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Optimizing parameters of salinity stress reduction function using the relationship between root-water-uptake and root nitrogen mass of winter wheat

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ABSTRACT

Delineating the root-water-uptake (RWU) under the salinity stress condition accurately is important for making rational saline water irrigation schedules. However, RWU is very complex and still incompletely understood, especially under the salinity stress condition. In this study, the linear relationship between RWU and root nitrogen mass (RNM) of winter wheat, which was obtained under the optimal water condition (without any water or salinity stress) from the greenhouse experiments, was further verified and applied to optimize the parameters of the salinity stress reduction function (β), and simulate soil water dynamics under the salinity stress condition and in the field. Three saline water irrigation experiments, with winter wheat cultured in nutrient solution (Exp. 1), soil columns (Exp. 2) and field (Exp. 3) were conducted. The results of Exp. 1 showed that the daily transpiration of winter wheat decreased with increasing salinity, but was proportional to the RNM under the same salinity stress. The RWU rate distributions in Exps. 2 and 3 were estimated using an inverse method. The estimated RWU rate was also verified to be proportional to the RNM density under the optimal water condition. The verified linear relationship was then used to optimize the parameters of β, simulate the distributions of RWU rate and soil water content in the soil columns (Exp. 2) and field (Exp. 3). The simulated results matched the estimated RWU rates and the measured soil water contents well. In Exp. 2, the maximal absolute error (MAE), root mean squared error (RMSE) and absolute coefficient of residual mass (CRM) were not more than 0.0021, 0.0062 $cm^3\,cm^{-3}\,d^{-1}$ and 9.93% between the simulated and estimated RWU rates, and 0.007, 0.004 $cm^3\,cm^{-3}$ and 2.12% between the simulated and measured soil water contents, respectively. The relative errors between the calculated transpiration rates from the simulated RWU rate distributions and the measured values were less than 10%. In Exp. 3, the maximum MAE, RMSE and absolute CRM were 0.0012, 0.0007 $cm^3\,cm^{-3}\,d^{-1}$ and 5.81% for RWU rate, and 0.011, 0.010 $cm^3\,cm^{-3}$ and 3.51% for soil water content, respectively. The linear relationship between RWU and RNM of winter wheat should be reliable and rational. The optimization method should be applicable in optimizing the parameters of the salinity stress reduction function, establishing the RWU model and simulating soil water flow under the salinity stress condition in the soil–wheat system.

1. Introduction

Because of water resources shortage, the shallow ground water has to be used for irrigation in some arid and semi-arid regions (Shani and Dudley, 2001; Chauhan et al., 2008; Wan et al., 2010), in which the water is beneficial to the crop growth but the salt is usually harmful. The salinity stress restrains the crop root-water-uptake (RWU) and influences crop growth (Hansegawa et al., 2000; Munns, 2002). It is important to study and delineate the crop RWU function under salinity stress so as to simulate soil water flow in the soil–crop system and make reasonable saline water irrigation schedules.

The root system plays a vital role in crop water absorption (Feddes and Raats, 2004). Unfortunately, water uptake by plant roots is very complex and still incompletely understood. To avoid the difficulty in delineating the uptake function of roots, a few existing models such as HYDRUS, SWAP and ENVIRO-GRO, estimated the RWU distribution by apportioning the transpiration (i.e. the RWU from the whole root zone) throughout the root zone empirically (Pang and Letey, 1998; van Dam et al., 1997; Šimůnek et al., 2008; Jarvis, 2010). Obviously, whether the corresponding apportioning rules can reflect the mechanism of root uptake function still needs

Abbreviations: DAP, days after planting; RNM, root nitrogen mass; RWU, root-water-uptake.

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further research. To consider the effect of roots on the uptake function, a lot of RWU models (Feddes et al., 1978; Prasad, 1988; Musters and Bouten, 2000) were established explicitly or implicitly on the assumption that RWU is proportional to root length or surface area under the optimal water condition (without any water or salinity stress). However, many other researchers reported that younger roots (e.g., root tips, root hairs or fine roots) were much more active to extract water and nutrients than older roots (Gao et al., 1998; Pierret et al., 2005). The greenhouse experimental results by Shi and Zuo (2009) also showed that the RWU under the optimal water condition was not proportional to the root length density, but linearly related to the root nitrogen mass (RNM) density of winter wheat, whether for the whole root zone or for different soil layers. The relationship between RWU and RNM was applied to establish a RWU model, and simulate the soil water dynamics in the soil–wheat system successfully. Nevertheless, the relationship, which was obtained from the controllable greenhouse experiments, should be examined further through actual field experiments and under more complex conditions such as salinity stress and changing atmospheric conditions.

The effect of salinity stress on plant RWU is usually characterized with a salinity stress reduction function, which is related to the soil osmotic potential (Homaee et al., 2002a,b; Skaggs et al., 2006a,b; Xie et al., 2011). The parameters of the salinity stress reduction function are influenced by many factors, and cannot be measured directly up until now. They were often optimized through measuring the actual transpiration rate $T_a(t)$, in which t is the time, under salinity stress but with sufficient water supply; the potential transpiration rate $T_p(t)$ under the optimal water condition, in the absence of both water and salinity stress; and the average soil osmotic potential over the root zone $\overline{\varphi_o}(t)$ (Homaee et al., 2002a; Fujimaki et al., 2008). During the optimization process, the distributions of the actual RWU rate $S(z, t)$, in which z is the depth; the maximum RWU rate $S_{\max}(z, t)$ and the soil osmotic potential $\varphi_o(z, t)$ along the soil profile in the root zone were approximately integrated and represented by $T_a(t)$, $T_p(t)$, and $\overline{\varphi_o}(t)$, respectively. The optimization would be reliable if $\varphi_o(z, t)$ changed slightly along the soil profile in the root zone. Otherwise, the optimization would be irrational with significant errors. In fact, it would be very difficult for the distribution of $\varphi_o(z, t)$ to meet the requirement of slight change in practice. Therefore, it is still a necessary task to develop an effective and reasonable method to optimize the parameters of the salinity stress reduction function.

The objectives of this study were to investigate the relationship between the RWU and RNM of winter wheat in different culture mediums, and develop a method to optimize the parameters of the salinity stress reduction function directly using the distributions of $S(z, t)$, $S_{\max}(z, t)$ and $\varphi_o(z, t)$, not the values of $T_a(t)$, $T_p(t)$, and $\overline{\varphi_o}(t)$. Three saline water irrigation experiments with winter wheat growth in nutrient solution (Exp. 1), soil columns (Exp. 2) and field (Exp. 3), were conducted. Thereupon, the RWU model under salinity stress was established and used to simulate the soil water flow in the soil–wheat system under the condition of saline water irrigation.

2. Materials and methods

2.1. Soil water flow with RWU under salinity stress

Water flow in the soil–plant system is described by the Richards equation combined with a RWU sink term as follows (Wu et al., 1999; Nishida and Shiozawa, 2010):

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

$$h(z, 0) = h_0(z) \quad 0 \le z \le L \tag{2}$$

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

$$h(L, t) = h_L(t) \quad t > 0 \tag{4}$$

where h is the soil matric potential (cm); $C(h)$ is the soil water capacity (cm^{-1}); $K(h)$ is the soil hydraulic conductivity ($cm\,d^{-1}$); z is the vertical coordinate originating from the soil surface and positive downward (cm); t is the time (d); $h_0(z)$ is the initial soil matric potential distribution of the soil profile (cm); $E(t)$ is the soil surface evaporation rate ($cm\,d^{-1}$); L is the simulation depth (cm) and $L \ge L_r$, in which L_r is the rooting depth (cm); $h_L(t)$ is the matric potential at L (the lower boundary), (cm); and $S(z, t)$ is the RWU rate ($cm^3\,cm^{-3}\,d^{-1}$).

The RWU rate under water and salinity stresses is calculated by (van Dam et al., 1997; Šimůnek et al., 2008):

$$S(z, t) = \alpha(h)\beta(\varphi_o)S_{\max}(z, t) \tag{5}$$

where $\alpha(h)$ and $\beta(\varphi_o)$ are dimensionless water and salinity stress reduction functions, respectively; φ_o is the soil osmotic potential (cm); $S_{\max}(z, t)$ is the maximum RWU rate under the optimal water condition ($cm^3\,cm^{-3}\,d^{-1}$).

When RWU is related to the RNM, $S_{\max}(z, t)$ in Eq. (5) can be evaluated as (Shi and Zuo, 2009):

$$S_{\max}(z, t) = W_{NP}N_d(z, t) \tag{6}$$

where W_{NP} is the potential RWU coefficient per unit RNM ($cm^3\,mg^{-1}\,d^{-1}$), which is relevant to the atmospheric condition (Shi and Zuo, 2009); $N_d(z, t)$ is the RNM density ($mg\,cm^{-3}$), defined as the RNM per soil volume.

The salinity stress reduction function $\beta(\varphi_o)$ is used to describe the effect of salinity stress on plant RWU, and expressed in different forms such as linear and decreasing power functions (Homaee et al., 2002a,b; Dudley and Shani, 2003; Skaggs et al., 2006a,b; De Jong van Lier et al., 2009). In this study, a decreasing power function was chosen to delineate $\beta(\varphi_o)$ as follows (Skaggs et al., 2006b; Fujimaki et al., 2008):

$$\beta(\varphi_o) = \frac{1}{1 + (\varphi_o/\varphi_{o50})^p} \tag{7}$$

where φ_{o50} is the soil osmotic potential when the RWU rate $S(z, t)$ under the condition of sufficient water supply (viz. $\alpha(h) = 1$) decreases to the half of $S_{\max}(z, t)$ (cm); p is a shape parameter. Since plant salt tolerance is influenced by many factors such as plant, soil and solute (Maas and Hoffman, 1977), the parameters φ_{o50} and p in the salinity stress reduction function change greatly with different environments and should be determined according to the actual situation.

2.2. Optimization of the parameters of the salinity stress reduction function

Under the condition of sufficient water supply, $\alpha(h)$ in Eq. (5) is equal to 1, and integration of $S(z, t)$ and of $S_{\max}(z, t)$ over the root zone give, respectively, the actual transpiration rate $T_a(t)$ with salinity stress but no water stress, and the potential transpiration rate $T_p(t)$ for the optimal water condition with neither water nor salinity stress, viz.

$$T_a(t) = \int_0^{L_r} S(z, t)\,dz; \quad \text{and} \quad T_p(t) = \int_0^{L_r} S_{\max}(z, t)\,dz \tag{8}$$