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Dynamics of root water uptake and water use efficiency under alternate partial root-zone irrigation

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ABSTRACT

The distribution of root length density of maize in ridge culture under alternate partial root-zone furrow irrigation (APFI) and conventional furrow irrigation (CFI) was investigated, and two-dimensional models of root length density and root uptake were developed to investigate the water use efficiencies under different furrow irrigation modes. Results indicated that APFI increased root depth and horizontal extended distance of maize, as well as water use efficiency (WUE). Values of the mean absolute error (MAE), the root mean square error (RMSE), and the index of agreement (d_i) between measured and simulated values of root length density of maize under APFI ranged from 0.26 to 0.68, 0.03 to 1.51, and 0.64 to 0.85 cm m^{-3}, respectively; and the coefficient of determination (R^2) was greater than 0.80. Values of MAE, RMSE, and d_i between measured and simulated values of root length density of maize under CFI ranged from 0.01 to 0.26, 0.01 to 0.60, and 0.61 to 0.96 cm m^{-3}, respectively; and R^2 was higher than 0.86. Dynamics of root uptake at different sites were simulated using the model of root water uptake. Root growth of maize under furrow irrigation was modeled using the 2D model of root length density with reasonable accuracy. Compared with CFI, water consumption rate of the maize in APFI was lower in key water requirement period, root uptake rate was higher in the end period, and WUE in APFI was higher by 5% than that in CFI.

Keywords: Alternate furrow irrigation; Conventional furrow irrigation; Root water uptake; Maize; WUE

1. Introduction

Root uptake is one important component of SPAC. The study method of root uptake model includes microcosmic methods and macroscopic methods. The difficulties in obtaining much information limit the application of microcosmic methods. Macroscopic methods have been developing due to the requirement of practical application, and are generally categorized into three types: (1) Root uptake models with soil water physical parameters as dominant factors [1–5], which reflect physical and physiological nature partly,

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but does not allow for the effects of root length density on root uptake. (2) Root uptake models with proportional uptake distribution in root zone, such as Feddes et al. [6] and Li et al. [7], which only allow for the vertical distribution and uptake of root system, while Monteith and Greenwood [8] and Passioura [9] suggested that the assumption of uniform distribution of root on horizontal direction was not suitable for simulating root growth. (3) Root uptake model are derived by back-stepping procedure from soil water movement equation under crop growth condition, such as the model proposed by Dardanelli et al. [10]. The three types of models above are developed based on their respective assumption and particular situation, and it is necessary to be selected and modified according to the particular situation in their applications. Under partial root-zone irrigation (alternate partial root-zone furrow irrigation, APFI), soil water environment and surface structure vary spatially. The variation of soil moisture results in the difference of root uptake from conventional furrow irrigation (CFI). In this paper, the two-dimensional root length densities and root uptake models of APFI and CFI were compared, and the root uptake's dynamic characteristics under furrow irrigation were discussed.

2. Materials and methods

2.1. Field experiment

Field experiment was conducted at the experimental station of Farmland Irrigation Research Institute (35˚19′N, 113˚53′E, 73.2 m) in 2009 and 2010. The study area is situated at Xinxiang city, Henan province, China. The city has a warm temperate continental climate. The mean annual temperature and rainfall are about 14.1℃ and 588.8 mm, respectively, with the mean annual potential evaporation of 2,000 mm. Average annual sunshine duration and annual frost-free days are 2398.8 h and 210, respectively.

APFI and CFI were adopted for spring maize planting. Each irrigation treatment had three replicas. When soil water content in irrigated furrow was lower than 75% of field capacity, irrigation was applied. The upper limit of CFI was field capacity. Two-third of irrigation quota of CFI was applied for APFI. Irrigation and rainfall during maize growing season in 2009 and 2010 are shown in Table 1. Each plot area was 100 m^2 (7.4 m × 13.5 m). The furrow profile was semicircular with a ridge height of 20 cm; and furrows were spaced at 60 cm (Fig. 1). Maize cultivar was

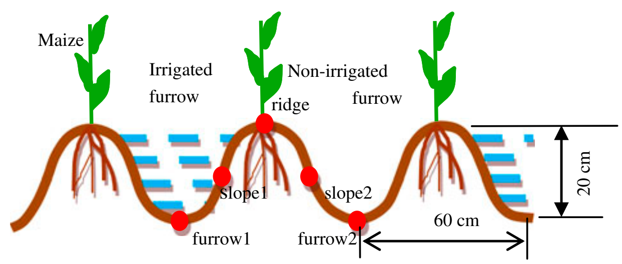

Fig. 1 Ground surface structure and root sampling points (•).

Table 1
Irrigation and precipitation during maize growing season in 2009 and 2010

Treatment	Year	Irrigation date	Irrigation quota (mm)	Irrigation amount (mm)	Precipitation (mm)
CFI	2009	29 Apr	42	278	206.9
		6 May; 27 May	27		
		3 Jun; 16 Jun	39		
		24 Jun; 1 Jul	52		
	2010	30 Apr; 3 May; 22 May; 1Jun	27	277	289.2
		12 Jun; 18 Jun; 28 Jun	39		
		16 Jul	52		
APFI	2009	29 Apr	36	198	206.9
		6 May; 26 May	18		
		3 Jun; 16 Jun	27		
		24 Jun; 1 Jul	36		
	2010	30 Apr; 3 May; 22 May; 1 Jun	18	189	289.2
		12 Jun; 17 Jun; 28 Jun	27		
		14 Jul	36		

"Xundan 18". The maize was shown on 21st and 22nd April, and the harvesting days were 14th and 26th August in 2009 and 2012, respectively. Plant density was 41668.8 plants hm^{-2}. Plant space and row space were 40 and 60 cm, respectively. Before sowing, the experimental site was plowed and ridged, and 675 kg hm^{-2} of compound fertilizer (all N, P_2O_5, and K_2O were over 15%, respectively) was applied, and at the elongation stage 300 kg hm^{-2} of urea (N, 46%) was applied.

2.2. Measurements

Root samples were collected to measure root length density using root auger with a diameter of 7 cm and a height of 10 cm. Five sample points were specified in the symmetrical slope and furrow region on the sides of ridge surface (Fig. 1). The sampling depth was the maximal root depth. Samples were soaked in freshwater for 6–8 h, and washed in nylon meshes with 0.1 mm pore diameter to clean root as soon as possible. The Newman method was used to measure root length and estimate root length density. Root samples were taken on the seeding, elongation, tasseling, filling, and maturity stage of spring maize in 2009 and 2010.

Water use efficiency (WUE, kg m^{-3}) was calculated as follows:

$$\mathrm{WUE} = Y/ET_c \tag{1}$$

where Y was the grain yield (kg m^{-2}) and ET_C was actual evapotranspiration (mm). ET_C was estimated with soil water balance equation as follows:

$$ET_c = P + I = U - R - D_W - \Delta S \tag{2}$$

where P is precipitation (mm), I is irrigation (mm), U is the upward capillary flow into the root zone (mm), R is the runoff (mm), D_W is the downward drainage out the root zone (mm), and ΔS is the change in soil moisture storage (mm). Runoff was never observed in the field. The upward and downward flow was estimated using Darcy's law. The capillary rise was negligible. Drainage from the root zone was calculated based on the relation of unsaturated water conductivity using volumetric soil moisture at 120 cm in the soil profile. Soil water content was measured gravimetrically for every 20 cm interval once a week from 0 to 120 cm.

Three 8 m^2 (4 m L × 2 m) W sample areas of plants were collected for each plot. Grain yield was measured after natural drying with water content of about 12%. The results were then converted to kg ha^{-1}.

3. Root uptake model

One-dimensional vertical root uptake mode is suitable for the condition of uniform soil structure and water distribution. Under the condition of non-uniform soil moisture, however, two-dimensional mode is more applicable. Feddes et al. [6] introduced water stress function $\gamma(h)$ and defined two-dimensional root uptake model, but assumed that the root uptake zone was an uniform rectangle. Vrugt et al. [11] introduced a non-uniform root length density function $\beta(x, z, t)$. In terms of the relationship between transpiration rate and root uptake rate, a two-dimensional root uptake model can be derived:

$$S(x,z,t) = \frac{T_r \beta(x,z,t)\gamma(h)}{\int_0^{z_m}\int_0^{x_m} \beta(x,z,t)\gamma(h)dxdz} \tag{3}$$

where T_r is transpiration rate, $\beta(x, z, t)$ is root length density function, $\gamma(h)$ is water stress function, x and z are the maximal horizontal and vertical extended length of the root system, respectively. The determination of $\beta(x, z, t)$ is very important to solve the equation.

3.1. Two-dimensional root length density model

3.1.1. Root length density distribution

The maximal root depths at the three positions increased linearly with the days after sowing (DAS) under two furrow irrigation methods. The maximal horizontal extended distance of root (X_m) has a significant linear relationship with DAS. The horizontal extended distance of root for APFI increased faster than for CFI. The root length density decreased with exponent function in horizontal and vertical directions.

3.1.2. Two-dimensional root length density model

Root length density had exponent relationship with vertical depth and horizontal extended distance of root. According to Vrugt et al. [11], two-dimensional root length density mode can be expressed as:

$$\beta(x,z,J_d) = (1 - x/x_m) \times (1 - z/z_m) \times e^{-[(P_x/x_m)|x^* - x| + (P_z/z_m)|z^* - z|]} \tag{4}$$

where z (m) and x (m) are vertical depth and horizontal extended distance of root, respectively, z_m (m) and x_m (m) are the maximal extended distance of root in horizontal and vertical direction, respectively, J_d is DAS; Z_m is a function of J_d; P_z, z^*, P_x and x^* are undetermined parameters; z^* and x^* are the vertical and horizontal distance, where the maximal root length density is located. When $z > z^*$ and $x > x^*$, $P_z = P_x = 1$ [11,12]. In simulation, the portion of root soil between two furrows was taken as a symmetrical zone, and the root density changes due to the root stretching out and entering the zone were assumed to offset each other. $X_m = 30$ cm, x^*, z^*, P_x and P_z are assigned to be 5, 10, 1, and 5, respectively.

3.2. Model evaluation

The SPSS software was used to compare the calculated value with the measured value. The analysis includes the coefficient of determination (R^2), the mean absolute error (MBE), the root mean square error (RMSE), and the index of agreement (d_i),

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |(y_i - x_i)| \tag{5}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (y_i - x_i)^2} \tag{6}$$

$$d_i = 1 - \frac{\sum_{i=1}^{n} |y_i - x_i|}{\sum_{i=1}^{n} (|y'_i| + |x'_i|)} \tag{7}$$

where x_i and y_i are the measured and calculated values, respectively; n is the number of the paired set data; $x'_i = x_i - x_n$, $y'_i = y_i - x_n$ and x_n are the measured mean.

4. Results and discussion

4.1. Simulation of root length density

Values of MAE, RMSE, d_i, and R^2 between simulated and measured values of root length density of maize under APFI and CFI are shown in Table 2. The lateral root length density of maize under APFI was greater than that under CFI in the same growing

Table 2
Evaluation on the simulation of root length density in 2010

		APFI				CFI			
Site	Date	MAE (cm cm^{-3})	RMSE (cm cm^{-3})	d_i	R^2	MAE (cm cm^{-3})	RMSE (cm cm^{-3})	d_i	R^2
Furrow 1	6–10	0.08	0.12	0.75	0.82	0.01	0.01	0.80	0.91
	6–23	0.10	0.10	0.68	0.81	0.01	0.01	0.96	0.95
	7–3	0.09	0.11	0.66	0.92	0.04	0.04	0.65	0.90
	7–18	0.06	0.08	0.66	0.88	0.08	0.07	0.69	0.89
	8–6	0.08	0.10	0.70	0.83	0.06	0.06	0.77	0.90
Slope 1	6–10	0.12	0.19	0.67	0.95	0.06	0.06	0.61	0.86
	6–23	0.11	0.18	0.66	0.81	0.09	0.14	0.66	0.91
	7–3	0.08	0.11	0.67	0.80	0.06	0.07	0.71	0.86
	7–18	0.08	0.09	0.72	0.84	0.08	0.10	0.63	0.97
	8–6	0.05	0.06	0.85	0.92	0.08	0.11	0.76	0.85
Ridge	6–10	0.11	0.21	0.70	0.87	0.15	0.18	0.71	0.90
	6–23	0.18	0.29	0.66	0.90	0.08	0.12	0.89	0.99
	7–3	0.22	0.37	0.68	0.90	0.26	0.60	0.73	0.91
	7–18	0.68	1.51	0.70	0.96	0.14	0.14	0.86	0.98
	8–6	0.43	0.92	0.64	0.88	0.15	0.30	0.71	0.85
Slope 2	6–10	0.06	0.07	0.66	0.86	0.05	0.06	0.65	0.92
	6–23	0.06	0.07	0.74	0.99	0.06	0.08	0.78	0.92
	7–3	0.07	0.10	0.76	0.95	0.06	0.08	0.76	0.83
	7–18	0.03	0.06	0.85	0.98	0.08	0.09	0.63	0.88
	8–6	0.07	0.12	0.76	0.97	0.09	0.12	0.78	0.88
Furrow 2	6–10	0.10	0.12	0.72	0.83	0.01	0.01	0.79	0.99
	6–23	0.04	0.06	0.64	0.97	0.06	0.05	0.69	0.97
	7–3	0.06	0.06	0.69	0.82	0.09	0.07	0.73	0.93
	7–18	0.02	0.03	0.76	0.86	0.06	0.07	0.67	0.90
	8–6	0.02	0.03	0.77	0.98	0.03	0.04	0.81	0.98

stage. Other studies have shown that APFI improved the lateral growth of root system and increased root length density [13,14], and consistent with the findings of this paper. Based on the comparative analysis of the simulated and measured values of root length density in different sites under APFI and CFI, MAE was lower than 0.26 cm cm^{-3}, values of RMSE, d_i, and R^2 ranged from 0.01 to 1.51 cm cm^{-3}, 0.60 to 0.96, and 0.809 to 0.993, respectively (Table 2).

4.2. Simulation of root water uptake

Root water uptake rate of maize under APFI was high during the mid to late growing period (Fig. 2). Differences in root water uptake rates between different sites followed the order of ridge > slope > furrow. After June 10, 2010, the average value of root water uptake rate in the first sample site of furrow, the first sample site of slope, the sample site of ridge, the second sample site of slope, and the second sample site of furrow was 2.58, 4.56, 7.64 4.83, and 2.90 mm d^{-1}, respectively. Maize root water uptake rate under CFI was high in the mid growing period, and decreased gradually in later period. The average value of root water uptake rate in the first sample site of furrow, the first sample site of slope, the sample site of ridge, the second sample site of slope, and the second sample site of furrow was 3.66, 4.27, 5.33, 4.31, and 4.01 mm d^{-1}, respectively.

Maize root depth in slope under APFI was greater than that under CFI, and root water uptake was also higher than CFI. Water condition of CFI was sufficient, maize root in different sites was little affected by water deficit, thus the differences of root water uptake between different sites under CFI were lower than APFI. Root water uptake rate increased after rainfall or irrigation. Roots adapt to drought not only by changing the morphology and distribution in soil, but also by physiological and chemical response enabling crop to resist environmental stress. Investigation of root system was an important part of crop drought-tolerant and efficient production. There were no significant differences in root water uptake rate between APFI and CFI before July (Fig. 2(c)). July and August are the critical water demand period for maize, and also the main stage of water consumption. Water condition of CFI was sufficient, but APFI was non-sufficient. Root water uptake rate of maize under APFI was lower than that under CFI because of water regulation. After August, maize went into mature stage. During the maturation stage, root water uptake rate of APFI was greater than that of CFI mainly because in maize maturation process delayed as compared to CFI due to higher root activity in APFI than CFI [15].

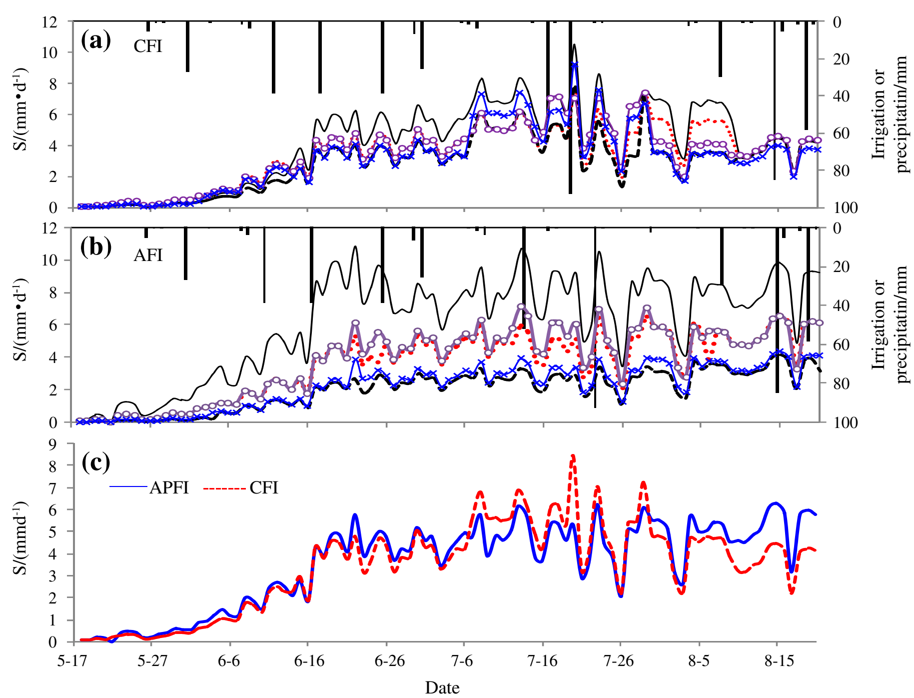

Fig. 2 Simulation of root water uptake for CFI (a) and APFI (b) at different point, and each deal with average (c) in 2010. (■ irrigation or precipitation, — furrow 1, … slope 1, — sample site of ridge, —○— slope 2, —×— furrow 2).

Table 3
Maize yield and WUE under two furrow irrigation methods

Irrigation method	2009 Irrigation/mm	2009 Water consumption /mm	2009 Yield / (kg hm^{-2})	2009 WUE/ (kg m^{-3})	2010 Irrigation/mm	2010 Water consumption /mm	2010 Yield / (kg hm^{-2})	2010 WUE/ (kg m^{-3})
APFI	198	389.22	7400.56	1.90	189	393.33	7501.01	1.91
CFI	278	438.41	7892.62	1.80	277	456.90	8283.67	1.81

4.3. WUE of maize under different furrow irrigation methods

There was significant correlation between root length density and WUE of maize under APFI and CFI. Maize yield and water utilization in two growing seasons, irrigation water of APFI was lower than that of CFI by 40.40–46.56%, maize yield lower than CFI by 40.40–46.56%, and WUE greater than CFI by 5.24–5.26% (Table 3).

5. Conclusion

The determination coefficient (R^2) between the simulated and measured values of root length density at different sites was between 0.809 and 0.993, and the fitting degree (d_i) between 0.60 and 0.96. The 2D model of root length density developed in this paper could simulate the dynamic distribution of root length density of maize with furrow irrigation with reasonable accuracy. Root water uptake rate of maize increased after rainfall or irrigation. APFI decreased water consumption of the critical water demand period of maize, increased the maize root water uptake rate in later period, and improved WUE by 5.24–5.26%.

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References

[1] M. Van den Berg, P.M. Driessen, Water uptake in crop growth models for land use systems analysis: I. A review of approaches and their pedigrees, Agric. Ecosyst. Environ. 92 (2002) 21–36.

[2] R.A. Feddes, P.A.C. Raats, Parameterizing the soil-water-plant root system, in: R.A. Feddes, G.H. de Rooij, J.C. Van Dan, (Eds.), Unsaturated-zone Modeling: Progress, Challenges and Applications, Dordrecht, Wageningen UR Frontis Series, Kluwer Academic Publishers, 2004, pp. 95–141.

[3] J.A. Kozak, L.R. Ahuja, L. Ma, T.R. Green, Scaling and estimation of evaporation and transpiration of water across soil textures, Vadose Zone J. 4 (2005) 418–427.

[4] K. Metselaar, Q. De Jong van Lier, The shape of the transpiration reduction function under plant water stress, Vadose Zone J. 6 (2007) 124–139.

[5] Q. De Jong van Lier, D. Dourado Neto, K. Metselaar, Modeling of transpiration reduction in van Genuchten–Mualem type soils, Water Resour. Res. 45 (2009) 2422–2431.

[6] R.A. Feddes, P.J. Kowalik, H. Zaradny, Simulaiton of Field Water Use and Crop Yield, John Wiley, New York, NY, 1978.

[7] K.Y. Li, R. De Jong, J.B. Boisvert, An exponential root-water-uptake model with water stress compensation, J. Hydrol. 252 (2001) 189–204.

[8] J.L. Monteith, D.J. Greenwood, How do crops manipulate water supply and demand? Philos. Trans. R. Soc. London, Ser. A 316 (1986) 245–259.

[9] J.B. Passioura, Water transport in and to roots, Annu. Rev. Plant Physiol. Plant Mol. Biol. 39 (1988) 245–265.

[10] J.L. Dardanelli, J.T. Ritchie, M. Calmon, J.M. Andriani, D.J. Collino, An empirical model for root water uptake. Field Crops Res. 87 (2004) 59–71.

[11] J.A. Vrugt, J.W. Hopmans, J. Šimůnek, Calibration of a two-dimensional root water uptake model. Soil Sci. Soci. Am. J. 65 (2001) 1027–1037.

[12] J. Šimůnek, M. Šejna, M.Th. van Genuchten, The HYDRUS Software Package for Simulating the Two- and Three-Dimensional Movement of Water, Heat and Multiple Solutes in Variably-Saturated Media, User Manual, Version 1.0, PC Progress, Prague, Czech Republic, 2007.

[13] Z.S. Liang, S.Z. Kang, P.Z. Shi, Y.H. Pan, L.J. He, Effect of alternate furrow irrigation on maize production, root density and water-saving benefit, Scientia Agricultura Sinica 33 (2000) 26–32 (in Chinese).

[14] C.X. Li, J.S. Sun, F.S. Li, X.G. Zhou, Z.Y. Li, X.M. Qiang, D.D. Guo, Response of root morphology and distribution in maize to alternate furrow irrigation, Agric. Water Manage. 98 (2011) 1789–1798.

[15] C.X. Li, X.F. Chen, C.Y. Yin. Effect of controlled alternate irrigation on growth of corn, Agric. Res. Arid Areas 24 (2006) 81–83 (in Chinese).