



Root Growth, Fruit Yield and Water Use Efficiency of Greenhouse Grown Tomato Under Different Irrigation Regimes and Nitrogen Levels

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Abstract

Soil water and nutrients are the two important factors affecting vegetative growth and the reproduction of greenhouse tomatoes (*Solanum lycopersicum* L.), but the effect of the interaction between irrigation and nitrogen (N) rates on fruit yield, root characteristics and N uptake have not yet been studied. Tomatoes were irrigated at 100% (W1), 80% (W2), and 60% (W3) of reference crop evapotranspiration (ET_0) and N fertilizer was supplied at 240 kg N ha⁻¹ (N240), 180 kg N ha⁻¹ (N180), and 120 kg N ha⁻¹ (N120) under drip fertigation in 2015 and 2016. In 2015, the fruit yield of the irrigation and N rates varied from 54.1 to 75.9 t ha⁻¹. In 2016 (where the total irrigation amount was higher than in 2015), the fruit yield varied from 55.6 to 78.7 t ha⁻¹. The average fruit yield in W1 was 17.8% and 21.4% higher than W3, in 2015 and 2016 respectively. The mean root weight density in N240 was 13.4% and 10.7% lower than N180, in 2015 and 2016, respectively. Averaging the irrigation levels, the total dry-matter production in N180 and N120 was, respectively, 1.4% and 13.2% lower than N240 in 2015. With the application of the irrigation and N fertilizer rates, plant N uptake increased from 28.7 to 94% in 2015 and from 14 to 92.3% in 2016. The water use efficiency (WUE) of the irrigation and N rates varied from 25.4 to 37.2 kg m⁻³ and from 20.8 to 36 kg m⁻³ in 2016. The partial factor productivity of the N fertilizer (PFP_N) varied from 274.6 to 529.3 kg kg⁻¹ and from 260.1 to 592.1 kg kg⁻¹ in 2016 with the irrigation and N fertilizer rates. We conclude that the effect of irrigation and N rates on fruit yield, dry-matter production and N uptake significantly changes with the root characteristics. Considering the trade-off among the plant N uptake, WUE and PFP_N, W2N180 may give a satisfactory fruit yield for greenhouse tomato in north-west China.

Keywords Nitrogen uptake · Total root length · Total root volume · Root weight density · Partial factor productivity of the nitrogen fertilizer (PFP_N)

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Introduction

The tomato (*Solanum lycopersicum* L.) is one of the most popular, nutritious, and palatable vegetables in the world (Martin 2013; Padayachee et al. 2017; Sturm and An 2014). It helps in supplying a varying commixture of nutrients that are necessary for human health and nutrition (Ilahy et al. 2016). In addition, tomatoes are rich in lycopene, which could improve the endothelial function of cardiovascular disease patients and reduce the risks of prostate cancer and possibly several other cancers (Zhang et al. 2015). In recent years, the tomato has been one of the main vegetable crops grown in greenhouses in China, because it offers a lot of health benefits for consumers and has a high potential profitability (Li et al. 2016).

The fruit yield of tomatoes depends heavily on biological factors and environmental conditions (D'Esposito et al.

2017; Raza et al. 2017). Amongst environmental conditions, soil water and nutrient status are two major factors affecting the vegetative growth and the reproductive phase of tomatoes. Therefore, appropriate and time-specific irrigation and fertilization strategies can significantly enhance fruit yields. The influence of soil water status on tomato growth and yield has been extensively discussed via a series of experiments (Wang and Xing 2017; Zhang et al. 2017; Zotarelli et al. 2009). The tomato plant has the ability to morphologically adapt to extreme water-shortage and water-rich environments (Preece and Peñuelas 2016). Both the crop roots as sensors of the soil–water status, and the shoots' ability to morphologically adapt to the soil environment, often rely on better root growth and soil moisture conditions (Koevoets et al. 2016; Turner 1986). This is because a good root structure will benefit plant nutrient uptake and will help attain more leaf area and dry matter (Ayi et al. 2016; Faucon et al. 2017). On the one hand, water-logged soil causes a reduction in the rate of leaf extension and dry-matter accumulation by the shoots (Drew and Sisworo 1979). On the other hand, water-shortage triggers plant roots to grow deeper in search of water and modifies root morphological behavior by simultaneously reducing lateral roots (Faucon et al. 2017; Romero-Aranda et al. 2001). A significant decline of dry-matter accumulation was caused by drought and waterlogging, resulting in poor fruit yield (Bisbis et al. 2018; Shao et al. 2016; Sharma et al. 2014).

The soil nutrient status is another important factor in the limitation of fruit yield in greenhouse vegetables (Bates 1971; Nordey et al. 2017; Yang et al. 2018). Nitrogen (N) fertilization is one of the classical agronomic practices used in agricultural systems, with the aim of increasing soil fertility, crop yield, and agricultural sustainability (Goron et al. 2017; Mancinelli et al. 2015; Mitchell et al. 2007; Wang et al. 2015; Weiner 2017; Zheng et al. 2017). Therefore, selecting suitable N-fertilizer rates to maximize fruit yield with an optimal irrigation level is an objective of both producers and agronomists. Although much information is available on the combination of irrigation and fertilization controlling fruit yield and quality traits (Akhtar et al. 2014; Li et al. 2017a; Lu et al. 2016; Pascale et al. 2001; Patané and Saita 2015; Topcu et al. 2007; Zaller 2007), very little is known about how intermediary systems of root characteristics are affected by the coupling of irrigation and N-fertilizer application rates.

In practice, irrigation and N-fertilization techniques usually rely on management skills, but the concurrent yield improvement must also be taken as a combined effect of soil factors and root characteristics. It is a well-known fact that most plant roots require an adequate and continuous supply of soil water and nutrients to grow, develop, and function normally. In other words, the roots act as ducts that help the translocation of absorbed moisture

and nutrients move from the soil to the nutritive organs and reproductive organs of the plants. Therefore, it is necessary to quantify the root distribution under different conditions to comprehend the processes of soil water and nutrient uptake (Gregory 1979). Progress in understanding these processes had been inhibited by methods involving the complex root systems. Nevertheless, many researchers have tried to solve this problem; Zotarelli et al. (2009) reported that root length and density distribution were affected by varying quantities of irrigation. Similarly, a larger proportion of roots were distributed in moisture areas by the dripper, whereas lower quantities were found at a greater distance to drippers (do Rosário et al. 1996). Better irrigation management can significantly decrease nitrate-N leaching during the growing season (Quemada et al. 2013). Furthermore, a precise N supply combined with good irrigation may not only reduce nitrate-N leaching loss but may also help the root system to grow healthily and with better nutrient uptake, thus ensuring an increase in yields. Good agronomic management must improve the nutrient uptake and must enhance the efficient use of both soil water and N-fertilizer.

The objectives of the present study were to evaluate the effects of irrigation and N fertilizer application rates on greenhouse-grown tomatoes in terms of (1) the soil water status, (2) the root characteristics, (3) the dry-matter production, fruit yield and crop N uptake, and (4) the water and N use efficiency in greenhouse tomatoes of North-west China. Answering these questions will help maximize the use-efficiency of both water and fertilizer for tomato production and will give a better understanding of the inter-relationship between fruit yield and root characteristics under adjusted soil environmental conditions.

Materials and Methods

Site Description

The field experiments were conducted over two consecutive years at the Agricultural Experiment Station of Yan'an University, China (36°38'N, 109°26'E, altitude of 972 m above the sea level) during the growing seasons of 2015 and 2016. The climate of this area is warm-temperate and semi-humid. The long-term mean temperature is 9.9 °C, and the annual average maximum and minimum temperatures are 17.2 and 4.3 °C, respectively. The average annual amount of precipitation from 1980 to 2015 at the site was 508 mm, and rainfall occurred mainly from May to September. The average annual sunshine duration is 2449 h with more than 181 frost-free days (Wang and Xing 2017).

Soil Characteristics

Following the United States Department of Agriculture (USDA) soil taxonomy, the soil texture of the experimental site is calcareous (Wang and Xing 2017; Xu et al. 2016). The average sand, silt, and clay contents in the 0–60 cm soil profile were $21 \pm 4.2\%$, $54 \pm 3.3\%$, and $19 \pm 1.4\%$, respectively, as measured by a laser particle size analyzer (Dandong Haoyu Technology Co., Ltd, Liaoning, China). The detailed soil characteristics of the experimental site are described in Table 1.

Experimental Design

The experiment was carried out in a randomized design that has three irrigation regimes and three N-fertilizer application rates with four replicates of each treatment. Three irrigation levels included W1: 100% ET_0 (ET_0 , the reference evapotranspiration), W2: 80% ET_0 , and W3: 60% ET_0 . Three N-fertilizer application rates were assessed: 240 kg N ha^{-1} (N240), 180 kg N ha^{-1} (N180), and 120 kg N ha^{-1} (N120). Each treatment plot received the same rates of phosphate fertilizer (P) and potassium fertilizer (K), with 120 kg P ha^{-1} and 150 kg K ha^{-1} being applied simultaneously for both years. Urea (N 46.4%), diammonium phosphate (P_2O_5 44%), and potassium chloride (K_2O 60%) were used for the fertilization. These fertilizer rates were selected based on a wide range of local fertilizer application rates and were considered based on prior research carried out in this region (Wang and Xing 2017). Each experimental plot was 7 m long and 5 m wide for each treatment ($7\text{ m} \times 5\text{ m} = 35\text{ m}^2$), and the same plots were used for 2 years. There were nine ridged experimental plots, which were divided by a water barrier sheet (PVC boards, 60 cm height). The drip line consisted of an inserted cylinder head, a drip irrigation pipe with an inner diameter of 8 mm, a drop head span of 45 cm, a head flow of 1.38 L h^{-1} , and a drip irrigation operating pressure of 0.3 MPa.

The cultivar ‘Meifen 863’ (Ju Feng Seed Co., Ltd, Ningxia, China) of the tomato (*Solanum lycopersicum* L.) was used for the experiments. Plants were transplanted at the four-leaf stage on May 8th, 2015 and on May 12th, 2016.

After transplantation, the plastic film mulch was cultivated using the local traditional planting patterns and calendars, using tomato ridging in a tube with a one-line layout, spaced 50 cm apart, and with a 45 cm planting distance and 86 plants in each experimental plot. The fertilizer was applied five times (14, 30, 48, 73, and 95 days after transplantation (DAT) in 2015; 15, 29, 49, 75, and 96 DAT in 2016) at a fertilization ratio of 1:1:3:3:2. The irrigation frequency ranged from 3 to 10 days, which was according to the sum of the reference crop evapotranspiration (ET_0) rates between two adjacent irrigation times. The computing methods were the same as for our previous studies (Wang and Xing 2017). The irrigation and fertilization treatment details are shown in Fig. 1.

Meteorological Data Measurements

Each year, the meteorological data inside the greenhouse were recorded using a small meteorological station with a multi-channel data acquisition recorder (HOBO H21-002, USA), which was installed at the centre of the greenhouse. Data were recorded via a data logger every 30 min (Supplementary Table S1).

Soil Water Content Measurements

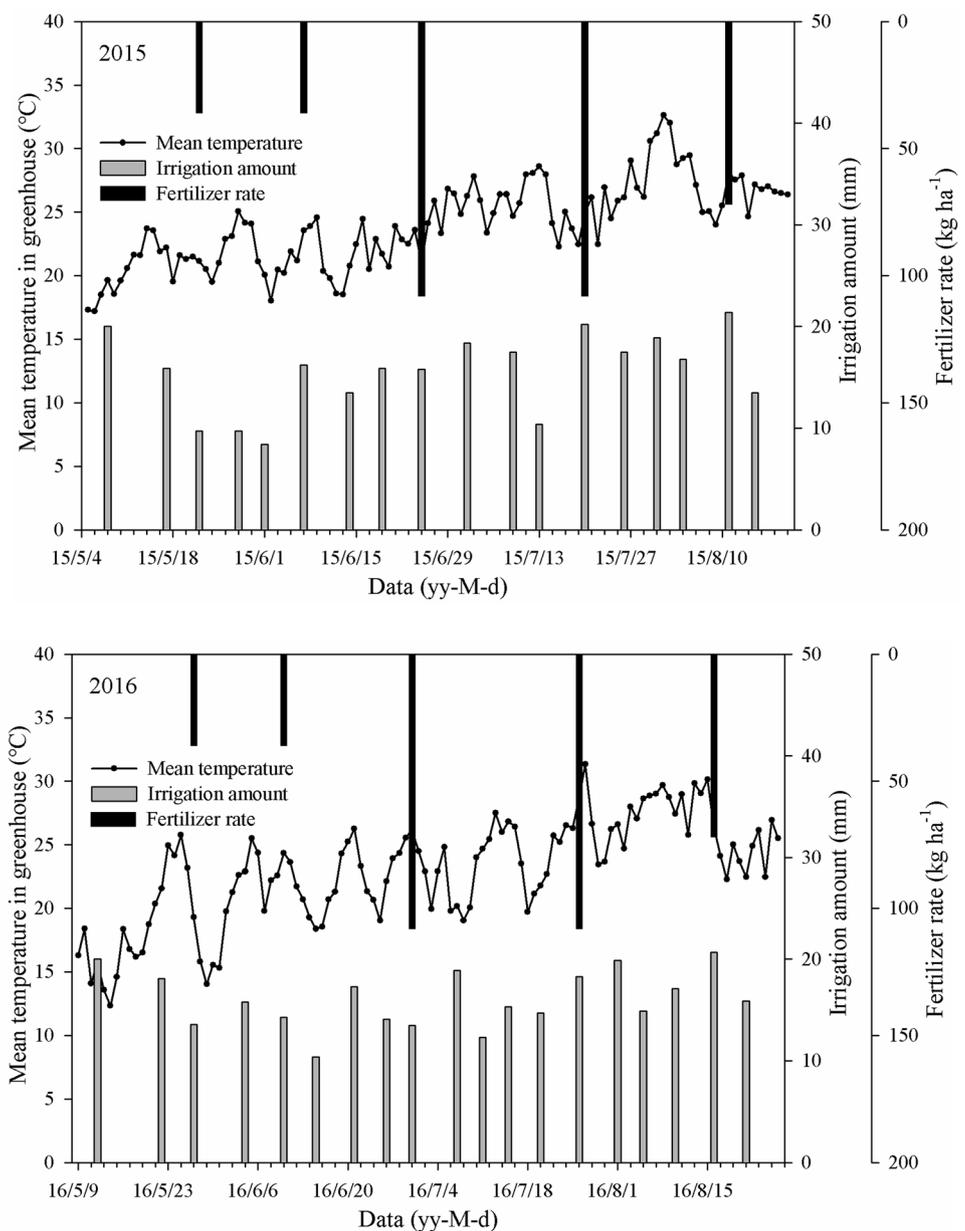
The soil water content was measured eleven times via a weighing method in both years (–5, 14, 21, 32, 40, 49, 60, 68, 79, 91, and 105 DAT in 2015; –3, 10, 19, 30, 41, 50, 62, 71, 80, 92, and 107 DAT in 2016). Soil water contents were measured at every 20 cm from 20 to 140 cm of soil depth, 5 days before transplanting and at the end of the harvest (105 DAT) in 2015, 3 days before transplanting and at the end of the harvest (107 DAT) in 2016. For all the other sampling dates mentioned above, soil water contents were measured at every 20 cm from 20 to 60 cm of soil depth. The soil samples were collected through a soil auger (4 cm inner diameter, TC-300B, Changzhi, China) from each plot. After collection from the field, the soil water content of each sampled soil layer was determined by weighing to a constant weight at 105 °C.

Table 1 Soil characteristics of the experimental site were measured before the start of experiment

Years	Depth (cm)	pH	EC ($\mu\text{s cm}^{-1}$)	BD (g cm^{-3})	OM (g kg^{-1})	TC (g kg^{-1})	TN (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
2015	0–30	7.85	140.5	1.14	15.43	13.3	0.82	18.9	107.2
	30–60	8.26	168.5	1.26	10.12	10.5	0.54	21.8	69.4
2016	0–30	7.9	144.4	1.13	13.88	13.5	0.91	22.4	95.2
	30–60	8.14	126.1	1.25	9.56	11.4	0.75	20.9	83.2

EC electric conductivity, BD bulk density, OM organic matter, TC total carbon, TN total nitrogen, AP available phosphorus, AK available potassium ($n=4$, repeated four times for each value)

Fig. 1 The dynamics of daily mean air temperature in the greenhouse, irrigation amounts (100% ET_0 , total irrigation amount: 279.7 mm in 2015 and 305.1 mm in 2016) and fertilizer rates (240 kg N ha^{-1} , 120 kg P ha^{-1} and 150 kg K ha^{-1}) during the growing season in 2015 and 2016



Root Characteristics Measurements

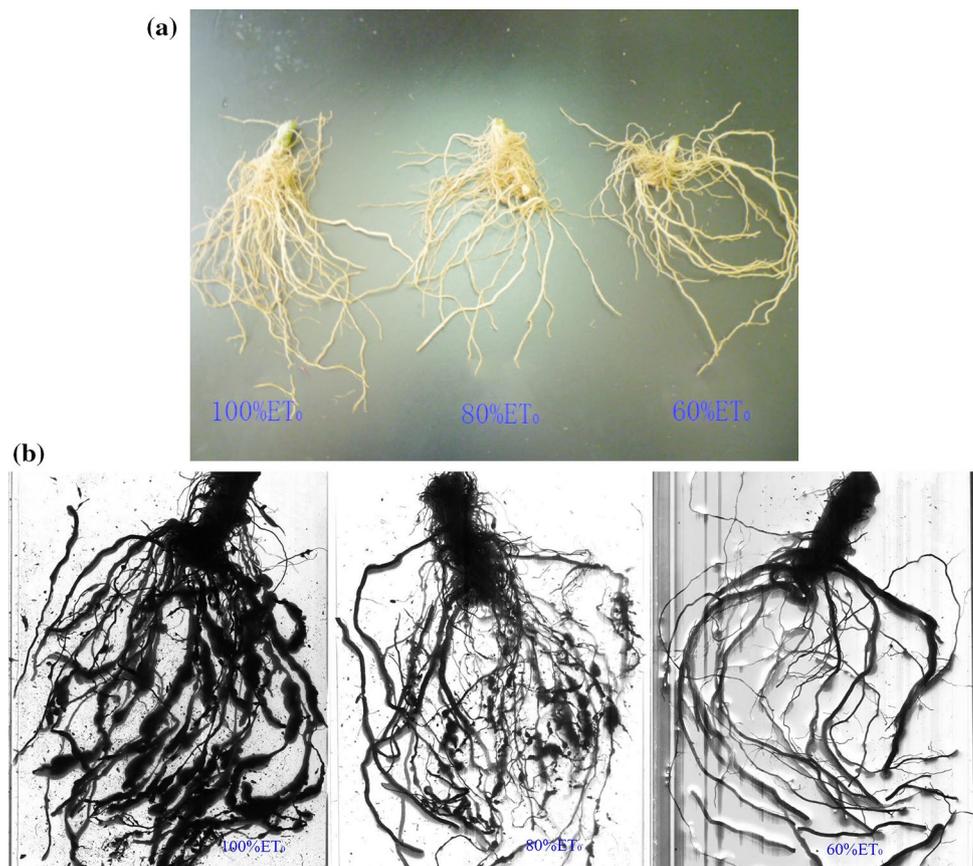
The root samples were gathered at the end of the harvest time. The first step was to dig out the soil columns (length \times width \times height = 60 cm \times 60 cm \times 40 cm) using a spade, and the emphasis was on considering the plant located at the centre of the soil column. Secondly, the integrated soil column was moved to a large water pool and was soaked for loosening, before being flushed to get the complete root system (Fig. 2a). Thirdly, the root samples in each plot ($n=4$) were scanned with a scanner (Epson Perfection v700 Photo, EPSON Company, Japan) (Fig. 2b). Fourth, the photos were analyzed using WinRHIZO (Regent Instruments Company, Canada), from which the total

root length, total root surface area, average diameter, and total root volume were determined.

Dry-matter Production and Fruit Yield, and Crop Nitrogen Uptake

During the different growth stages of the tomatoes, four tomato plants from each plot were randomly selected and harvested as whole plants. The roots, leaves, stems, and fruits were separated and dried for 30 min at 105 °C, before being oven-dried at 75 °C to a constant weight. The dry-matter production (DMP) refers to the sum of the roots, leaves, stems, and fruits. Root weight density was determined by:

Fig. 2 The root samples after **a** flushing and **b** scanning



$$RWD = \frac{RW}{SV} \quad (1)$$

where RWD is the root weight density (g m^{-3}), RW is the root weight (g) and SV is the soil volume (m^{-3}). The soil volume was calculated as: $SV = \text{length} \times \text{width} \times \text{height} = 60 \text{ cm} \times 60 \text{ cm} \times 40 \text{ cm} = 0.144 \text{ m}^3$.

The fruit yield estimation of mature tomatoes in each plot was done manually, and immediately measured via the electronic balance on each picking day. The fruit production was the sum of each of the harvests.

After analyzing the root characteristics and biomass measurement of the leaves, stems and fruits, the oven-dried plant material was milled to a fine powder, separately for each component. The total N content in each organ was analyzed using a Dumas-type elemental analyzer system (model Rapid N, Elementar, Analysensysteme GmbH, Hanau, Germany). The plants' total N uptake was the sum of the N contents' uptake in roots, leaves, stems, and fruits (Soto et al. 2015).

Water and Nitrogen Use Efficiency

Crop evapotranspiration (ET_c) was calculated using the soil water balance equation (Zhang et al. 2017). Because there was no chance of precipitation in the greenhouse and no surface runoff from the plots and because all of the furrows were blocked, the surface run-off was negligible. Additionally, in this region, the groundwater table was located 70 m below the earth surface, so the upward flow into the root zone was also negligible. Following this, the ET_c was calculated as follows:

$$ET_c = I + \Delta W \quad (2)$$

where I is the irrigation amount and ΔW is the change of soil water storage at the beginning and end of the trials. Each year, before transplantation and at harvest, soil water contents in the 140 cm soil profile were converted into soil water storage (mm) using both soil bulk density (measured at the start of the experiment) and the depth of the soil layer. The soil water storage in the soil profile was, therefore, the sum of the seven soil layers.

The WUE (kg m^{-3}) was determined using the following equation (Li et al. 2017b):

$$WUE = \frac{Y}{ET_c} \times 0.1 \quad (3)$$

where Y is the total fruit yield (kg ha^{-1}) and ET_c is the crop evapotranspiration (mm).

The partial factor productivity of the N fertilizer (PF_{PN}) (kg kg^{-1}) was determined using the following equation (Fan et al. 2014):

$$PEP_N = \frac{Y}{F_N} \quad (4)$$

where Y is the total fruit yield (kg ha^{-1}) and F_N is the N fertilizer applied (kg ha^{-1}).

Statistical Analysis

The analysis of variance (ANOVA) test was employed with the N fertilizer, irrigation, and cropping years as the three fixed factors, and was used to assess variations in the root characteristics, dry-matter production, fruit production, crop N uptake, WUE, and PF_{PN} . Differences between all treatments were detected using least significant difference (LSD) testing at the 0.05 significance level. Statistical analyses and data plotting were performed using SPSS Statistics Software 16.0 and Sigma Plot 10.0, respectively.

Results

Meteorological Observation and Soil Water Contents

Throughout the whole growth period, the daily mean air temperature in the greenhouse was 4.6% higher in 2016 (24 °C) than in 2015 (22.9 °C) (Fig. 1). The solar radiation was slightly higher in May, June and August for 2016 than for 2015, but it was lower in July (Supplementary Table S1). The total irrigation supply was consistent with the daily mean air temperature, which was 9.1% higher in 2016 (total irrigation water in the whole growth period, 305.1 mm) than in 2015 (total irrigation water in the whole growth period, 279.7 mm). Relative to W2 and W3, the increased soil water content in the 0–20 cm soil depth under W1 mainly happened during the first 70 DAT in 2015, with an opposite tendency in 2016 (Fig. 3a, b). At the early stage, relative to W1, the increased soil water content in the soil depths of 20–40 cm under W2 were observed in both years (Fig. 3c, d). The mean air temperature in July and August, which was higher for 2016 than for 2015 (Fig. 1), lowered the soil water contents in the 40–60 cm soil layers in 2016 (Fig. 3e, f). Averaged over N-fertilizer rates, the soil water content in W1 was 5.7% and 12.1% higher than W2 and W3 in 0–20 cm soil depths over the whole growth period of 2015. Similar results were observed for depths of 20–40 and 40–60 cm. In general, for both years, with the advancement of the

reproductive period the effect of the N-fertilizer on the soil water content was minor and insignificant (Fig. 3).

Root Characteristics

The irrigation and N-fertilizer effects on root characteristics (total root length, total root surface area, average diameter, total root volume, and root weight density) during the 2 years of the experiments are summarized in Fig. 4. The individual treatments of irrigation or N-fertilizer significantly ($p < 0.01$) affected the root characteristics, but the year significantly affected total root length, average diameter, and root weight density (Fig. 4; Table 2). The interactions between the irrigation and N-fertilizer rates were recorded as being highly significant ($p < 0.01$) for the root characteristics, but there was no significant interaction between the irrigation and N-fertilizer for the total root volume (Fig. 4; Table 2). There was a triple interaction among the year, N-fertilizer and irrigation for total root length and total root surface area ($p < 0.05$) (Fig. 4a–d; Table 2). Intriguingly, root characteristics were more sensitive to irrigation amounts than to N-fertilizer rates (Supplementary Tables S2–6).

Averaging across years and N-fertilizer application rates, the total root surface area, average diameter, and total root volume increased with increased levels of the irrigation. Averaging across irrigation levels, total root surface area and total root volume were increased with increased N-fertilizer application rates. Conversely, the treatment W2N180 did not induce any loss in the total root length and average diameter (Fig. 4a, b, f), compared to W1N240. Averaging across irrigation treatments, the mean root weight density in N240 was 13.4% (6.1 g m^{-3}) and 10.7% (5 g m^{-3}) lower than N180 in 2015 and 2016, respectively (Fig. 4i, j). Under irrigation and N-fertilizer rates, the average total root surface area was similar between 2015 (289 cm^2) and 2016 (284.3 cm^2) (Fig. 4c, d). A similar result was obtained for total root volume (Fig. 4g, h). The values of total root length, root average diameter, and root weight density were significantly greater in 2016 than in 2015 (Fig. 4a, b, e, f, i, j; Table 2).

Dry-matter Production, Fruit Yield and Crop N Uptake

There was a significant triple interaction among irrigation, N-fertilizer and year for root dry-matter production, fruit yield, and crop N uptake (Table 2); and there was a double interaction among irrigation and N fertilizer for fruit yield, all the organs' dry-matter production and N uptake (Table 2); in particular, the individual factors of irrigation or N fertilization affected fruit yield, all the organs' dry-matter production and N uptake in a highly significant way ($p < 0.001$) (Table 2). Dry-matter production, fruit yield, and N uptake were more sensitive to irrigation than

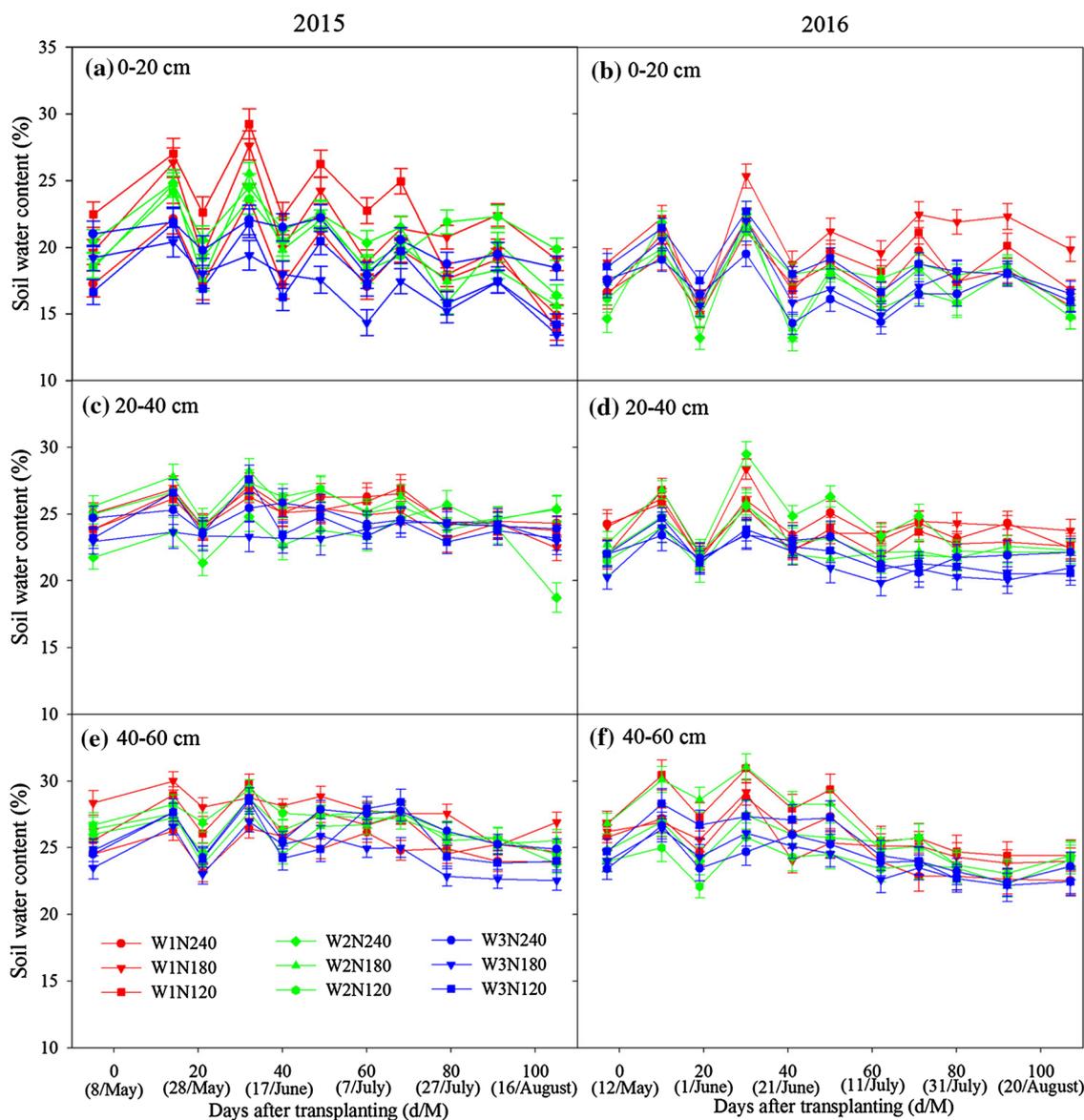


Fig. 3 Soil water contents in the soil depths of **a, b** 0–20 cm; **c, d** 20–40 cm and **e, f** 40–60 cm throughout the greenhouse tomato growing seasons of **(a, c, e)** 2015 and **(b, d, f)** 2016 for three irrigation levels (W1: 100% ET_0 , W2: 80% ET_0 and W3: 60% ET_0) and for three

nitrogen fertilizer application rates (N240: 240 kg N ha^{-1} , N180: 180 kg N ha^{-1} and N120: 120 kg N ha^{-1}) in 2015 and 2016. Bars are the means + one standard error of the mean ($n=4$)

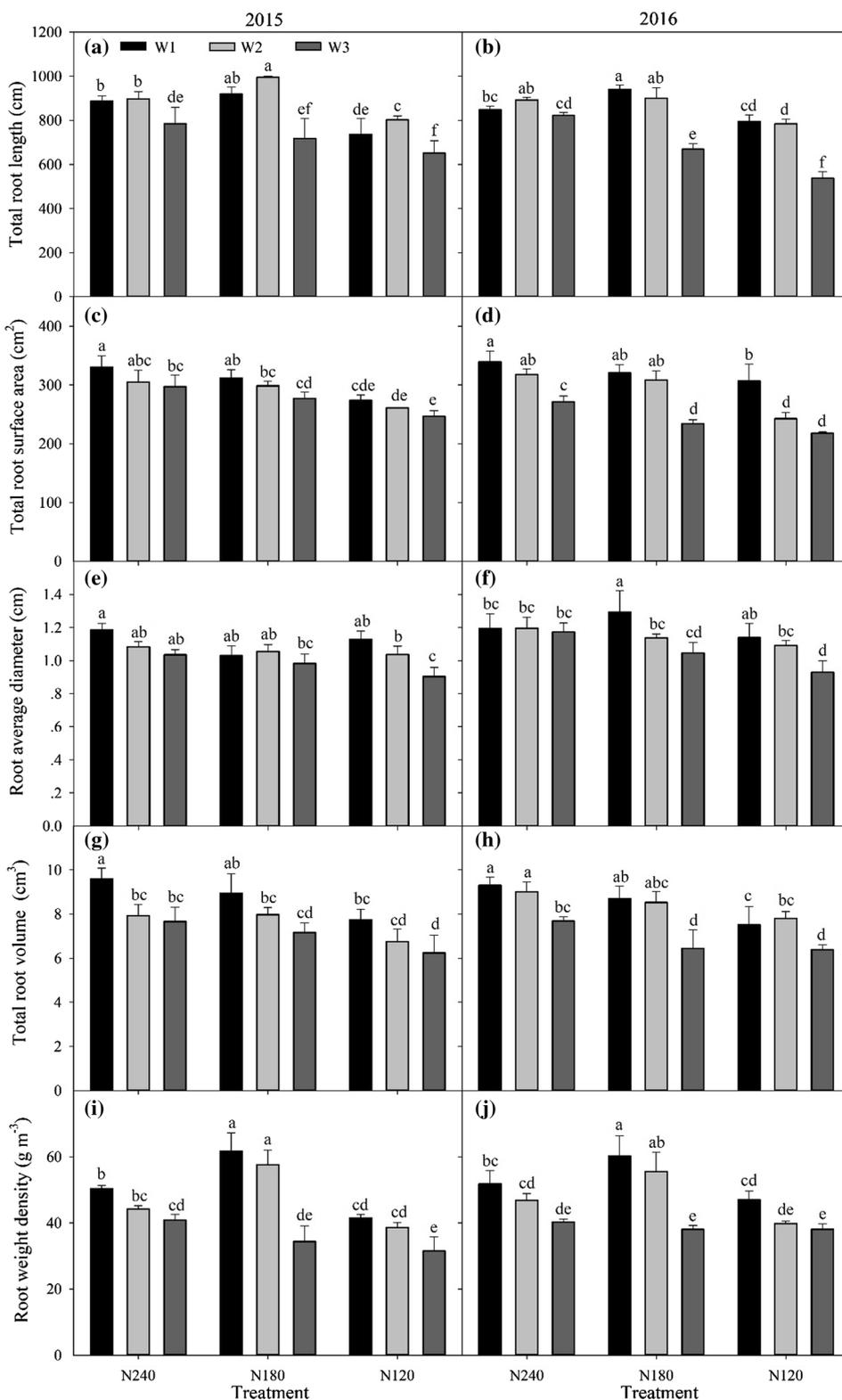
to N-fertilizer treatments (Supplementary Tables S7–11, 13–16).

Averaging across N-fertilizer rates, the deficit irrigation of W2 and W3 decreased total dry-matter production by 11.8% and 21.7%, compared to W1 in 2015; averaging across irrigation levels, N180 and N120 were 1.4% and 13.2% lower than N240 in 2015, respectively (Fig. 5a). The 2016 experiment was also recorded with similar results (Fig. 5b). In the N180 treatment, root dry-matter production in W2 was 30% (65.4 kg ha^{-1}) and

9.1% (20.3 kg ha^{-1}) higher than in W1, in 2015 and 2016 respectively (Fig. 5a, b). The total dry-matter production in N240 and N180 was closer to each other under W1 and W2 treatments in both years (Fig. 5).

On average over the three N-fertilizer rates, fruit yield in W1 (73.1 t ha^{-1} in 2015 and 74.2 t ha^{-1} in 2016) was 17.8% (13 t ha^{-1}) and 21.4% (15.9 t ha^{-1}) higher than in W3, in 2015 and 2016 respectively (Fig. 6a, b). Overall, fruit yield was greater in the W1N240 treatment than in the other treatments; fruit yield increased with an increasing

Fig. 4 The tomato root system of **a, b** the total root length; **c, d** the total root surface area; **e, f** the average diameter; **g, h** the total root volume and **i, j** the root weight density with the three irrigation levels (W1: 100% ET₀, W2: 80% ET₀ and W3: 60% ET₀) and three nitrogen fertilizer application rates (N240: 240 kg N ha⁻¹, N180: 180 kg N ha⁻¹ and N120: 120 kg N ha⁻¹) in 2015 and 2016. Bars are the means + one standard error of the mean (*n*=4)



amount of irrigation (averaging across the N fertilizer application rate) or an increasing N-fertilizer application rate (averaging across the irrigation treatments) (Fig. 6). In contrast, in the W2 treatment, fruit yield was higher in the

N180 treatment than in the N240 treatment; in the N180 treatment it was 3.6% and 4.4% higher than for N240, in 2015 and 2016 respectively (Fig. 6a, b). Compared to N120, the increase of the fruit yield in 2015 and 2016

Table 2 Three groups of treatment effects (*p* values) on the greenhouse tomato root characteristics (total root length, total root surface area, average diameter, total root volume and root weight density), fruit yield, dry-matter production (root, stem, leaf and fruit), water use efficiency (WUE), N uptake (root, stem, leaf and fruit) and partial factor productivity of the N fertilizer (PFP_N), using cropping year (Y), nitrogen fertilizer (N) and irrigation (W) as three fixed factors

Source	Root characteristics				Fruit yield				Dry-matter production				WUE				N uptake				PFP _N										
	Length		Surface area		Diameter		Volume		Weight density		Fruit yield		Root		Stem		Leaf		Fruit		WUE		Root		Stem		Leaf		Fruit		
Y	0.028	ns	<0.001	<0.001	<0.001	ns	0.021	ns	<0.001	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	ns	
N	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
W	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Y × N	ns	ns	0.015	ns	ns	ns	ns	ns	ns	ns	0.015	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	
Y × W	0.044	<0.001	ns	0.001	ns	ns	ns	0.049	ns	0.032	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.028	0.02	0.003	0.003	<0.001	<0.001	<0.001	<0.001	0.009	
N × W	<0.001	<0.001	<0.001	ns	ns	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Y × N × W	0.001	0.039	ns	ns	ns	ns	ns	<0.001	ns	0.022	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.002	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

ns not significant (*p* > 0.05)

reached 4.9–23.9% and 9.1–17.5% at the same irrigation levels, respectively (Fig. 6).

Under the N-fertilizer treatments, the deficit irrigation decreased root N uptake by 9.5–32.9% in 2015 (Fig. 7a) and by 17.2–33.8% in 2016 (Fig. 7b). Under the W3 treatment, root N uptake was similar between 2015 (3.67 kg ha⁻¹) and 2016 (3.68 kg ha⁻¹); but leaf N uptake was significantly greater in 2016 than in 2015 (Fig. 7; Table 2). Across the cropping years, the W1N240 treatment had the largest plant N uptake among the irrigation and N-fertilizer treatments (Fig. 7). Plant N uptake increased from 28.7 to 94% (23.9–78.5 kg ha⁻¹) in 2015 and from 14 to 92.3% (12.4–81.9 kg ha⁻¹) in 2016, with the increase of the irrigation and N-fertilizer rates. Fruit N uptake was significantly increased by the increase of the irrigation amount from W3 (60% ET₀) to W1(100% ET₀) (Fig. 7).

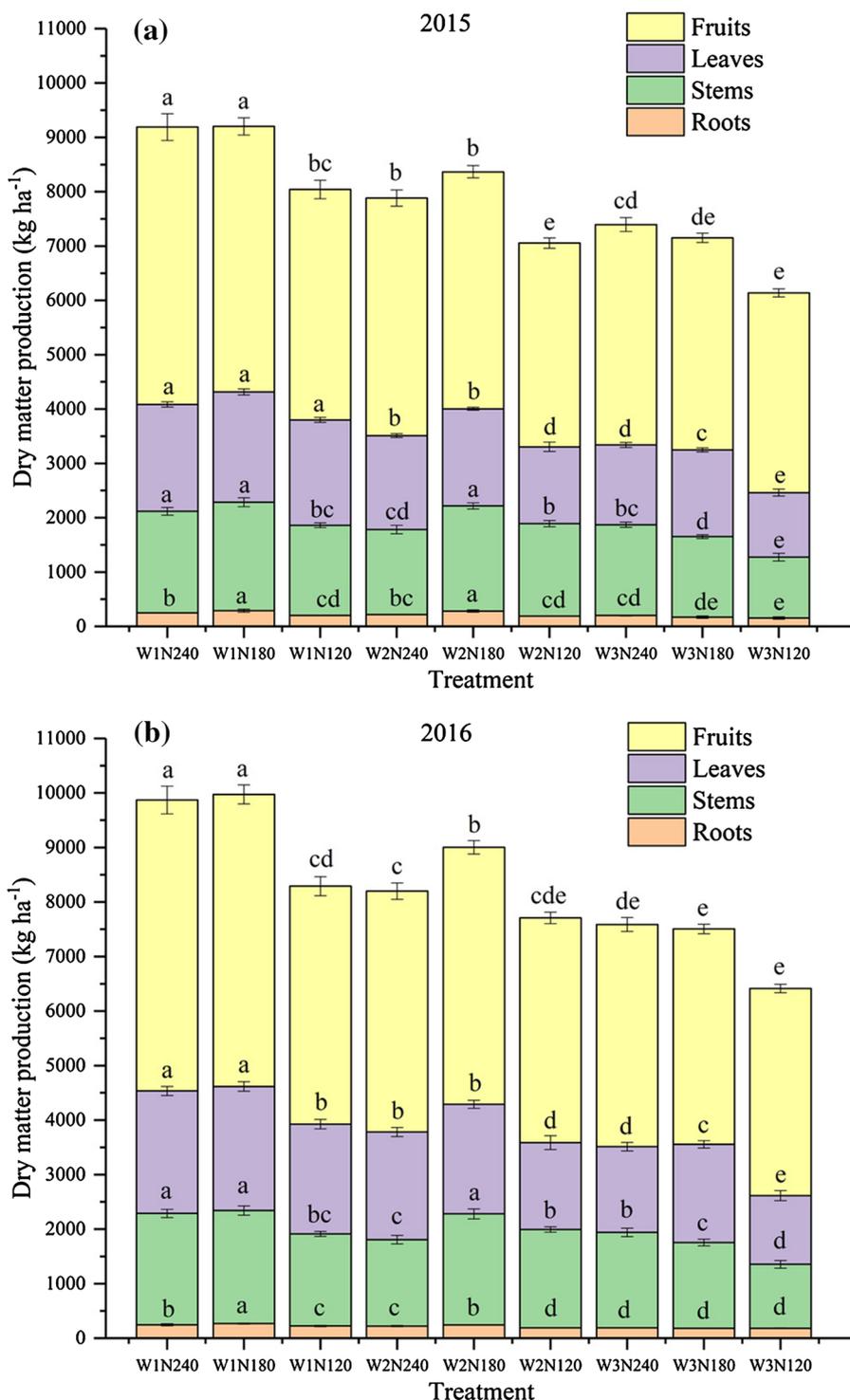
Water Use Efficiency and Partial Factor Productivity of the Nitrogen Fertilizer

There was a significant triple interaction among irrigation, N-fertilizer and year for water use efficiency (WUE) and partial factor productivity of the N-fertilizer (PFP_N); and there was a double interaction among irrigation and N-fertilizer for the WUE and PFP_N; the individual factors of the irrigation or N-fertilization affected WUE and PFP_N very significantly (*p* < 0.001) (Table 2). However, there were no significant differences in the PFP_N between the 2 years (*p* > 0.05) (Table 2). It was expected that the WUE would be more sensitive to water than to the N-fertilizer (Supplementary Table S12), and the PFP_N was also more sensitive to the N-fertilizer than to water (Supplementary Table S17).

Averaging across the N-fertilizer and years, the deficit irrigation increased the WUE by 33.9% (W1: 25.2 kg m⁻³ vs. W2: 33.8 kg m⁻³) and by 17.6% (W1: 25.2 kg m⁻³ vs. W2: 29.7 kg m⁻³) (Fig. 8a, b). At the same irrigation level, the WUE increased with increasing N-fertilizer rate in both years, except for the W2 treatment (Fig. 8a, b). Under the W2 treatment, the WUE for N180 was 3.6% (1.1 kg m⁻³) and 4.4% (1.4 kg m⁻³) higher than N240 in 2015 and 2016, respectively (Fig. 8a, b). In 2015, the N-fertilizer increased the WUE by 21.4–23.9% for W1 and by 5.7–18.4% for W3 (Fig. 8a). In 2016, the N-fertilizer increased the WUE by 6.5–6.8% for W1 and 7.9–15.3% for W3 (Fig. 8b).

At the same N-fertilizer rate, the PFP_N had a positive correlation with the irrigation amount; moreover, at the same irrigation levels, the PFP_N had a positive correlation with the N-fertilizer rate in 2015 and 2016 (Supplementary Figs. S1, S2). The PFP_N was significantly decreased when increasing the amount of applied N-fertilizer; averaging across the irrigation amounts and cropping years, the N-fertilizer

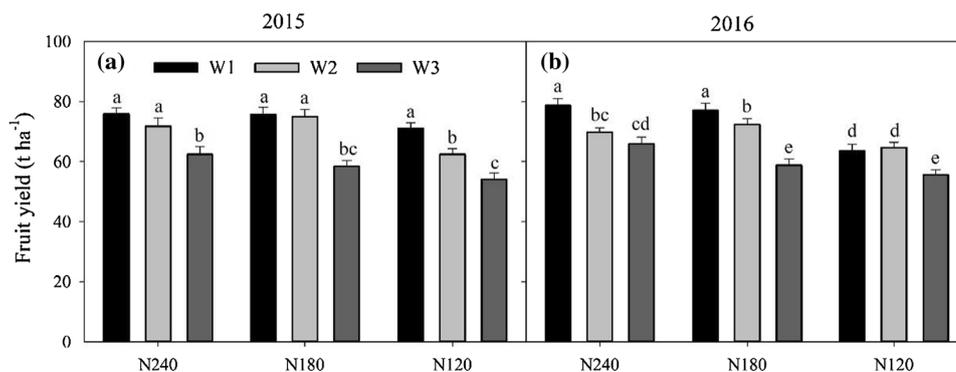
Fig. 5 Tomato dry-matter production in the three irrigation levels (W1: 100% ET_0 , W2: 80% ET_0 and W3: 60% ET_0) and the three nitrogen fertilizer application rates (N240: 240 kg N ha^{-1} , N180: 180 kg N ha^{-1} and N120: 120 kg N ha^{-1}) in 2015 and 2016. Bars are the means + one standard error of the mean ($n=4$)



dramatically reduced the PFP_N by 25.1% (129.3 kg kg^{-1}) for N180 and 42.9% (221.2 kg kg^{-1}) for N240, compared to N120 (516 kg kg^{-1}) (Fig. 8c, d). Averaging across the N-fertilizer treatments and cropping years, the irrigation amounts increased the PFP_N by 24.5% (85.6 kg kg^{-1}) for

W1 and 17.5% (61.2 kg kg^{-1}) for W2, compared to W3 (350 kg kg^{-1}) (Fig. 8c, d).

Fig. 6 The tomato fruit yield was affected by the three irrigation levels (W1: 100% ET_0 , W2: 80% ET_0 and W3: 60% ET_0) and the three nitrogen fertilizer application rates (N240: 240 kg N ha^{-1} , N180: 180 kg N ha^{-1} and N120: 120 kg N ha^{-1}) in 2015 and 2016. Bars are the means + one standard error of the mean ($n=4$)



Discussion

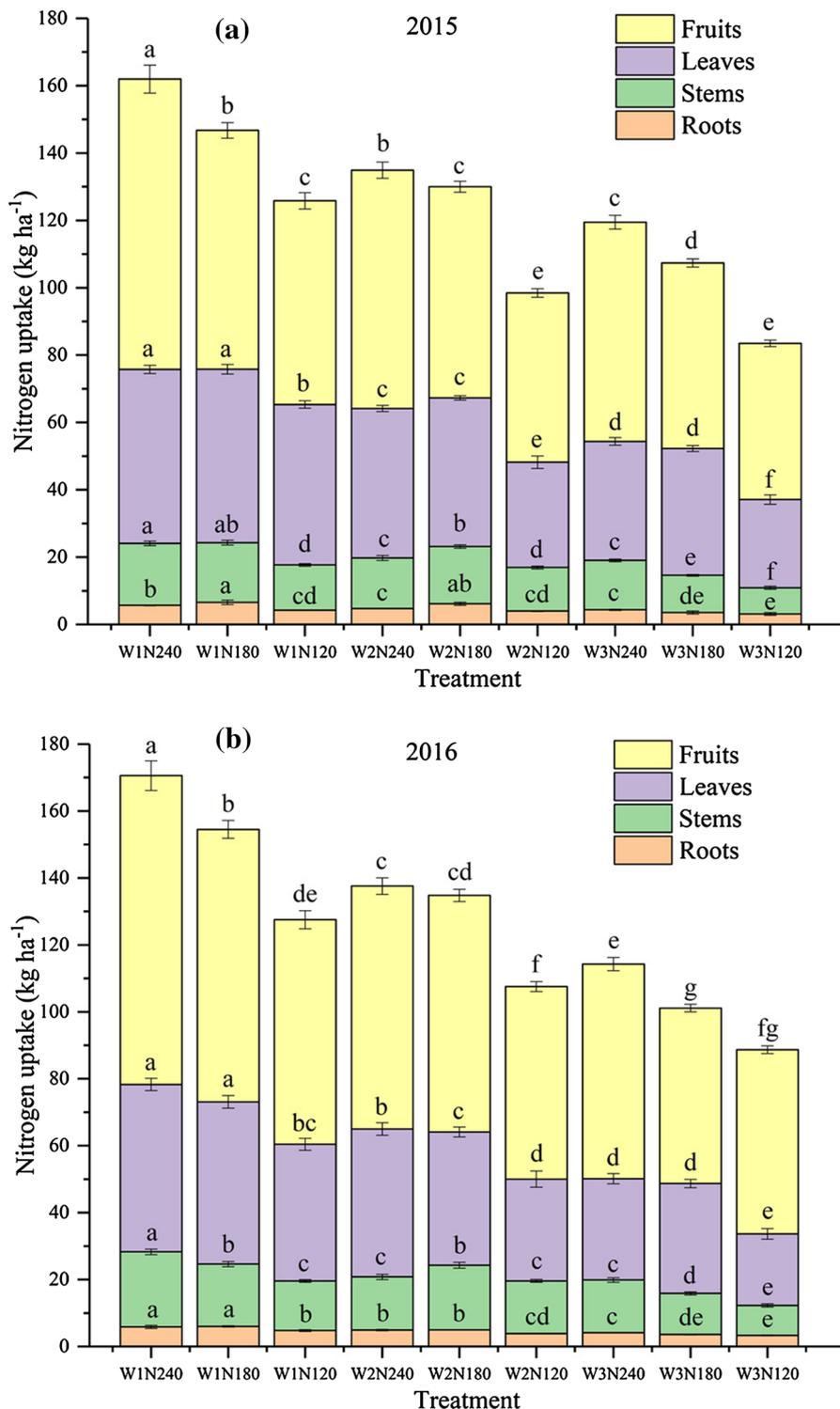
In this study, the soil water contents were not associated with a significant increase of irrigation levels during the whole growth stage; overall, however, higher levels of irrigation were associated with greater soil water contents (Fig. 3). The soil water contents varied more widely, and frequently at different irrigation levels, which could be consistent with soil characteristics' capacity for water infiltration to the deeper soil layers, with environmental conditions and with crop water consumption (Giuliani et al. 2017; Patanè and Cosentino 2010; Patanè et al. 2011; Zotarelli et al. 2009). These results provided evidence that higher soil moisture could enhance root growth and root hydraulic conductivity, which may contribute to an enhanced root biomass (Fig. 5a, b). The soil water content increased with an increased soil depth, and the soil water content in W2 was closely related to W1 treatments at 20–40 and 40–60 cm (Fig. 3). This result is consistent with a previous study that showed that the soil water contents in the top soil layer (0–20 cm) were more affected by tomato root growth, but that the soil moisture in deep soil layers was not significantly affected by root growth (Li et al. 2017b). This might be the main factor that explains why, under the N180 treatment, total root length, and average diameter in W2 did not significantly decrease in comparison with W1. The other reason might be that water channel aquaporins play an important role in soil water uptake during different levels of water deficit (Martre et al. 2002; Savić et al. 2008). However, the mechanisms through which the water deficit level of W2 (80% ET_0) might possibly regulate root growth were not fully revealed by the present study. In general, water deficit decreases soil nutrient uptake through the root and transport to the shoot due to a limited transpiration rate, but an appropriate water deficit may also promote the ability of plants to assimilate nitrogen through the contribution of enzymes implicated in nitrogen metabolism (Lahoz et al. 2016; Sánchez-Rodríguez and Ruiz 2013).

The mean root weight density in N240 was 10.7–13.4% lower than in N180, but the root weight density was positively associated with irrigation levels. The relationship

between the root weight density and irrigation level, and between the root weight density and N-fertilizer application rate might have occurred for two reasons. First, the differences in the soil bulk density offers one explanation for tomato root proliferation at different levels of irrigation (Purushothaman et al. 2017; Zotarelli et al. 2009). Second, the fact that the growth in N240 is greater than that in N180 could be inferred by the dry-matter accumulation (Fig. 5), and this was linked to plant roots having a larger spatial range to imbibe water and nutrients under higher irrigation levels (Alrajhi et al. 2017; Li et al. 2017b). The higher root surface area and total root volume occurred at higher irrigation levels and N-fertilizer rates. This might be related to higher soil water and greater nitrate-N availability under higher irrigation and N-fertilizer application (Bloom et al. 1993, 2002). Moreover, a good soil water and nutrient environment in the root zone can promote a root to shoot signal and produce abscisic acid in the xylem for the regulation of the stomata switch and vegetative growth (Aiken and Smucker 1996; Balliu et al. 2015; Chai et al. 2015; Davies et al. 2005; Sarker et al. 2016). For these reasons, our results were more reasonable, showing that plant N uptake increased from 14 to 94% and that dry-matter accumulation increased from 16.5 to 55.5% with increased irrigation levels and N-fertilizer rates. Furthermore, this result might be related to the residual effects of nitrate-N in the soil (Badr et al. 2016; Chu et al. 2016).

The fruit yield was higher in 2016 than in 2015, which could be associated with the higher total irrigation level and lower soil water contents in 2016 when compared to 2015 (Figs. 3, 6). Many studies had proven that tomato yield increases when an increasing amount of water and N fertilizer is applied (Cai et al. 2016; Wang and Xing 2017; Weiner 2017). The fruit yield was higher during full irrigation than during the deficit irrigation treatment; nearly or more than twice as high than the yield from much more stressful conditions (Patanè and Cosentino 2010). The main reason for the lower tomato fruit yield under the water deficit was the reduced total dry-matter production and water consumption (Badr et al. 2016; Costa et al. 2007; Patanè et al.

Fig. 7 Nitrogen uptake by the greenhouse tomatoes with the three irrigation levels (W1: 100% ET₀, W2: 80% ET₀ and W3: 60% ET₀) and the three nitrogen fertilizer application rates (N240: 240 kg N ha⁻¹, N180: 180 kg N ha⁻¹ and N120: 120 kg N ha⁻¹) in 2015 and 2016. Bars are the means + one standard error of the mean (n=4)



2011). Furthermore, fruit yield and dry-matter production were significantly reduced by a lower level of irrigation and N fertilizer in tomatoes (Li et al. 2017a; Singandhupe et al. 2003; Topcu et al. 2007). There was a significant interaction between irrigation and N-fertilizer on fruit yield and

dry-matter production; fruit yield and dry-matter production were positively correlated with the irrigation level and N-fertilizer rate. The higher fruit yield must be attributed to a higher N uptake; consequently, a significant increase in the N uptake was closely related to root characteristics;

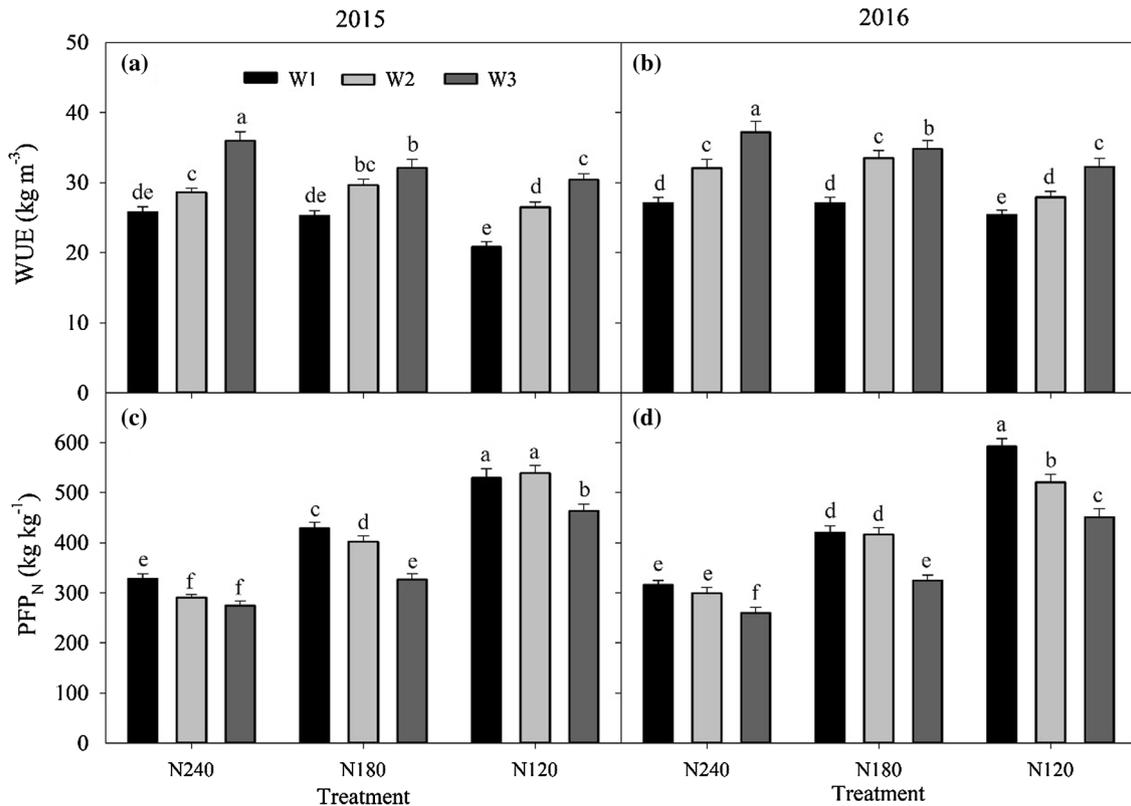


Fig. 8 WUE and PPF_N with the three irrigation levels (W1: 100% ET_0 , W2: 80% ET_0 and W3: 60% ET_0) and the three nitrogen fertilizer application rates (N240: 240 kg N ha^{-1} , N180: 180 kg N ha^{-1} and

N120: 120 kg N ha^{-1}) in 2015 and 2016. Bars are the means + one standard error of the mean ($n=4$)

root characteristics might be closely related to irrigation and N-fertilizer (Supplementary Table S18). In this study, root characteristics were very significantly correlated with fruit yield and dry-matter production; in particular, the highest correlation was observed between total root volume and fruit yield ($r=0.971$). It is, therefore, important to further underpin the mechanisms of the water deficit and N-fertilizer rates on root growth, as well as the relationship between root characteristics and fruit yield of tomatoes.

WUE and PPF_N were significantly influenced by water and N-fertilizer inputs (Fan et al. 2014; Zhang et al. 2011), the most important indicator used to assess a production system (Chen et al. 2018; Giuliani et al. 2017). In this study, WUE decreased with an increased total irrigation level, and PPF_N decreased when the N-fertilizer application rate was increased. Tomato plants only took up a small amount of inorganic N from the large volume of soil explored by the root system, and the root distribution showed significant positive relation to the amount of N taken up (Jackson and Bloom 1990). Particularly in the N-rich top and deep soil layers, root development was limited, which could explain the low N-fertilizer use by tomatoes (Chen and Liao 2017; Sorensen and Thorup-Kristensen 2006). Excessive irrigation

and N fertilization reduced WUE and PPF_N over two consecutive years (Fig. 8), while also bringing about a higher potential risk of environmental pollution (Ju et al. 2009; Li et al. 2017a; Zhang et al. 2018). The root is the main plant organ for the uptake of water and nutrients and its distribution determines the plant's ability to uptake water and nutrients. The capacity for N uptake is significantly linked to total root length (Guo et al. 2008). This resulted in a greater N uptake by plants in N240 than in N180 and N120 (Fig. 7). However, the amount of residual nitrate-N in the soil was significantly increased with an excessive application of the N fertilizer (Fan et al. 2014). Hence, the fact that PPF_N in N240 was lower than in N180 and N120 reasonably supports our findings.

Conclusions

Our results demonstrated a positive correlation between soil water contents and irrigation levels. The individual factors of the irrigation or N-fertilizer, along with their interaction significantly affected total root length, total root surface area, average diameter, and root weight density. Interestingly, root

characteristics, dry-matter production, fruit yield, N uptake, and WUE were more sensitive to water than to N-fertilizer, but, in contrast, PFP_N was more sensitive to N-fertilizer than to water. Considering the trade-off amongst fruit yield, WUE and PFP_N, W2N180 was the best water and N-fertilizer management strategy for greenhouse-grown tomato in Northwest China. In addition, the overall results confirmed that fruit yield, dry-matter production, and N uptake were closely linked to root characteristics, but the WUE and PFP_N were not correlated with these.

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Author Contributions W-XK, L-ZB, and LP conceived and designed experiments; W-XK and LP analyzed the data and drafted the work; YJ, SP and X-YY carried out experiments, W-XK and LP wrote the manuscript. All authors contributed to the manuscript.

Compliance with Ethical Standards

Conflict of interest The authors declare no competing interests.

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