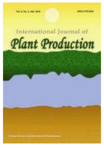

International Journal of Plant Production 11 (2), April 2017
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

GUASNR

Responses of root growth and distribution of maize to nitrogen application patterns under partial root-zone irrigation

D. Qi[a,b], T. Hu[a,b,*], X. Niu[a,b,c]

[a]*College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, P.R. China.*
[b]*Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education, Northwest A&F University, Yangling 712100, P.R. China.*
[c]*Key Laboratory for Crop Water Requirement and Its Regulation, Ministry of Agriculture, Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China.*
*Corresponding author. E-mail: hutiant@nwsuaf.edu.cn

Received 16 July 2016; Accepted after revision 30 November 2016; Published online 20 March 2017

Abstract

A field experiment was carried out to investigate the effects of varying nitrogen (N) supply and irrigation methods on the root growth and distribution of maize (*Zea mays* L.) in Wuwei, northwest China in 2011 and 2012. The irrigation treatments included alternate furrow irrigation (AI), fixed furrow irrigation (FI) and conventional furrow irrigation (CI). The N supply treatments included alternate N supply (AN), fixed N supply (FN) and conventional N supply (CN), were applied at each irrigation method. The root growth across the plant row was measured in 0-100 cm soil profile (20 cm as an interval) at maturity. The results showed that root distribution of two sides of the row was uniform for AI or CI coupled with CN or AN. Root length density (RLD) in 0-40 cm soil depth was significantly increased by AI compared to other irrigation methods while decreased by FN compared to other N supply treatments. Though RLD decreased more with soil layer deepening under AI, RLD in 60-100 cm soil depth in AI treatment was still larger than that in CI and FI treatments. In general, total fine root (diameter<2 mm) length, root dry weight, root surface area, and grain yield of maize were significantly increased by AI coupled with CN or AN when compared to other treatments. These results indicate that alternate partial root zone irrigation coupled with conventional or alternate nitrogen supply is useful to improve the root growth and grain yield of maize in the arid area.

Keywords: Root volume; Root distribution; Nitrogen supply method; Irrigation method; *Zea mays*.

Abbreviations: AI, alternate furrow irrigation; FI, fixed furrow irrigation; CI, conventional furrow irrigation; AN, alternate nitrogen supply; FN, fixed nitrogen supply; CN, conventional nitrogen supply; NP, north of the plant; SP. south of the plant; UP, under the plant; RLD, root length density.

Introduction

Declining freshwater resources have stimulated research into developing novel irrigation strategies in order to increase crop water use efficiency (Morison et al., 2008). Partial root-zone irrigation (PRI) is a new strategy of deficit irrigation. PRI can be applied in two ways: alternate PRI and fixed PRI. Alternate PRI is considered as a water-saving irrigation technique and has been intensively studied in field crops (Kang et al., 1998, 2000, 2002a, b; Tang et al., 2005, 2010; Shahnazari et al., 2007; Du et al., 2006, 2008).

Root morphology is important not only for uptake of immobile nutrients in soil, such as phosphorus (Marschner, 1998), but also for uptake of mobile nutrients such as nitrate N (Linkohr et al., 2002; Wang et al., 2006). Moreover, soil water uptake is a function of root distribution and root activity (e.g. larger root biomass is favorable for greater uptake of water and nutrients under drought conditions, thus resulting in greater growth and yield) (Ehdaie et al., 2010). Fine root (diameter <2 mm) and root surface area also have a vital role in water and nutrient uptake and plant growth (Zobel et al., 2007; Hodge et al., 2009). A positive correlation between yield and root length in maize hybrid B73_Mo17 was reported by Mackay and Barber (1986). Furthermore, spatial distribution of roots and root length density are critical determinants of crop ability to acquire nutrients and water necessary to sustain plant growth (Craine et al., 2003).

It has been demonstrated that the distribution of roots in soil is determined by crop growth duration, soil water content and nutrient availability in the soil (Lincoln et al., 2009). Roots always tend to proliferate in regions of high nutrient (Jackson and Caldwell, 1989; Benjamin and Nielsen, 2006) and water availability (Asseng et al., 1998; Songsri et al., 2008). Moreover, root growth was stimulated by alternate PRI (Kang et al., 1998; Mingo et al., 2004), which may increase the root surface area facilitating overall water and nutrient uptake. Alternate PRI could greatly induce the initiation and growth of secondary roots (Liang et al., 1996). Roots of alternate PRI plants have a greater capacity for deeper (Dry et al., 2000) and more widespread soil exploration (Kang et al., 1998, 2000; Hu et al., 2008).

Soil nitrogen (N) and water availability is closely linked and mutually influence one another (Hodge and Neculai, 1994). Under PRI, the situation is always that only partial root-zone of crops is wet due to irrigation but other parts remain dry. However, in most investigations on PRI, the most commonly used method of N supply is uniform application either as basal application or topdressing, in which coordination of N and water supply was seldom taken into consideration. Thus, an appropriate N supply method should be helpful to improve the use efficiency of both N and water under PRI.

The specific objective of this investigation was to understand the root growth and distribution of maize under different N supply methods coupled with application of alternate PRI, fixed PRI and conventional furrow irrigation (CI). We hypothesized that root characteristics and their spatial distribution will vary with irrigation and fertilizer N application methods and subsequently affect the grain yield.

Materials and Methods

Experimental site

A field study was conducted during the 2011 and 2012 growing seasons at Wuwei Experimental Station for Efficient Use of Crop Water, Ministry of Agriculture, northwest China (latitude 37° 52′ 20″ N, longitude 102° 50′ 50″ E, altitude 1581 m). The site is in a typical continental temperate climate zone with mean annual precipitation of 164.4 mm (about 85% of it is fallen during May to September), mean annual evapotranspiration of 2000 mm. Mean annual sunshine duration is over 3000 h and mean annual temperature is 8.8 ºC. The groundwater level is consistently 40 m below the soil surface. The soil is a light sandy loam. The physical properties of 0-100 cm soil are shown in Table 1. Total precipitation in the growing season was 173 mm in 2011 and 129 mm in 2012 (Figure 1). In the top layer of the soil (0-40 cm), organic matter is 15.90 g kg^{-1}, total N is 0.85 g kg^{-1}, available N(NO_3-N+NH_4-N) is 60.43 mg kg^{-1}, total phosphorus is 0.93 g kg^{-1}, available phosphorus is 6.22 mg kg^{-1} and available potassium is 236.24 mg kg^{-1}.

Table 1. Physical properties of soil used in the experiment.

Physical properties of soil	Soil depth (cm)					
	0-20	20-40	40-60	60-80	80-100	0-100
Bulk density (g cm^{-3})	1.31	1.42	1.55	1.58	1.60	1.49
Specific density (g cm^{-3})	2.63	2.61	2.64	2.57	2.60	2.60
Porosity (%)	49.82	45.95	41.20	38.76	38.63	42.86
Field moisture capacity (%)	22.10	21.20	21.20	22.03	22.20	21.75

Liu et al. (2009).

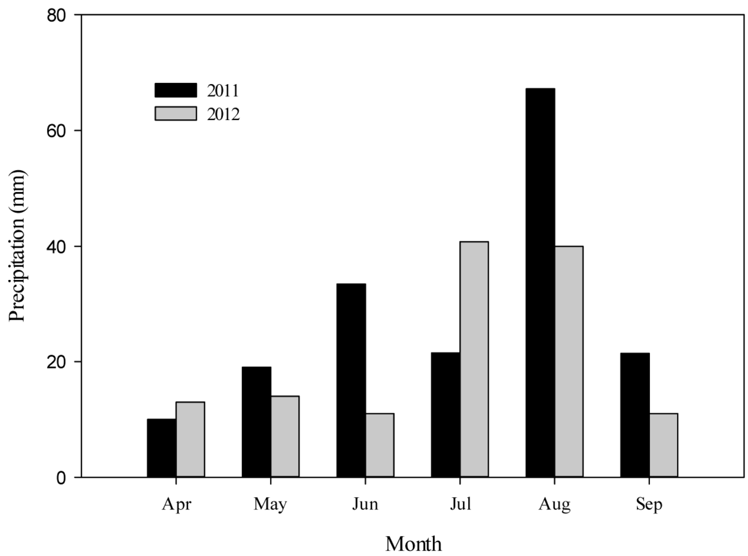

Figure 1. Monthly precipitation during the growth period at the experimental site in 2011 and 2012.

Crop management

Furrow irrigation was adopted in the field experiment. Furrows were established to obtain a trapezoid fracture surface for furrows and ridges. Furrows were 30 cm in depth and 20 cm in width at the bottom. Ridges were 20 cm and 35 cm in width at top and bottom, respectively. This resulted in a ridge spacing of 55 cm (Figure 2). All experimental ridges were built in a west-east direction. Superphosphate fertilizer was applied at 20 kg P ha^{-1} one day prior to furrows were established each year. Then ridges were covered using plastic film. Grain maize, cultivar 'Jinsui No.4' and 'Golden northwest No. 22' (*Zea mays* L.) were sown in the ridges at a density of 73000 plants ha^{-1} on April 25 and 19 in 2011 and 2012, respectively. Different cultivars in two years were used because the local government had signed a contract on maize cultivar with a Business Company, which was beyond our control. Crop was harvested on September 24 and 20 in 2011 and 2012, respectively.

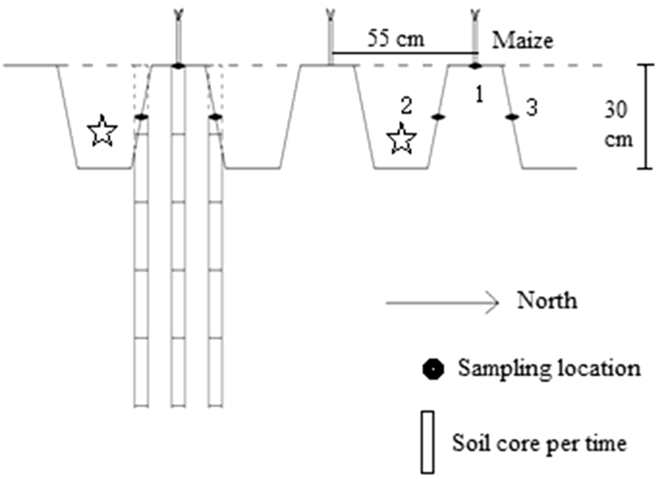

Figure 2. Schematic of root sampling.
Arabic numerals 1, 2 and 3 represents sampling position of under, south and north of the plant, respectively. Five-pointed star represents the irrigated/nitrogen application furrow (south furrow) for fixed furrow irrigation/nitrogen supply.

Experimental design

The goal of most published researches on partial root zone irrigation (PRI) has been to assess whether PRI will allow a reduction in total irrigation, in which PRI treatments generally received less water (up to 50% less) than control (conventional irrigation) (Davies et al., 2000; Stoll et al., 2000; Santos et al., 2003). In this study, all treatments received equal volumes of irrigation water to investigate the effects of different PRIs and N supply methods. The experiment factors were irrigation method and N fertilizer supply method. Irrigation methods included conventional furrow irrigation (CI), alternate furrow irrigation (AI) and fixed furrow irrigation (FI). CI means that all furrows were irrigated for every irrigation event. AI means that one of the two neighboring furrows was alternately irrigated during consecutive watering. FI means that irrigation was fixed to one of the two neighboring furrows (fixed to south furrow, Table 2). N supply methods included conventional N supply (CN), alternate N supply (AN) and fixed N supply (FN). CN means that N fertilizer was applied to all furrows. AN means that N fertilizer was alternately applied to one of the neighboring two furrows in consecutive fertilization. FN means that N fertilizer was fixed to one of every two furrows (fixed to south furrow, Table 2). This experimental plan yielded 9 treatments, i.e. CIAN, CICN, CIFN, AIAN, AICN, AIFN, FIAN, FICN and FIFN. These treatments were arranged in a randomized block design with three replicates. Each plot was 32 m^2 (4 m in width and 8 m in length) in 2011 and 24 m^2 (4 m in width and 6m in length) in 2012. Seven rows were established for each plot, resulting in eight furrows.

Twice as much water and/or N was applied to the irrigated/fertilized furrow in AI/AN and FI/FN as that to the furrow in CI/CN treatment, so that the total amount of water and/or N was the same for all treatments. Urea was broadcasted at a rate of 200 kg N ha^{-1} to the center of the furrows in 5 cm deep, which is optimum amount for maize production in the local area (Yang et al., 2009). N fertilizer application included basal application (50%) and topdressing at 12 collars (25%) and tasseling (25%) stages of maize. Irrigation was applied after planting and at the 6 collars, 12 collars, tasseling and filling stages of maize (75 mm per time), respectively. This irrigation regime is considered appropriate for maize production using CI in the local area (Zhang et al., 2007). The irrigation water, underground water with electrical conductivity of 0.52 dS m^{-1}, was supplied by a soft plastic pipe with a diameter of 55 mm and the pipe was removable so as to irrigate each plot separately. The amount of water applied was measured with a water meter installed at the discharging end of the pipe. Irrigation and N fertilizer application was conducted within a same day (N application before irrigation) at 12 collars and tasseling stages of maize. The details of partial irrigation and N application for all treatments are described in Table 2.

Table 2. Time and position of localized irrigation and nitrogen (N) application to maize grown for different irrigation and nitrogen supply methods.

Maize growth period	Position of localized irrigation and nitrogen application					
	Irrigation method			Nitrogen supply method		
	AI	CI	FI	AN	CN	FN
Before planting	/	/	/	South furrow	Both furrows	South furrow
After planting	Both furrows	Both furrows	Both furrows	/	/	/
6 collars	South furrow	Both furrows	South furrow	/	/	/
12 collars	North furrow	Both furrows	South furrow	North furrow	Both furrows	South furrow
Tasseling	South furrow	Both furrows	South furrow	South furrow	Both furrows	South furrow
Filling	North furrow	Both furrows	South furrow	/	/	/

"/" represents no treatment; AI, alternate furrow irrigation; CI, conventional furrow irrigation; FI, fixed furrow irrigation; AN, alternate N supply; CN, conventional N supply; FN, fixed N supply. 100, 50 and 50 kg N ha^{-1} was applied before planting, and at 12 collars and tasseling stages of maize, respectively. Irrigation amount of 75 mm per time was conducted for each irrigation event. The rate of irrigation and N application per time was the total supply of N and water to the both furrows (south and north furrow).

Measurements

Root sampling and measurement

Soil samples for root measurements were taken from three plants in the middle of the plot on September 23 and 19 in 2011 and 2012, respectively. A hand-driven auger with 7 cm diameter and 1.25 m length was used for sampling. The above-ground of the plant was removed before sampling. The sampling was collected to 100 cm soil depth from three positions around one plant. The three positions were: (1) directly over the crown of the plant (under the plant), (2) south and (3) north side of the plant directly opposite the crown (Figure 2). For position (2) and (3), sampling sites were positioned one quarter of row spacing from the plant row (approximately 14 cm). The core was sectioned into 20 cm depths (Figure 2). The approach by which root sample was separated from the soil was described in detail by Benjamin and Nielsen (2006). In short, the sample was placed in a plastic bag, sealable bag and the bag placed in refrigeration storage until washing the next day. Roots were washed from soil cores and debris as well as dead roots was removed from the samples. Root samples were then scanned to measure root parameters. During scanning, the root was placed in a glass dish containing water to untangle the roots and to minimize root overlap. Images were analyzed for root length, fine root length, root surface area by WinRHIZO (Vision Pro 5.0a, Regent Instrument, Canada). Samples were then dried at 75 ºC to constant mass and weighed. Root length density (RLD, cm cm^{-3}) was calculated as the ratio of root length (cm) to soil volume of 20 cm soil sections (3.14×3.5^2 $cm^2 \times 20$ cm=769.30 cm^3) for each sampling.

Soil water content

Soil water content of AICN, CICN and FICN treatments was measured at 6 collars, 12 collars, tasseling, filling and maturity stages of maize development, which corresponds to 43, 80, 95, 114 and 149 days after planting (DAP) in 2011 and 44, 82, 97, 117 and 152 DAP in 2012, respectively. These sampling dates were earlier than corresponds irrigation dates. The soil water content test using the gravimetric method based on the conventional oven-dry weight and multiplied by the bulk density (Qiu et al., 2001). The sampling position of soil core for soil water content was exactly following that for roots sampling (Figure 2).

Grain yield

Two central rows of each plot were harvested for grain yield. Measurement of grain weight was obtained after cobs were shelled; a subsample (approximately 150 g) was kept for moisture determination. According to Li et al. (2011), the original moisture content (Gw) of grain was determined as follows:

$$G_w = [(w_1 w_3 - w_2 w_4)/\ w_1 w_3] \times 100\% \tag{1}$$

where w_1 is fresh weight of the subsample, w_2 is air-dried weight of the subsample, w_3 is the subsampled of w_2 (between 20 to 30 g), w_4 is consistent weight of w_3 after oven-dried at 105 ºC for 36 h.

Grain yield (kg ha^{-1}) was then corrected to 15.5% of moisture content.

Root distribution function and data analysis

According to Bodner et al. (2010), the vertical distribution of root was characterized by the exponential function of Gerwitz and Page (1974), which describes the decrease in root length density (RLD) with soil depth by:

$$RLD_i = L_0 \times \exp(-a \times z_i) \tag{2}$$

where RLD_i (cm cm^{-3}) is root length density at soil depth z_i (cm), L_0 (cm cm^{-3}) is root length density at the soil surface ($z = 0$) and a (dimensionless) is a parameter describing the decrease in RLD with soil depth.

Root distribution functions (Equation 2) was fitted using non-linear regression by the procedure PROC NLIN in SAS (SAS 9.1, SAS institute Ltd., USA).

To compare measured root parameters as well as the fitted parameters of root distribution function among treatments, analysis of variance (ANOVA) was performed using the general linear model-univariate procedure from SPSS 12.0 software. All the treatment means were compared for any significant differences using the Duncan's multiple range tests at significant level of $P = 0.05$.

Results

Root growth

As shown in Table 3, both irrigation and N supply methods had a significant impact on total root parameters (root length, fine root length, root dry weight and root surface area) in 2011 and 2012. The total root parameters are means of the sum of measured root parameters from three sampling points of north, south and under the plant in five layers of 0-100 cm soil profile. Interaction effects of irrigation by N supply method only influenced total root surface area in 2011.

In most cases of 2011 and 2012, compared to conventional furrow irrigation (CI), each of total root parameters was significantly increased by alternate furrow irrigation (AI) when coupling with conventional N supply (CN)or alternate N supply (AN), while that were significantly reduced by fixed furrow irrigation (FI) in any N supply method. Compared to CN treatment, each of total root parameters of AN was comparable while those of fixed N supply (FN) were significantly reduced irrespective of irrigation method (Table 3). Thus, in general, root growth was increased by AI or CN and AN compared with other irrigation or N supply methods. Overall, AICN and AIAN treatments had the largest root lengths, biomass and surface area, whereas the FIFN treatment had the smallest root parameters (Table 3). These indicated that root growth was enhanced by alternate partial root zone irrigation coupled with conventional N supply or alternate N supply.

Table 3. Maize root parameters in 0-100 cm soil depth for different treatments at maturity stage in 2011 and 2012.

Treatment	Total root length (cm)		Total fine root (diameter<2cm) length (cm)		Total root dry weight (mg)		Total root surface area(cm^2)	
	2011	2012	2011	2012	2011	2012	2011	2012
CIAN	1170^{b}	1045^{b}	936^{b}	836^{ab}	949^{b}	763^{b}	1573^{b}	1258^{c}
CICN	1185^{b}	1056^{b}	948^{b}	845^{ab}	972^{ab}	788^{abc}	1628^{ab}	1302^{c}
CIFN	1124^{c}	1032^{b}	899^{bc}	826^{ab}	949^{b}	727^{bc}	1511^{b}	1209^{c}
AIAN	1241^{a}	1154^{a}	993^{ab}	923^{a}	993^{ab}	832^{a}	1964^{a}	1571^{a}
AICN	1274^{a}	1173^{a}	1019^{a}	938^{a}	1057^{a}	812^{ab}	1810^{a}	1448^{b}
AIFN	1166^{b}	1037^{b}	933^{b}	830^{ab}	869^{b}	754^{b}	1298^{c}	1138^{c}
FIAN	1145^{c}	1006^{bc}	912^{bc}	805^{c}	860^{b}	724^{bc}	1265^{c}	1109^{c}
FICN	1132^{c}	1012^{bc}	906^{bc}	810^{c}	952^{ab}	725^{bc}	1324^{c}	1159^{c}
FIFN	1088^{d}	954^{c}	870^{c}	763^{d}	742^{c}	692^{c}	1154^{d}	1003^{d}
Significance test (*P* Values)								
IM	<0.0001	0.0056	0.0085	0.0034	<0.0001	<0.0001	0.0057	0.0014
NSM	0.0325	0.0087	0.0235	0.0431	0.0396	0.0214	0.0113	0.0365
IM×NSM	0.1307	0.3258	0.1132	0.6850	0.5238	0.0565	0.0172	0.0895

Values are means (n=3) of the sum of measured root parameters from three sampling points of north, south and under the plant in five layers of 0-100 cm soil profile, which related to soil volume of 11539.5 cm^3, 15 times (5 depths×3 positions) of soil volume of 20 cm soil sections (769.30 cm^3). *P* values of analysis of variance (ANOVA) were shown ($P < 0.05$, significance; $P < 0.01$, markedly significance; $P > 0.05$, no significance). IM, NSM and IM×NSM represents irrigation method, nitrogen supply method and the interaction of irrigation method and nitrogen supply method, respectively. Different letters in the same column indicate significant difference ($P < 0.05$).

Root distribution across the plant row

Root length density (RLD) is chosen for analyzing root spatial distribution of maize. RLD at north of the plant (NP, sampling point 3), south of the plant (SP, sampling point 2) and under the plant (UP, sampling point 1) (Figure 2) for different treatments are separately shown in Figure 3, which values were averaged across 0-100 cm soil depth. The results showed that in 2011 and 2012, RLD of UP was markedly larger than those of both NP and SP for all treatments. AICN treatment could maintain largest RLD under UP, SP and NP while FIFN treatment had a smallest RLD under NP among different treatments (Figure 3). The RLD of NP was significantly lower than RLD of SP under FI coupled with any N supply method ($P<0.05$) or FN coupled with any irrigation method ($P<0.05$) and the greatest differences of RLD between NP and SP was found in FIFN treatment. On the contrary, differences of RLD between NP and SP was not significant for CIAN and CICN treatments, so did AIAN and AICN treatments ($P>0.05$). This indicated that root distribution across the plant row was uniform under alternate PRI or conventional/alternate N supply and a large gap between the irrigated/fertilized and non-irrigated/non-fertilized side under fixed PRI or fixed N supply, especially for fixed PRI coupled with fixed N supply.

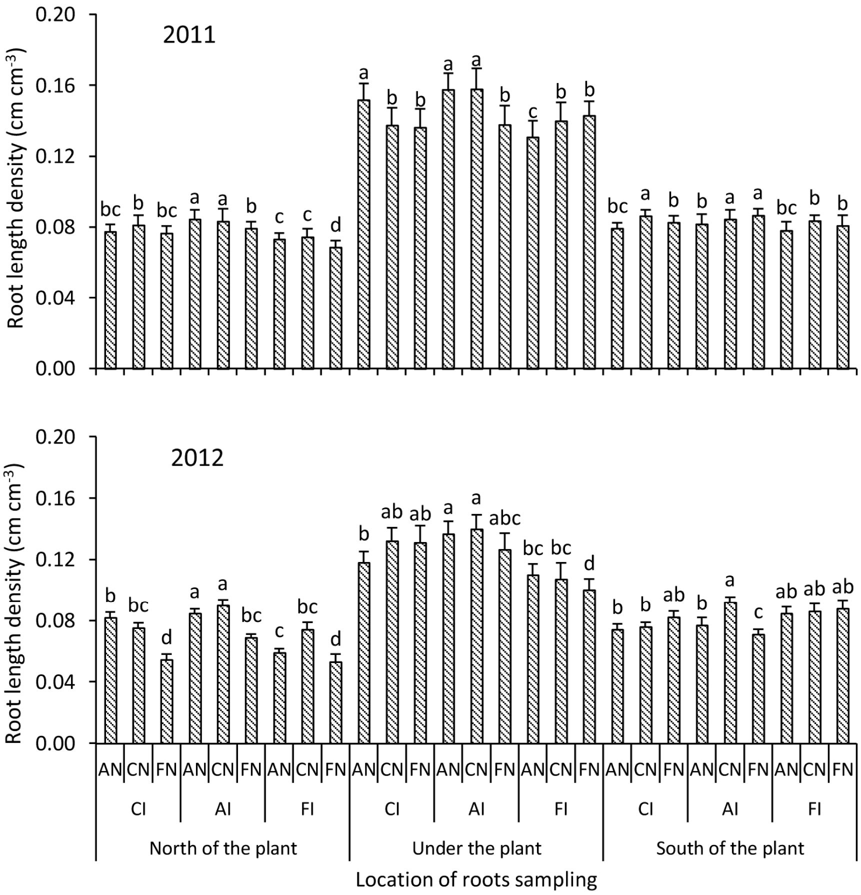

Figure 3. Mean root length density across 0-100 cm soil depth for different treatments for the north, south and under the plant in 2011 and 2012.
Bars show mean± SE (n = 3); Different letters within the same horizontal position indicate significant difference ($P < 0.05$). The symbols represent as in Table 2.

Vertical root distribution

RLD at each soil depth for different treatments are shown in Figure 4, in which the data were averaged across different sampling positions (UP, SP and NP, Figure 2) and two years. RLD decreased consistently with increasing soil depth (Figure 4). In the 0-40 cm soil depth, compared to CI treatment, RLD was significantly increased by AI while markedly reduced by FI in any N supply method (Figure 4). Compared to CN treatment, RLD of AN was comparable while for FN was significantly reduced in any irrigation method ($P<0.05$). However, in the 60-100 cm, only small statistically differences of RLD were observed among different treatments. Moreover, the percentage of total root length of 0-40 cm soil depth to 0-100 cm ranged from 68.6% to 73.9%, while that of 60-100 cm soil depth to 0-100 cm ranged from 16.3% to 18.2% (Table 4). This indicated that the differences of root vertical distribution for different treatments mainly occurred in the 0-40 cm soil depth.

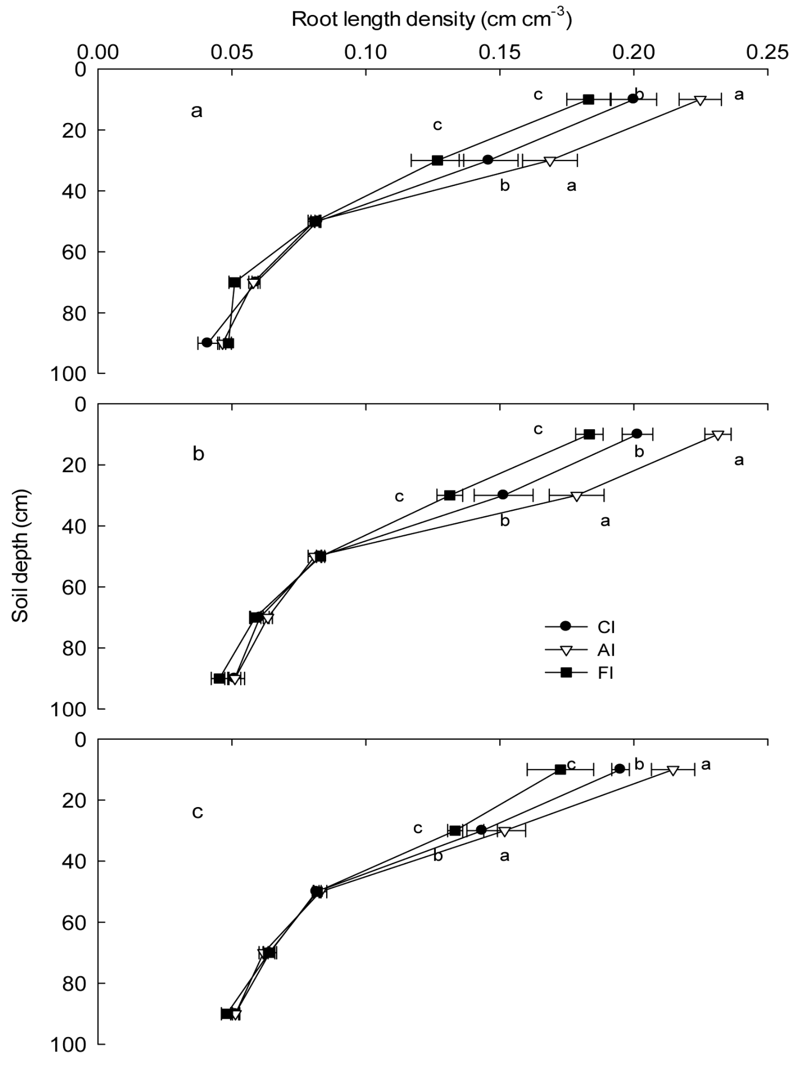

Figure 4. Root length density of different irrigation methods for AN (a), CN (b) and FN (c) treatments in 0-100 cm soil profile.
Data in each soil layer were averaged across different positions (north, south and under the plant) and two years. Different letters within same soil depth and nitrogen supply method indicate significant difference ($P< 0.05$). The symbols represent as in Table 2.

Table 4. The percentage of total root length in each soil depth to the sum of 0-100 cm soil depth (%).

Soil depth	CIAN	CICN	CIFN	AIAN	AICN	AIFN	FIAN	FICN	FIFN
0-20 cm	44.12	41.75	43.90	43.33	45.80	44.98	41.37	39.94	39.02
20-40 cm	25.33	26.87	25.41	28.65	28.09	27.61	29.33	30.29	30.14
40-60 cm	12.91	13.22	12.74	11.71	10.80	11.10	11.18	11.68	12.61
60-80 cm	10.29	10.34	10.78	9.27	8.26	9.39	9.81	9.75	9.92
80-100 cm	7.35	7.82	7.17	7.04	7.05	6.92	8.31	8.34	8.31

Total root length of each soil layer was averaged across different positions (north, south and under the plant) and two years for different treatments. Total root length of 0-100 cm depth was the sum of total root length of all soil layers.

Table 5 shows L_0 and a of the root distribution model for all treatments, in which the data was the mean RLD of the north, south and under the plant. L_0 denotes captures the intensity of rooting (root density) near the soil surface, a describes the decrease in rooting density with depth (Bodner et al., 2010). In 2011 and 2012, compared to CI treatment, L_0 was significantly increased by AI while reduced by FI in any N supply method. Compared to CN treatment, L_0 of AN was comparable while for FN was significantly reduced in any irrigation method (Table 5). For three irrigation methods, a had no response to varied N supply methods. For three N supply methods, AI had higher a than the other two irrigation methods. Of the largest L_0 and a were found in AICN and AIAN treatments, while the smallest L_0 was found in FIFN treatment (Table 5). The results indicated that alternate partial root zone irrigation achieved higher root production in the upper soil layers and less penetration into the deeper layers.

Table 5. Parameter values of vertical distribution model of maize root system for different treatments in 2011 and 2012.

Treatment	2011		2012	
	L_0	a	L_0	a
CIAN	2.456^c	0.051^b	2.043^c	0.053^b
CICN	2.557^c	0.052^b	2.156^c	0.054^b
CIFN	2.178^d	0.054^b	1.751^d	0.056^b
AIAN	3.303^a	0.061^a	2.878^a	0.063^a
AICN	3.622^a	0.064^a	3.013^a	0.066^a
AIFN	2.880^b	0.059^a	2.454^b	0.061^a
FIAN	2.172^d	0.051^b	1.761^d	0.053^b
FICN	2.016^d	0.055^b	1.734^d	0.055^b
FIFN	1.747^e	0.054^b	1.555^e	0.056^b

The fitted model was $RLD_i = L_0 \times \exp(-a \times z_i)$, where RLD_i is root length density (cm cm^{-3}) at soil depth z_i (cm). L_0 (cm cm^{-3}) and a (dimensionless) are the fitted parameters. Measured RLDi was mean RLDi across north, south and under the plant. Different letters in the same column indicate significant difference ($P < 0.05$).

Grain yield

As shown in table 6, in 2011 and 2012, compared to CI treatment, grain yield was increased by AI coupled with AN or CN while decreased by FI in any N supply method. Compared to CN treatment, grain yield of AN was comparable when coupling with CI and FI while decreased by FN in any irrigation method. Of the largest grain yield of maize was found in AICN treatment, followed by AIAN treatment, while the smallest in FIFN treatment (Table 6). This indicated that alternate partial root zone irrigation coupled with conventional or alternate N supply was more favorable for higher grain yield.

Table 6. Grain yield (kg ha^{-1}) for different treatments in 2011 and 2012.

Year	CIAN	CICN	CIFN	AIAN	AICN	AIFN	FIAN	FICN	FIFN
2011	9846^{b}	9725^{b}	9524^{c}	10145^{ab}	11524^{a}	9625^{c}	9365^{d}	9306^{d}	9021^{e}
2012	7632^{b}	7913^{b}	7235^{c}	8189^{b}	8415^{a}	7228^{c}	7266^{c}	7231^{c}	6871^{d}

Values are means (n = 3). Different letters in the same row indicate significant difference ($P < 0.05$).

Discussion

In the present study, conventional N supply (CN) and alternate N supply (AN) treatments were superior to fixed N supply (FN) in terms of root growth irrespective of irrigation method (Table 3). This likely resulted from the effect of N concentration and its distribution in the root-zone, which was manipulated by different N application methods. In CN treatment, N fertilizer was evenly distributed around maize rhizosphere. Our previous research suggested that uniform N supply contributed to improved root growth under conventional furrow irrigation (CI) (Qi et al., 2014). This effect was amplified by alternate furrow irrigation (AI) in this study (Table 3). In FN treatment, root length density (RLD) of the north of the plant (no N supplied side, Table 2) was dramatically reduced while that of the south of the plant (N supplied side, Table 2) was not always enhanced in any irrigation method in 2011 and 2012 (Figure 3), resulting in smaller total root length (Table 3). According to Yang et al. (2009), 200 kg N ha^{-1}, which was used in this experiment, is an appropriate N supply rate for local maize when conventional N application method was used. However, the amount of N fertilizer was applied only to the fixed furrow in FN treatment. Thus, soil N content in the fertilized furrow was twice that in CN treatment. In soils, rich with N content naturally, application of N fertilizer not only does not increase root volume (Angela et al., 2009), but it also inhabits root growth (Li et al., 2009). In AN treatment, N fertilizer was alternately applied to two adjacent furrows, so the maize rhizosphere was surrounded by relatively uniform N supply in the long term and resulted in superior root growth. Therefore, it is no surprise that root growth in the AIAN treatment was only inferior to AICN treatment, but superior to the other treatments (Table 3). The mechanism of N supply method on root growth under PRI needs to be further studied.

In this study, root length density (RLD) of south of the plant (irrigated side, Table 2) was significantly larger than RLD of north of the plant (non-irrigated side, Table 2) in FIFN treatment (Figure 3). This is in line with the findings of Songsri et al. (2008) that roots tend to proliferate in regions of relatively higher moisture availability. However, this result is contradictory to that of Skinner et al. (1998), where root biomass of the non-irrigated furrow was 26% higher than that of the irrigated furrow. In that study, there was twice the precipitation (average 331 mm in two years) and N was applied on the ridge. Therefore, the non-irrigated furrow may have received sufficient soil moisture from precipitation and N translocated from the ridge. Meanwhile, root growth may have been inhibited due to lower temperature and poor aeration in the irrigated furrow (Skinner et al., 1998). Our experimental area is prone to large evapotranspiration (about 2000 mm) and received only an average of 151 mm of precipitation over the two years (Figure 1). Moreover, there was no N application in the non-irrigated furrows (north of the plant) for FIFN treatment (Table 2). Roots in the non-irrigated furrow were exposed to extended drought (Figures 5 and 6) and minimal N supply, thus leading to limited root growth (Kang et al., 1998). These suggest that appropriate soil water and nutrient supply, neither excessive nor deficient, are favorable to root growth.

The results showed that compared to 60-100 cm soil depth, the difference of RLD in 0-40 cm among different treatments was more apparent (Figure 4). Apart from that root system grows mainly in the upper soil layer, greater variance of soil water (Figures 5 and 6) and nitrate N content (Qi et al., 2015) among treatments in 0-40 cm soil depth than that in 60-100 cm may account for that.

Figures 5 and 6 show that AI practiced successfully, especially in 0-40 cm soil depth in this experimental setup and the roots were alternately exposed to dry and wet environment. Thus, AI could greatly enhance the hydraulic conductivity of roots system by means of inducing the initiation and the growth of secondary roots (Liang et al., 1996). Our observations consistent with Liang et al. (1996) such that AI plants showed enhanced total fine root length (Table 3). Moreover, the value of a under AI was higher than that of CI and fixed furrow irrigation (FI) in any N supply method (Table 5), suggesting that RLD decreased more with soil layer deepening under AI. This is in line with the findings of Ahmadi et al. (2011) on potato root distribution in sandy loam soil under alternate PRI. In addition, the mean RLD in 60-100 cm soil layer in AI treatments was larger than that in the CI and FI treatments (0.064, 0.058 and 0.051 cm cm^{-3} for AI, CI and FI, respectively). These indicated that alternate PRI not only beneficial to root growth in the upper soil layer, but also enhanced root growth in the lower soil layer.

However, it can't be ignored here that root volume and grain yield were all greater in 2011 than those in 2012 across all treatments. This may be the result of different maize varieties among years. In addition, higher precipitation in 2011 may also have contributed to these results (Figure 1). Nevertheless, the patterns of root growth and grain yield among the treatments were consistent among years, suggesting that the results are robust among maize cultivars and environmental conditions.

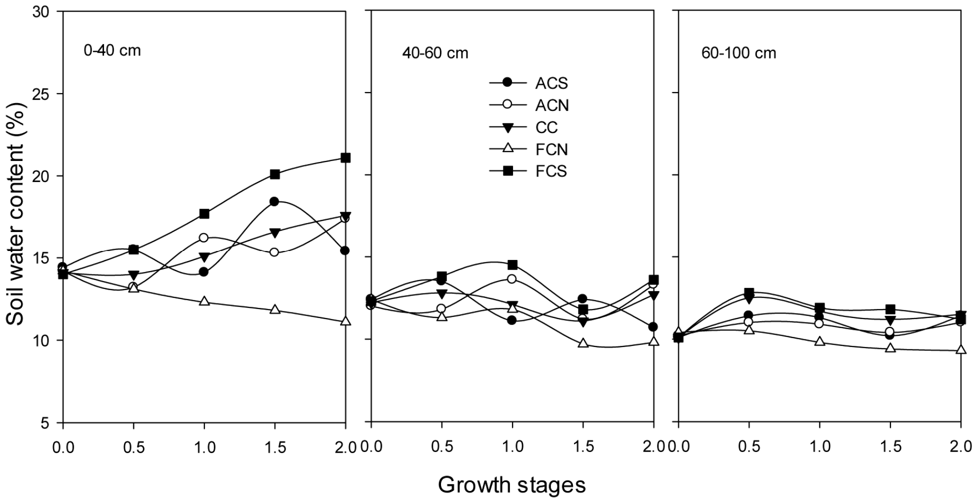

Figure 5. Changes of soil water content of south and north of the plant following maize growth stage in 0-100 cm soil profile for AICN, CICN and FICN treatments in 2011.
Note: Data were averaged across different soil depths (0-40 cm, 60-100 cm). Digit 0.0, 0.5, 1.0, 1.5 and 2.0 represents at 6 collars, 12 collars, tasseling, filling and maturity stages of maize growth, respectively. CC is a mean of soil water content of south and north of the plant of CICN treatment; ACS and ACN represents south and north of the plant of AICN treatment respectively; FCN and FCS represents north and south of the plant of FICN treatment respectively. The other symbols represent as in Table 2.

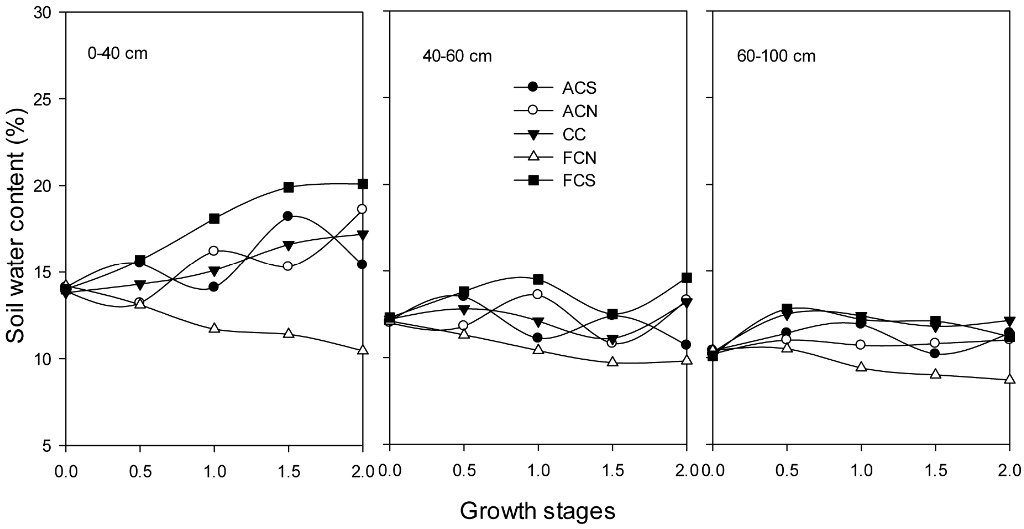

Figure 6. Changes of soil water content of south and north of the plant following maize growth stage in 0-100 cm soil profile for AICN, CICN and FICN treatments in 2012.
Data were averaged across different soil depths (0-40 cm, 60-100 cm). Digit 0.0, 0.5, 1.0, 1.5 and 2.0 represents at 6 collars, 12 collars, tasseling, filling and maturity stages of maize growth, respectively. CC is a mean of soil water content of south and north of the plant of CICN treatment; ACS and ACN represents south and north of the plant of AICN treatment respectively; FCN and FCS represents north and south of the plant of FICN treatment respectively. The other symbols represent as in Table 2.

Conclusion

Alternate PRI as well as conventional and alternate N supply resulted in greater total root parameters at the same N supply and irrigation amount. Alternate PRI or conventional irrigation coupled with conventional or alternate N supply achieved comparable roots between two sides across the plant row thanks to its relatively uniform distribution of N and water. Root distribution in the 0-40 cm soil depth varied more among the treatments compared with that in 40-100 cm. For alternate PRI, root length density decreased more with increasing of soil depth. Alternate PRI coupled with conventional or alternate N supply had higher grain yield and root production than the other couple of irrigation and N supply methods. Therefore, root growth and grain yield were improved under alternate partial root zone irrigation when conventional or alternate nitrogen application methods are used.

Acknowledgment

We are grateful to the research grants from the National Natural Science Fund of China (51079124) and the National High Technology Research and Development Program of China (2011AA100504). Meantime, we thank Dr. John L. Lindquist in Department of Agronomy and Horticulture, University of Nebraska, Lincoln for his valuable comments on an earlier version of this manuscript.

References

Angela, H., Graziella, B., Claude, D., Francisco, M., Martin, C., 2009. Plant root growth, architecture and function. Plant Soil. 321, 153-187.

Ahmadi, S.H., Plauborg, F., Andersen, M.N., Sepaskhah, A.R., Jensen, C.R., Hansen, S., 2011. Effect of irrigation strategies and soils on field grown potatoes: Root distribution. Agric. Water Manage. 98, 1280-1290.

Asseng, S., Ritchie, J.T., Smucker, A.J., Robertson, M.J., 1998. Root growth and water uptake during water deficit and recovering in wheat. Plant Soil. 201, 265-273.

Benjiamin, J.G., Nielsen, D.C., 2006. Water deficit effects on root distribution of soybean, field pea and chickpea. Field Crops Res. 97, 248-253.

Bodner, G., Himmelbauer, M., Loiskandl, W., Kaul, H.P., 2010. Improved evaluation of cover crop species by growth and root factors. Agronomy Sustain. Dev. 30, 455-464.

Craine, J.M., Wedin, D.A., Chapin F.S., Reich, P.B., 2003. Relationship between the structure of root systems and resource use for 11 North American grassland plants. Plant Ecology. 165, 85-100.

Davies, W.J., Bacon, M.A., Thompson, D.S., Sobeih, W., Rodriguez, L.G., 2000. Regulation of leaf and fruit growth in plants growing in drying soil: exploitation of the plant's chemical signaling system and hydraulic architecture to increase the efficiency of water use in agriculture. J. Exp. Bot. 51, 1617-1626.

Dry, P., Loveys, B., During, H., 2000. Partial drying of the root-zone of grape, II. Changes in the pattern of root development. J. Vitis. 39, 9-12.

Du, T., Kang, S., Zhang, J., Li, F., Hu, X., 2006. Yield and physiological responses of cotton to partial root-zone irrigation in the oasis field of northwest China. Agric. Water Manage. 84, 41-52.

Du, T., Kang, S., Zhang, J., Li, F., 2008. Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China. Irrigation Sci. 26, 147-159.

Ehdaie, B., Merhaunt, D.J., Ahmadian, S., 2010. Root system size influences water-nutrient uptake and nitrate leaching potential in wheat. Agronomy & Crop Sci. 196, 455-466.

Gerwitz, A., Page, E.R., 1974. An empirical mathematical model to describe plant root systems. J. Appl. Ecol. 11, 773-381.

Hodge, C.A., Neculai, N.P., 1994. Pollution control in fertilizer production. New York: CRC Press. pp. 35-81.

Hodge, A., Berta, G., Doussan, C., Merchn, F., Crespi, M., 2009. Plant root growth, architecture and function. Plant Soil. 321, 153-187.

Hu, T., Kang, S., Yuan, L., Zhang, F.L.Z., 2008. Effects of partial root-zone irrigation on growth and development of maize root system. Acta. Ecolo. Sinica. 28, 6180-6188.

Jackson, R.B., Caldwell, M.M., 1989. The timing and degree of root proliferation in fertile-soil microsites for three cold-desert perennials. Oecologia. 81, 149-153.

Kang, S., Liang, Z., Hu, W., Zhang, J., 1998.Water use efficiency of controlled alternate irrigation on root-divided maize plants. Agric. Water Manage. 38, 69-76.

Kang, S., Liang, Z., Pan, Y., Shi, P., Zhang, J., 2000. Alternate furrow irrigation for maize production in arid area. Agric. Water Manage. 45, 267-274.

Kang, S., Hu, X., Goodwin, I., Jerie, P., 2002a. Soil water distribution, water use and yield response to partial root-zone drying under flood-irrigation condition in a pear orchard. Scientia Hort. 92, 277-291.

Kang, S., Shi, W., Cao, H., Zhang, J., 2002b. Alternate watering in soil vertical profile improved water use efficiency of maize (*Zea mays*). Field Crops Res. 77, 31-41.

Liang, J., Zhang, J., Wong, M.H., 1996. Effects of air-filled soil porosity and aeration on the initiation and growth of secondary roots of maize (*Zea mays*). Plant Soil. 186, 245-254.

Liu, Y., Li, Y., Pan, T., Qu, L., Du, Z., 2009. Study on effects of different irrigation treatments on evapotranspiration and yield in spring maize. Agri. Res. in Arid Area. 27, 67-72.

Li, S., Wang, Z.S.S.M., Li, S., Gao, Y., Tian, X., 2009. Nutrient and water management effects on crop production and nutrient and water use efficiency in dry land area in China. Advance in Agronomy. 102, 223-265.

Li, D., Gong, X., Qian, C., 2011. Difference and correlation analysis of grain milking rate and grain dehydrating rate on maize. Chinese Agri. Sci. Bulletin. 27, 92-97.

Linkohr, B.I., Williamson, L.C., Fitter, A.H., Leyser, H.M.O., 2002. Nitrate and phosphate availability and distribution have different effects on root system architecture of Arabidopsis. Plant J. 29, 751-760.

Lincoln, Z., Johannes, M.S., Michael, D.D., Rafael, M.C., Jason, I., 2009. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96, 23-34.

Marschner, H., 1998. Role of root growth, arbuscular mycorrhiza and root exudates for the efficiency in nutrient acquisition. Field Crops Res. 56, 203-207.

Mackay, A.D., Barber, S.A., 1986. Effects of nitrogen on root growth of two corn genotypes in the field. Agron. J. 78, 699-703.

Mingo, D.M., Theobald, J.C., Bacon, M.A., Davies, W.J., Dodd, I.C., 2004. Biomass allocation in tomato (*Lycopersicon esculentum*) plants grown under partial root-zone drying: enhancement of root growth. Function Plant Biol. 31, 971-978.

Morison, J.I.L., Baker, N.R., Mullineaux, P.M., Davies, W.J., 2008. Improving water use in crop production. Phil. Trans. R. Soc. B. 363, 639-658.

Qi, D., Hu, T., Wu, X., 2014. Effects of nitrogen supply methods on root growth, yield and nitrogen use efficiency. Sci. Agri. Sin. 47, 2804-2813.

Qi, D., Hu, T., Wu, X., Niu, X., 2015. Rational irrigation and nitrogen supply methods improving root growth and yield of maize. Trans. CASE. 31, 144-149.

Qiu, Y., Fu, B., Wang, J., Chen, L., 2001. Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau China. J. Hydro. 240, 243-263.

Santos, T.P., Lopes, C.M., Rodrigues, M.L., Souza, C.R., Maroco, J.P., Pereira, J.S., Silva, J.R., Chaves, M.M., 2003. Partial root-zone drying: effects on growth and fruit quality of field-grown grapevines (*Vitisvinifera*). Functional Plant Biol. 30, 663-671.

Shahnazari, A., Liu, F., Andersen, M.N., Jacobsen, S., Jensen, R.C., 2007. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions. Field Crops Res. 100, 117-124.

Skinner, R.H., Hanson, J.D., Benjamin, G.H., 1998. Roots distribution following separation of water and nitrogen supply in furrow irrigated corn. Plant Soil, 199, 187-194.

Songsri, P., Joyloy, S., Vorasoot, N., Akkasaeng, C., Patanothai, A., Holbrook, C.C., 2008. Root distribution of drought-resistant peanut genotypes in response to drought. J. Agron. Crop Sci. 194, 92-103.

Stoll, M., Lovey, B., Dry, P., 2000.Hormonal changes induced by partial root-zone drying of irrigated grapevine. J. Exp. Bot. 51, 1627-1634.

Tang, L., Li, Y., Zhang, J., 2005. Physiological and yield responses of cotton under partial root-zone irrigation. Field Crops Res. 94, 214-223.

Tang, L., Li, Y., Zhang, J., 2010. Partial root zone irrigation increase water use efficiency, maintains yield and enhance economic profit of cotton in arid area. Agric. Water Manage. 97, 1527-1533.

Wang, H., Inukai, Y., Yamauchi, A., 2006. Root development and nutrient uptake. Crit. Rev. Plant Sci. 25, 279-301.

Yang, R., Su, Y., 2009. Effects of nitrogen fertilization and irrigation rate on grain yield, nitrate accumulation and nitrogen balance on sandy farmland in the marginal oasis in the middle of Heihe River basin. Acta. Ecolo. Sinica. 28, 1460-1469.

Zobel, R.W., Kinraide, T.B., Baligar, V.C., 2007. Fine roots diameters can change in response to changes in nutrient concentrations. Plant Soil. 297, 243-254.

Zhang, L., Ma, Z.E.S., 2007. Effects of ridge cultivation with plastic film mulching-furrow irrigation on yield and water use efficiency of seed corn. Acta Agri. Bore. Sin. 16, 83-86.