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Full Length Article

Root Water Uptake and Root Nitrogen Mass Distributions of Soybean under Different Nitrogen and Water Supply

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Abstract

As the essential information to modelling soil water and nutrient transport, the distributions of root water uptake (RWU) have been studied extensively. However, most RWU models are based on root length density (RLD) on some irrational assumption (e.g. water uptake is proportional to RLD). In this study, soybean (*Glycine max* L.) was grown in soil columns under different water and nitrogen supply to explore the distributions of root nitrogen mass (RNM) and RWU. The RWU model based on RNM density was then established and compared with models based on RLD. Results showed that the maximum RWU rate was correlated with the RNM density that was linear and weak. In general, all relative errors (RE) between measured and simulated values of the total water mass absorbed by soybean using model based on RNM were larger than 10%. It indicated that the RWU model based on RNM was not reliable for simulating RWU in a soil-soybean system, which probably owed to special characteristics of nitrogen absorption of legume plant.

Keywords: Nitrogen; Inverse method; Numerical simulation; Water and nitrogen supply; Soybean

Introduction

Root water uptake (RWU) from the soil and its distribution plays an important role in understanding solute transport dynamics in soil-plant systems. RWU depends upon climate, soil, and roots. Due to the fact that it is difficult to measure RWU distributions directly, mathematical method is commonly used to describe it (Perrochet, 1987; Gardner, 1991; Zarebanadkouki *et al*., 2014, 2016).

Since 1981, various mechanistic RWU models have been established. Considering that plant root systems play a crucial role in water absorption (Wu *et al*., 2015), most of them choose root length density (RLD) rather than root weight density to delineate root water uptake (Chassot *et al*., 2001; Besharat *et al*., 2010). Additionally, these models are usually set up based on the assumption that water uptake is proportional to RLD under optimal water conditions. However, younger roots are much more active for extraction of water than old roots (Gao *et al*., 1998; Haberle and Svoboda, 2015). In other words, root uptake activity decreased with maturity of root.

Since nitrogen is a principal component of substances including proteins, nucleic acids, enzymes and chlorophyll, which are vital for plant photosynthesis, respiration, metabolism and root absorption (Jones, 1998), root uptake capacity is most likely dependent on the allocation of nitrogen to the root system (Oscarson *et al*., 1989; Bibi *et al*., 2016). In greenhouse experiments, Shi and Zuo (2009) found that the maximum RWU rate of winter wheat was not proportional to RLD, but changed linearly with root nitrogen mass (RNM) density in the whole root zone. The RWU model was developed based on the linear correlation of RWU and RNM, and soil water and nitrate movement were then simulated successfully. Wang *et al*. (2012) tested the relationship through actual field experiment under different salinity stress. The linear correlation was also shown reliable and rational. The method provides a new alternative to set up RWU models and simulate water and nutrient movement in soils.

Soybean is a kind of legume plant, which is much more different from wheat in terms of nitrogen uptake. So far, relationship between RNM and RWU for legume plant has not well considered. One controlled greenhouse experiment, culturing soybean in soil columns under different water and nitrogen supply was carried out in this study. Thus, the objectives of this study were to explore whether the linear relationship was still applicable for soybean, and then compare the two models (i.e. model based on RNM and model based on RLD) at applying them to simulate RWU in a soil-soybean system.

Materials and Methods

RWU Function

The following one-dimensional model was employed to describe water movement in a vertical profile in the soil-plant system (Wu *et al*., 1999):

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S(z,t) \qquad (1)$$

$$h(z,0) = h_0(z) \qquad 0 \le z \le L \qquad (2)$$

$$\left[-K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right]_{z=0} = -E(t) \qquad t > 0 \qquad (3)$$

$$h(L,t) = h_L(t) \qquad t > 0 \qquad (4).$$

Where h, the pressure head (cm); $K(h)$, the hydraulic conductivity (cm d^{-1}); $C(h)$, the specific moisture capacity (cm^{-1}); z, vertical coordinate and positive downwards (cm); L, simulation depth (cm); $E(t)$, the soil surface evaporation rate (cm d^{-1}); t, time (d); and $S(z,t)$, the sink term representing RWU rate (cm^3 cm^{-3} d^{-1}) (Zuo and Zhang, 2002):

$$S(z,t) = S(z_r,t) = \gamma(\theta) S_{\max}(z_r,t) \qquad (5)$$

$$\gamma(\theta) = \begin{cases} 0 & \theta_H < \theta \le \theta_s \\ 1 & \theta_L < \theta \le \theta_H \\ \dfrac{\theta(z,t) - \theta_w}{\theta_L - \theta_w} & \theta_w < \theta \le \theta_L \\ 0 & \theta \le \theta_w \end{cases} \qquad (6)$$

$$S_{\max}(z_r,t) = \frac{T_p}{L_r} L_{nrd}(z_r) \qquad (7).$$

Where z_r $(= z / L_r)$ is the normalized root depth, in which L_r is the rooting depth (cm); $\gamma(\theta)$, a water stress function; T_p, the potential transpiration rate (cm/d); $S_{\max}(z_r,t)$, the maximal specific water extraction rate (cm^3 cm^{-3} d^{-1}); $\theta(z,t)$, the soil water content at z and t (cm^3 cm^{-3}); $L_{nrd}(z_r)$, the normalized RLD; θ_H, the "anaerobiosis point" (cm^3 cm^{-3}); θ_s, the saturated water content (cm^3 cm^{-3}); θ_w, the "wilting point" (cm^3 cm^{-3}); θ_L, the lower threshold water content (cm^3 cm^{-3}). According to the study of Yan and Han (2009), for soybean θ_L was about 80% of the field water capacity.

For winter wheat, $S_{\max}(z_r,t)$ can also be calculated as (Wang *et al*., 2012):

$$S_{\max}(z_r,t) = W_{NP} N_d(z_r,t) \qquad (8)$$

Where $N_d(z_r,t)$ is the RNM density, namely the RNM per soil volume (mg cm^{-3}); W_{NP} is defined as the potential RWU coefficient (cm^3 mg^{-1} d^{-1}).

Greenhouse Experiment

A soil column experiment with soybean (*Glycine max* L. Heinong 35) cultured in sand was carried out to investigate distributions of RWU and RNM. There were totally 80 columns made of PVC pipe used in the experiment. The inner diameter of the column was 15 cm with the height of 48 cm. Columns were filled with air-dried sand soil with a dry bulk density of 1.65 g cm^{-3} (L = 45 cm). The distribution of particle-size of the soil contained 95.72% sand, 4.14% silt and 0.14% clay. The content of total nitrogen was only 0.05 g kg^{-1}. The soil hydraulic parameters were calculated as (van Genuchten, 1980): θ_s = 0.373 cm^3 cm^{-3}, K_s = 68.2 cm d^{-1}, α = 0.08 cm^{-1}, θ_r = 0.012 cm^3 cm^{-3}, and n = 1.608. The field water capacity was chosen as 0.113 cm^3 cm^{-3}, corresponding to the soil water content at –100 cm of soil matric potential for sandy soil (Romano and Santini, 2002).

Uniform seeds were initially germinated in the dark for 2 d at 25°C. On Oct. 16 2013, three seedlings were then transplanted into each column. On Oct. 22, 2013 (6 DAS, days after sowing), the surface of each column was covered with a thin layer of quartz sand to reduce evaporation. Until Oct. 31, 2013, all the soybean seedlings were irrigated sufficiently using standard nutrient solution, which contained (μmol L^{-1}): $Ca(NO_3)_2$, 2000; K_2SO_4, 600; $MgSO_4$, 200; $CaC1_2$, 600; ZnSO4, 0.75; KH_2PO4, 30; H_3B0_3, 5; $MnSO^4$, 1; $CuSO_4$, 0.2; $(NH_4)_6Mo_7O_{24}$, 0.005; EDTA-Fe, 10 (Tang *et al*., 2001). Four water and nitrogen supply treatments were designed: high water + high nitrate (HWHN), high water + low nitrate (HWLN), low water + high nitrate (LWHN), and low water + low nitrate (LWLN). All treatments were irrigated every 6 days using different concentration and volume solutions. The average water contents within the root zone of HW treatments were kept at θ_L. The irrigation volume for treatments LW was 50% of HW treatments. The HN treatments were irrigated with standard solution (nitrate: 4 mmol L^{-1}), while the solution concentration for LN treatments was just taken as 10% of HN (nitrate: 0.4 mmol L^{-1}). The pH of the solution was kept as 5.6–6.0.

The experiment was continued for 54 days. At 20:00, 2 columns of each treatment were weighed daily to estimate the evapotranspiration. Sampling work was started on Nov. 15, 2013. Root and soil samples were taken at 0.5 days before and after irrigation and for 8 times in total. Two randomly chosen columns for each treatment were cleaved vertically to extract soils and roots. The soil cores were cut into 5 cm height layer. Firstly, appropriate amount of soil was collected for measuring soil water contents. Then, the remaining root samples collected from each plant were scanned for root length, dried at 70°C for weight, and finally measured for nitrogen content using an element analyzer.

In order to measure the actual transpiration rate of all treatments, another parallel experiment was meanwhile conducted. The parallel experiment used 8 same soil columns (2 columns for each treatment). But the columns didn't cultured soybean seedlings. The irrigation was also similar to columns with soybean seedlings. The average water content with the rooting depth in these 8 columns was kept similar as that of columns with soybean. The columns were also weighed daily at 20:00. Thus, the actual transpiration rate of all treatment was calculated by subtracting surface evaporation rate from evapotranspiration rate.

Results

Soil Water Content and RLD Distributions

The measured distributions of soil water content above the rooting depth during various growth periods for all treatments are shown in Fig. 1. During each irrigation period, the average water content for treatments HWHN and HWLN within the rooting depth was about 0.089 $cm^3\ cm^{-3}$, 79% of the field water capacity, which basically met requirements of sufficient irrigation for soybean at the seedling stage. Therefore, the estimated actual transpiration rate of soybean for treatments HWHN and HWLN can be approximately as T_p. While the average soil water content for treatments LWHN and LWLN during each irrigation period was about 0.05 $cm^3\ cm^{-3}$. It indicated that soybean growth was subjected to a certain degree of water stress. Measured RLD distributions for all treatments are shown in Fig. 2. In general, RLD decreased gradually with depth , but increased with time as the soybean grew.

RNM Density and RWU Distributions

The measured RNM density distributions for all the treatments are shown in Fig. 3. The RNM was influenced by both the water and nitrogen supply and the maturity of soybean. The changes in RNM density coincided well with those of RLD. With the inverse method proposed by Zuo and Zhang (2002), measured soil water content distributions (Fig. 1) and hydraulic parameters, the distribution of average RWU rate were estimated were shown in Fig. 4. The changing tendency of RWU was similar to that of RNM.

Correlation of RWU and RNM

Since the HWHN and HWLN treatments had a sufficient water supply, the estimated RWU rate distribution was reasonably used to approximate the maximal RWU rate $S_{\max}(z_r,t)$ in Equation (5). The correlation of $S_{\max}(z_r,t)$ and the measured RNM density are shown in Fig. 5. This shows that the maximum RWU rate was linearly correlated with the RNM density, but weakly. The determination coefficient was calculated as R^2 = 0.67. The potential RWU coefficient W_{NP} was fitted as

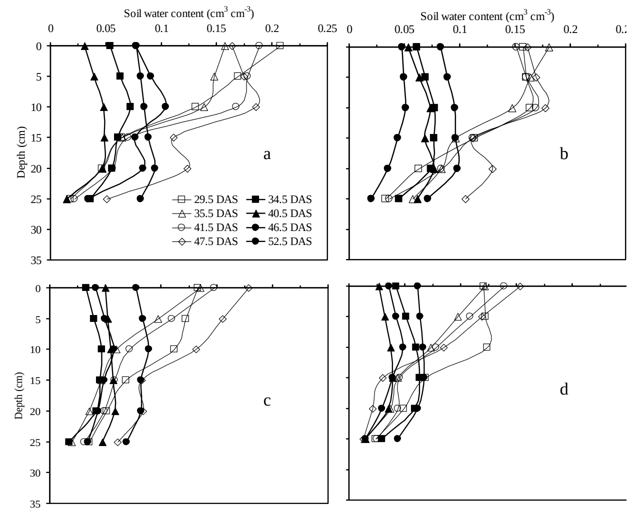

Fig. 1: Soil water content distributions at 0.5 and 5.5 days after each irrigation during different growth periods of soybean for treatments (a) HWHN, (b) HWLN, (c) LWHN, and (d) LWLN

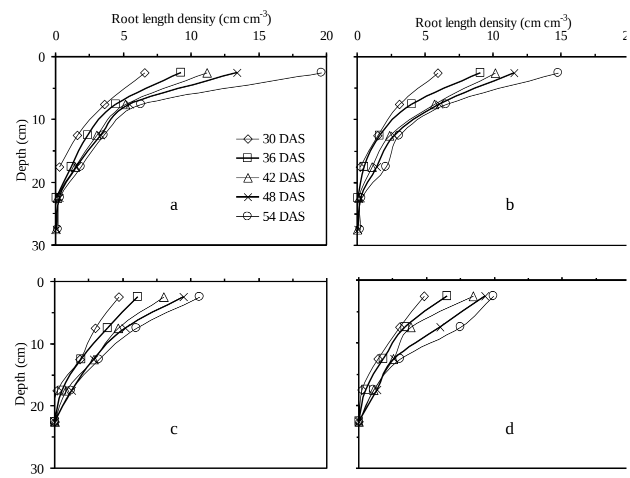

Fig. 2: Root length density distributions during different growth periods of soybean for treatments (a) HWHN, (b) HWLN, (c) LWHN, and (d) LWLN

2.17 $cm^3\ mg^{-1}\ d^{-1}$.

In order to further verify the stability of the correlation of maximum RWU rate and RNM density in simulating RWU rate, two RWU model approaches were compared. One is popularly described with RLD, such as Equation (7) (named as M1). The other is described with RNM density, such as Equation (8) (named as M2). According to the measured data, and established RWU model, the soil water transport and RWU distributions for treatments HWHN and HWLN during each irrigation period were simulated using Equations (1)-(4). Similarly, we simulated RWU

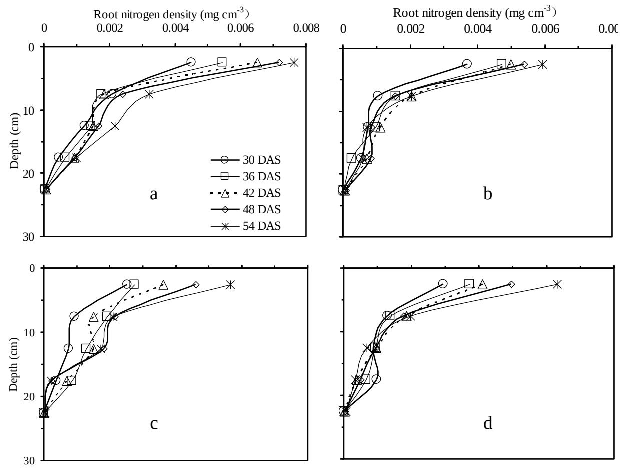

Fig. 3: Root nitrogen density distributions during different growth periods of soybean for treatments (a) HWHN, (b) HWLN, (c) LWHN, and (d) LWLN

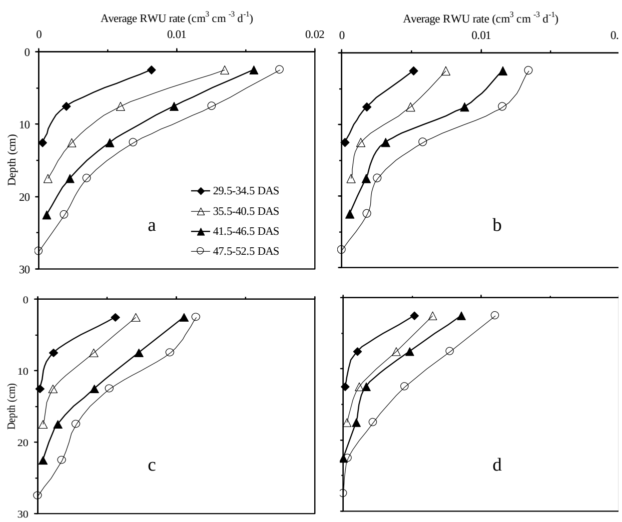

Fig. 4: Average RWU rate distributions during different growth periods of soybean for treatments (a) HWHN, (b) HWLN, (c) LWHN, and (d) LWLN

distributions with Equation (7) using measured RLD and other data.

The total water mass absorbed by soybean roots M_{RWU} (mg) in each column every 6 days was calculated by:

$$M_{RWU} = TA\int_0^{L_r} \overline{S}(z,T)\,\mathrm{d}z \qquad (9)$$

Where T, the period between two sampling times; A, the column surface area (cm^2); $\overline{S}(z,T)$, the average RWU rate of soybean during the 6 days. In addition, M_{RWU} could also be calculated by weighing the column weight between two successive measurements. The estimated M_{RWU} for treatments HWHN and HWLN during different periods using M1 and M2 were compared with the calculated

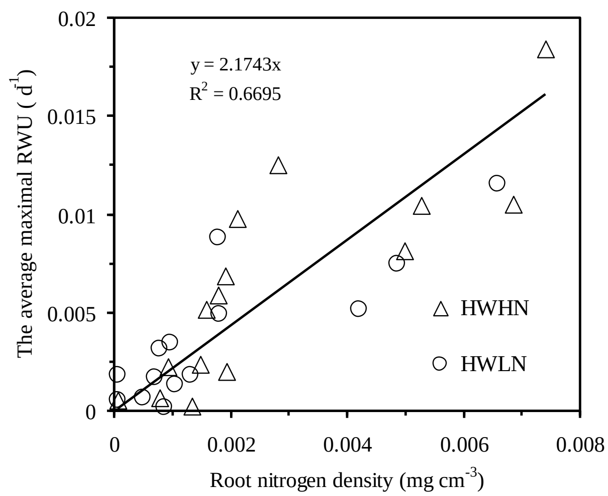

Fig. 5: The correlation of the maximum RWU rate S_{max} and RNM density N_d of soybean under treatments HWHN and HWLN

data in Table 1. Generally, the relative errors for M2 were much larger than for M1. The relative errors for M1 were less than 10%. In general, the relative errors were larger than 10% for M2, with a maximum error reaching 18.65%. The results indicated that M2 approach did not characterize RWU distributions well in soil-soybean system. Comparatively, the M1 model more accurately simulated RWU and water flow.

Discussion

The values of RLD for treatments HWHN and HWLN within 5 cm from the soil surface were significantly greater than of LWHN, and LWLN and attributable to different water content distributions (Fig. 2). However, below 5 cm from the soil surface the RLD distributions for all the four treatments were quite similar. This showed that soybean roots had strong self-adjustment ability in response to water stress (Yan and Han, 2009).

The values of average RWU rate for treatments of high water supply (HWHN and HWLN) were significantly higher than for treatments of low water supply (LWHN and LWLN). While vales of average RWU rate for treatments of high nitrogen supply (HWHN and LWHN) were just slightly higher than for treatments of low water supply (Fig. 4). It indicated that in this experiment, the effect of water supply was higher than of nitrogen supply. This was probably due to the ability of soybean nitrogen fixation (Shi and Zuo, 2009).

In soil-wheat system, the correlation of maximum RWU rate and RNM density was found significantly linear both in laboratory and field under various conditions (Shi and Zuo, 2009; Wang *et al*., 2012). And the determination coefficients R^2 in their experiments were larger than 0.90. However, R^2 were less than 0.7 in soil-soybean system in

Table 1: The measured, simulated by M1 (based on RLD) and M2 (based on RNM) total water mass extracted by soybean, and the corresponding relative errors during various periods under treatments HWHN and HWLN

Treatments	Period	Measured (g)	Simulated (g)		Relative Error (%)	
			M1	M2	M1	M2
HWHN	30-36 DAS	54.3	57.8	61.2	6.45	12.71
	36-42 DAS	113.2	118.9	125.7	5.04	11.04
	42-48 DAS	164.6	172.1	195.3	4.56	18.65
	48-54 DAS	195.6	210.3	223.6	7.52	14.31
HWLN	30-36 DAS	47.5	50.2	55.6	5.68	17.05
	36-42 DAS	103.8	110.7	121.3	6.65	16.86
	42-48 DAS	158.9	165.9	175.7	4.41	10.57
	48-54 DAS	183.2	200.1	191.8	9.22	4.69

this experiment. The correlation was not well linear in soybean in this study. This probably resulted from nitrogen fixation of soybean, which was much more different from wheat. In addition to absorbing nitrogen from the soil through roots, soybean can also fix nitrogen from the air through Rhizobium.

Conclusion

In order to explore the water and nitrogen uptake in the soil-soybean system completely, further attention should be paid for distinguishing different sources of nitrogen extraction. Comparatively, the RWU model based on RLD was more successfully in simulating water flow of soybean until now.

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