 and N3, the NUE of -50 kPa to -5 kPa was lower than that of -20 kPa to -5 kPa. The NUE of 2017 was significantly higher than that of 2016, mostly due to the less N chemical fertilizer applied in 2017 than in 2016.

Table 9. Nitrogen use efficiency (NUE) under different N × irrigation combinations in 2016 and 2017. (kg kg^{-1})

Treatment	2016*				2017			
	N1	N2	N3	Average	N1	N2	N3	Average
-50 to -35 kPa	358.3 e	311.6 fg	239.8 h	303.2 B	356.0 f	329.6 g	256.4 i	314.0 B
-35 to -20 kPa	503.6 a	432.6 c	319.4 f	418.5 A	541.5 a	466.9 c	336.4 g	448.3 A
-20 to -5 kPa	419.0 c	388.2 d	329.0 f	378.7 A	444.1 d	411.2 e	330.3 g	395.2 A
-50 to -5 kPa	458.9 b	349.5 e	294.9 g	367.8 A	491.1 b	355.5 f	307.9 h	384.8 A
Average	435.0 A	370.5 B	295.8 C	367.1	458.2 A	390.8 B	307.8 C	385.6

4. Discussion

The study on sensor-based irrigation management has been conducted of many crops, including cotton, potato, onion, tomato and so on. The optional irrigation threshold of different crops always ranged from about -20 kPa to -40 kPa (Kang & Wan, 2005; Kang, Wang, Liu, & Yuan, 2004; Meeks et al., 2017; Shock, Feibert, & Saunders, 2000). In this study, the best irrigation threshold is -35 kPa, which was similar to that of other crops. Montesano et al. (2015) reported that -30 hPa to -90 hPa of substrate matric potential was suitable for soilless tomato production, indicating a large difference of hydrodynamics between soilless and soil production systems. Higher soil moisture has no impact or even negative impact on NUE, N uptake, dry matter and yield. The extra water may cause more N loss or oxygen deficit in the root zone, which lead to a reduced yield (Fiebig & Dodd, 2016). In addition, high soil potential always has a negative effect on tomato fruit quality (Wang, Kang, Du, Li, & Qiu, 2011; Wang & Xing, 2017). To deal with the water shortage or improve the WUE in arid or semi-arid regions, several researches have tried lower irrigation threshold during crop growth. Wang, Kang, and Wan (2007) set 5 irrigation treatments (irrigation thresholds from -10 kPa to -50 kPa) and found the soil matric potential did not affect the tomato yield significantly. Meeks et al. (2017) applied 4 irrigation thresholds (from -20 kPa to -100 kPa) prior to cotton flowering and suggested that -100 kPa irrigation threshold can be applied to reduce irrigation times without yield loss. However, in this study, low soil moisture (-50 kPa irrigation threshold) significantly reduced the tomato yield, dry matter accumulation and N uptake. The surface fertigation system and high ground water table may result in a shallow root distribution (mostly in the 20 cm soil, field observation, data not shown), which leaded to a high sensitivity to water stress of tomato plants.

In this study, we fail to calculate the ETc (crop evapotranspiration) of tomato plants with the equation of water balance ET (mm) = (Pi + I + C) − (R + D) + ΔSWC (in this equation, Pi means precipitation, I means irrigation, C mans the upward flux into the root zone, R means surface runoff, D means downward drainage out of the root zone and ΔSWC means the change in soil water content between planting and harvesting), since we could not obtain the exact data of C and D in a soil with high groundwater table. Thus, we estimated the plant ETc with the equation ETc = ET_0 × Kc, where ET_0 (reference crop evapotranspiration) was estimated using the CROPWAT Software version 8.0 (Smith, 1992) with weather data detected from the experimental greenhouses, and Kc means the crop coefficient. The Kc durations and values were according to our records during plant growth and the data from Sun et al. (2013), similar tomato type and growth habit of this study). The estimated ETc of 2016 and 2017 was 353mm and 406 mm respectively, which was far more than the optimal irrigation water amount (258 mm in 2016 and 310 mm in 2017) in this study. These results suggested that high groundwater table had a significant contribution on the evapotranspiration of tomato plants, and a sensor-based irrigation program might be more accurate than the simulated ETc methods to evaluate the water need in this occasion. In addition, the -35 to -20 kPa treatment consumed similar irrigation water as -50 to -5 kPa treatment but obtain significant higher yield, dry matter and N uptake than those of -50 to -5 kPa treatment, suggesting that frequent irrigation is critical to reduce N leaching and improve WUE or NUE in this condition.

The data of this research revealed that the three forth of the recommended N rate was enough to obtain the optimal tomato yield and higher N dosage would cause luxury N consumption and serious N leaching. The parameters used to estimate the recommended N dosage in this experiment were used from the conventional fertilization practice in the local region directly, suggesting that the NUE of the sensor-based fertigation methods was remarkably higher than that of the conventional practice and the parameters about NUE should be reappraised for the new fertigation methods. Furthermore, our results indicated that the N leakage decreased and the groundwater level increased along the growth season and there was a negative correction between the N leakage and the groundwater level (Figures 3 and 4). Morari, Lugato, Polese, Berti, and Giardini (2012) reported that soil N and water downward movement was retarded and N leakage was reduced by the high water table. Our results suggested that the high groundwater level may play a similar role in this study. In a word, the soil nutrient

and water dynamics of the sensor-based fertigation system still need to be further researched to optimize the plastic tunnel vegetable management in this shallow groundwater region.

5. Conclusions

Surface fertigation-cultured tomato plants were sensitive to water supply in shallow water table regions. The results showed that the -35 to -20 kPa treatment was optimum to gain the highest tomato yield, NUE and WUE. In this treatment, the total irrigation water amount was far less than the value of estimated ETc, suggesting high groundwater level had a significant contribution on the tomato plant evapotranspiration. Comparing with conventional fertilization practice, the new sensor-based fertigation system improved the nutrient use efficiency significantly. The result indicated that three forth of the recommended N rate was enough for tomato growth and high N dosage cause luxury N consumption and severe N leakage. Finally, the recommended sensor-based fertigation strategy in these conditions was the combination of -35 to -20 kPa irrigation and three forth of the recommended N treatment, in which the highest tomato yield (121.9 tons ha^{-1}), WUE and NUE were achieved (data from the experiment of 2016).

Acknowledgements

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