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Effect of Crop Root on Soil Water Retentivity and Movement

Kozue Yuge[1*], Keiki Shigematsu[2], Mitsumasa Anan[3], Shinogi Yoshiyuki[1]

[1]Faculty of Agriculture, Kyushu University, Fukuoka, Japan; [2]Graduate School of Bioresource and Bioenvironment Science, Kyushu University, Fukuoka, Japan; [3]Takasaki Sogo Consultant Co., Ltd., Kurume, Japan.
Email: *yuge@bpes.kyushu-u.ac.jp

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ABSTRACT

The objective of this study was to clarify the effect of crop root on soil water retentivity and movement to improve the crop growth environment and irrigation efficiency. To simulate soil water movement considering the crop root effect on the physical properties of soil, a numerical model describing the soil water and heat transfers was introduced. Cultivation experiments were conducted to clarify the effect of the crop root on soil water retentivity and verify the accuracy of the numerical model. The relationship between soil water retentivity and the root content of soil samples was clarified by soil water retention curves. The soil water content displayed a high value with increasing crop root content in the high volumetric water content zone. The experimental results indicated that the saturated water content increased with the crop root content because of the porosity formed by the crop root. The differences of the soil water retentivity became smaller when the value of the matric potential was over pF 1.5. To verify the accuracy of the numerical model, an observation using acrylic slit pot was also conduced. The temporal and spatial changes of the volumetric water content and soil temperature were measured. Soil water and heat transfers, which considered the effect of the crop root on the soil water retentivity clarified by the soil water retention curves, were simulated. Simulated volumetric water content and temperature of soil agreed with observed data. This indicated that the numerical model used to simulate the soil water and heat transfer considering the crop root effect on soil water retentivity was satisfactory. Using this model, spatial and temporal changes of soil water content were simulated. The soil water condition of the root zone was relatively high compared with the initial conditions. This indicated that the volumetric water condition of the root zone increased with the soil water extraction and high soil water conditions was maintained because the soil water retentivity of root zone increased with the root effect.

Keywords: Water Consumption; Soil Water; Heat Transfer; Numerical Model; Irrigation Water Saving

1. Introduction

Irrigation scheduling is one of the most important factors for healthy breeding of crops. Quantification of water consumption is necessary for both adequate crop breeding and improved irrigation efficiency. Mechanism of water consumption and soil water movement is affected by crop roots because the soil structure and physical properties are changed by crop root physiological activities, including growth or water extraction. To quantify the water consumption in crop fields, the crop root effects on soil physical properties should be clarified.

Various researches have been conducted to clarify the biochemical and physical effects of soil on crop root growth. Drew (1975) [1] studied the adequate external concentrations of nitrogen and phosphorus required by root growth. Effects of various chemical materials of soil on crop root growth have been clarified [2-9]. Iijima *et al*. (1991) [10] determined the effects of soil compaction on the development of root system components of rice and maize. A combined root growth and water extraction model was introduced by Bengough (1997) [11]. Crop root cellular response to soil physical stress was evaluated by Bengough *et al*. (2006) [12]. Effects of the soil water content and bulk density on crop root development processes were investigated by Becel *et al*. (2012) [13].

Although the effects of soil biochemical and physical conditions on crop root growth have been extensively studied, the effects of the crop root on the physical properties and water consumption of soil have not been clarified.

Studies have been conducted to clarify soil water movement and quantify water consumption in the crop fields [14,15]. However, the crop root effect on the physical properties of soil was not considered in these

*Corresponding author.

studies, as a method to evaluate soil water movement considering the effect of the crop root on the soil physic properties has not been established.

The objective of this study is to clarify the effects of the crop root on soil water retentivity and soil water movement. A numerical model was introduced to simulate the soil water and heat transfer considering the crop root effect on soil water retentivity. Cultivation experiments were conducted to clarify the relationship between soil water retentivity and crop root content and to verify the accuracy of the numerical model.

2. Methodology

2.1. Governing Equations of Soil Water and Heat Transfer

To estimate the soil water transport considering the crop root effect on soil water retentivity and hydraulic conductivity, a numerical model was introduced. The governing equation describing soil water and heat transfers can be described as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D_w \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_w \frac{\partial \theta}{\partial z}\right) + \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_T \frac{\partial T}{\partial z}\right) + \frac{\partial K}{\partial x} + S \tag{1}$$

$$C_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + L\rho_l \left\{\frac{\partial}{\partial x}\left(D_{wv} \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_{wv} \frac{\partial \theta}{\partial z}\right)\right\} \tag{2}$$

where C_v is the volumetric heat capacity (J·m^{-3}·˚C^{-1}), D_θ is the isothermal water diffusivity (m^2·s^{-1}), $D_{\theta v}$ is the isothermal vapor diffusivity (m^2·s^{-1}), D_T is the thermal water diffusivity (m^2·s^{-1}·˚C^{-1}), K is the hydraulic conductivity (m·s^{-1}), L is the latent heat of water vaporization (J·kg^{-1}), S is the sink(m^3·m^{-3}·s^{-1}),T is the soil temperature (˚C), t is the time(s), λ is the thermal conductivity (W·m^{-1}·˚C^{-1}), ρ_l is the water density (kg·m^{-3}), and θ is the volumetric soil water content (m^3·m^{-3}).

2.2. Boundary Conditions

The energy budget on the soil surface at the crop field can be described as follows:

$$R_n = E + H + G \tag{3}$$

where R_n is the net radiation (W·m^{-2}), E is the latent heat flux (W·m^{-2}), H is the sensible heat flux (W·m^{-2}), and G is the ground heat flux (W·m^{-2}).

The net radiation R_n can be estimated using the following equation considering the shortwave and longwave radiation balance.

$$R_n = (1-\alpha) R_s + L_c + L_{\text{sky}} - L_{\text{soil}} \tag{4}$$

where R_s is the shortwave radiation on the soil surface (W·m^{-2}), L_c is the longwave radiation from the crop body (W·m^{-2}), L_{sky} is the longwave radiation from the sky (W·m^{-2}), and L_{soil} is the longwave radiation from the soil surface (W·m^{-2}).

The sensible heat flux and the latent heat flux on the soil surface can be estimated as follows

$$H = c_p \rho \frac{T_s - T_a}{r} \tag{5}$$

$$LE = \frac{c_p \rho}{\gamma} \frac{e_s - e_a}{r} \tag{6}$$

where T_s is the soil surface temperature (˚C), c_p is the specific heat of the air (J·kg^{-1}·˚C^{-1}), e_a is the air vapor pressure (hPa), e_s is the vapor pressure on the soil surface (hPa), r_a is the diffusion resistance (s·m^{-1}), α is the albedo, γ is the psychrometer constant (hPa·˚C^{-1}), and ρ_a is the air density (kg·m^{-3}).

The diffusion resistance can be calculated using the following equation (Chamberlain, 1968):

$$r_a = \frac{1}{\kappa u_*} \ln\left(\frac{z}{z_0}\right) + a\left(\frac{u_* \xi}{\nu}\right)^b \left(\frac{\nu}{D_v}\right)^c \tag{7}$$

where D_v is the molecular diffusion coefficient (m^2·s^{-1}), u_* is the friction velocity (m·s^{-1}), z is the height of the measurement of the wind velocity (m), z_0 is the roughness length (m), ξ is the effective soil surface roughness (m), and ν is the kinematic viscosity of air (m^2·s^{-1}). The constants a, b, and c are reported as 0.52, 0.45, and 0.8, respectively, by Chamberlain (1968) [16].

Using energy balance estimated by Equations (3)-(7), boundary conditions on the soil surface can be described as follows:

$$E = L\rho_w \left(-D_w \frac{\partial \theta}{\partial z} - D_T \frac{\partial T}{\partial z} - K\right) \tag{8}$$

$$G = -\lambda \frac{\partial T}{\partial z} - L\rho_w D_{wv} \frac{\partial \theta}{\partial z} \tag{9}$$

2.3. Model Structure

Figure 1 shows the numerical model describing water and heat transfers in the soil. To solve the two-dimensional transfers of water and heat, the finite-differential method was used. As the bottom boundary condition, the soil water potential was set as constant. The matric potential and hydraulic conductivity were set considering the root content for an interior node. The sink was set using the transpiration rate.

3. Cultivation Experiments

A cultivation experiment was conducted to evaluate the

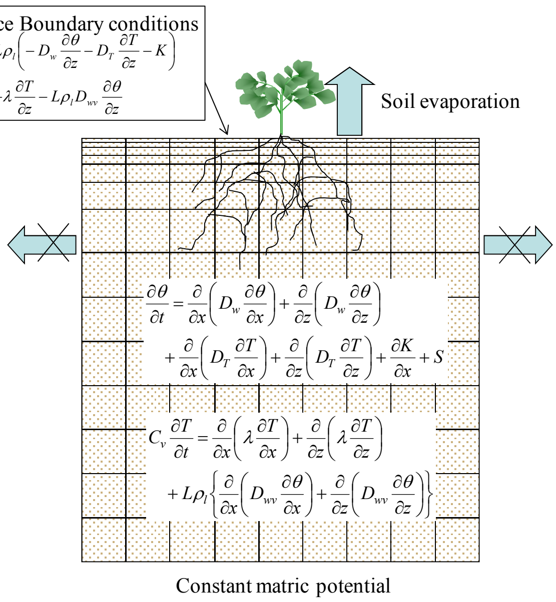

Figure 1. Schematic view of the numerical model describing the water and heat transfers in soil.

effect of the crop root on soil water retentivity. The soil containing the crop root was sampled. Soil moisture characteristic curves were estimated, and the volumetric root contents of soil samples were measured to clarify the relationship between the soil water retentivity and root contents.

To verify the numerical model accuracy, an observation using acrylic slit pot was also conduced. **Figure 2** shows the condition of the experiment. Broccoli was planted in the acrylic slit pot, at a size of 0.5 m × 0.6 m × 0.1 m. The ballasts were paved at the bottom of the acrylic slit pot, and the weathered granite soil was filled at a depth of 0.48 m. The volumetric water content and soil temperature were measured by soil moisture sensors (SM200, Delta-T) and thermo-couples at the depths shown in **Figure 3**. The solar radiations on the soil surface were measured by pyranometers (LI-200, LI-COR) to calculate the net radiation by Equation (4). In addition, the air temperature and humidity were measured to estimate the sensible and latent heat fluxes by Equations (5) and (6). The crop root content in 5 cm × 5 cm soil portion was measured by imaging analysis using the cross-sectional photograph taken from the front side of the acrylic slit pot.

4. Results and Discussion

4.1. Relationship between Soil Water Retentivity and Root Content

Figure 4 shows the relationship between the soil water retention curves and the crop root content in the soil sample. This figure indicates that the soil water retentive-

Figure 2. Condition of the cultivation experiment to verify model accuracy.

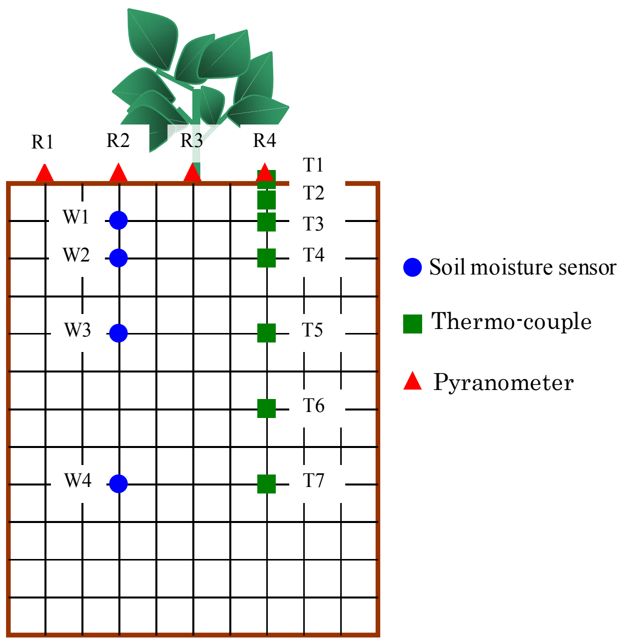

Figure 3. Schematic view of the observation.

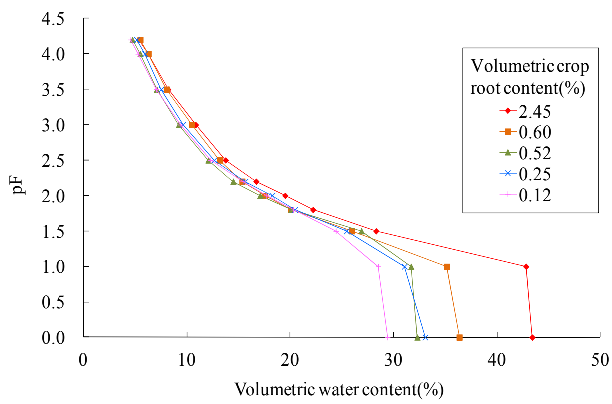

Figure 4. Relationship between the soil water retention curves and crop root content.

ity varied with the root content of the soil sample. In the high volumetric water content zone, the soil water content showed a high value with increasing root content. The experimental results indicate that the saturated water content increased with the crop root content because of the porosity generated by the crop root. The differences of the soil water retentivity became smaller when the matric potential was over pF 1.5.

4.2. Model Accuracy

Using the numerical model described in **Figure 1**, the soil water movement was estimated. **Figure 5** shows the distribution of root content measured by the cultivation experiment. Using these data, the matric potential for interior nodes was given using the soil water retention curves considering the root content in the simulation procedure.

Figure 6 shows the comparison of simulated and observed volumetric water contents at depths of 5 cm and 20 cm. Simulated values agree with the observed data. As the soil moisture movement was minimal in this period, the model accuracy was also verified using soil temperature. **Figure 7** shows the simulated and observed soil temperature at depths of 0 cm and 5 cm. The tendency of the simulated soil temperature were consistent with the observed data. This indicates that the numerical model to simulate the soil water and heat transfer considering the crop effect on soil water retentivity is satisfactory.

4.3. Spatial Distribution and Temporal Change of Volumetric Water Content

Using the numerical model, temporal and spatial changes of soil water condition were estimated. **Figure 8** shows the spatial distribution of volumetric water content of soil

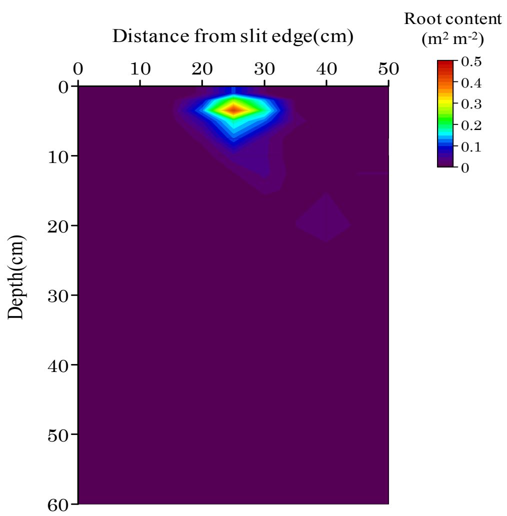

Figure 5. Spatial distribution of the crop root content.

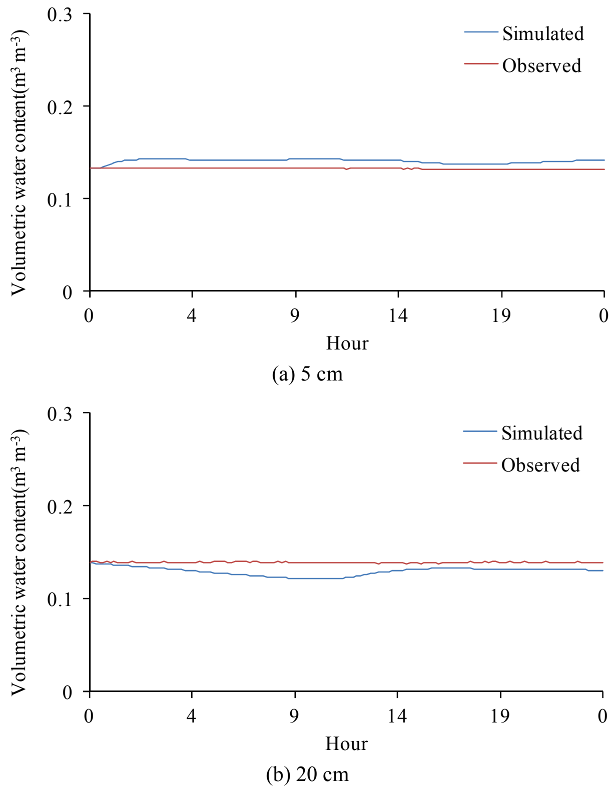

Figure 6. Comparison of simulated and observed volumetric water contents.

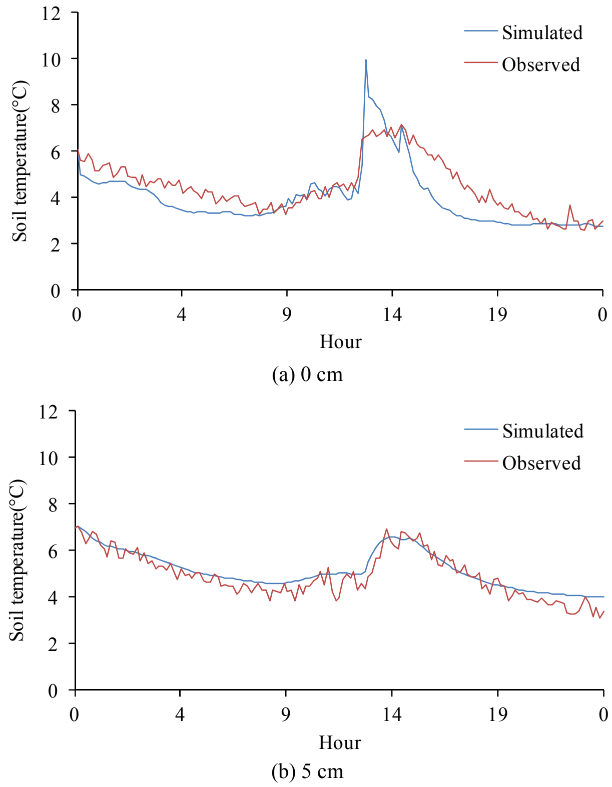

Figure 7. Comparison of simulated and observed soil temperature.

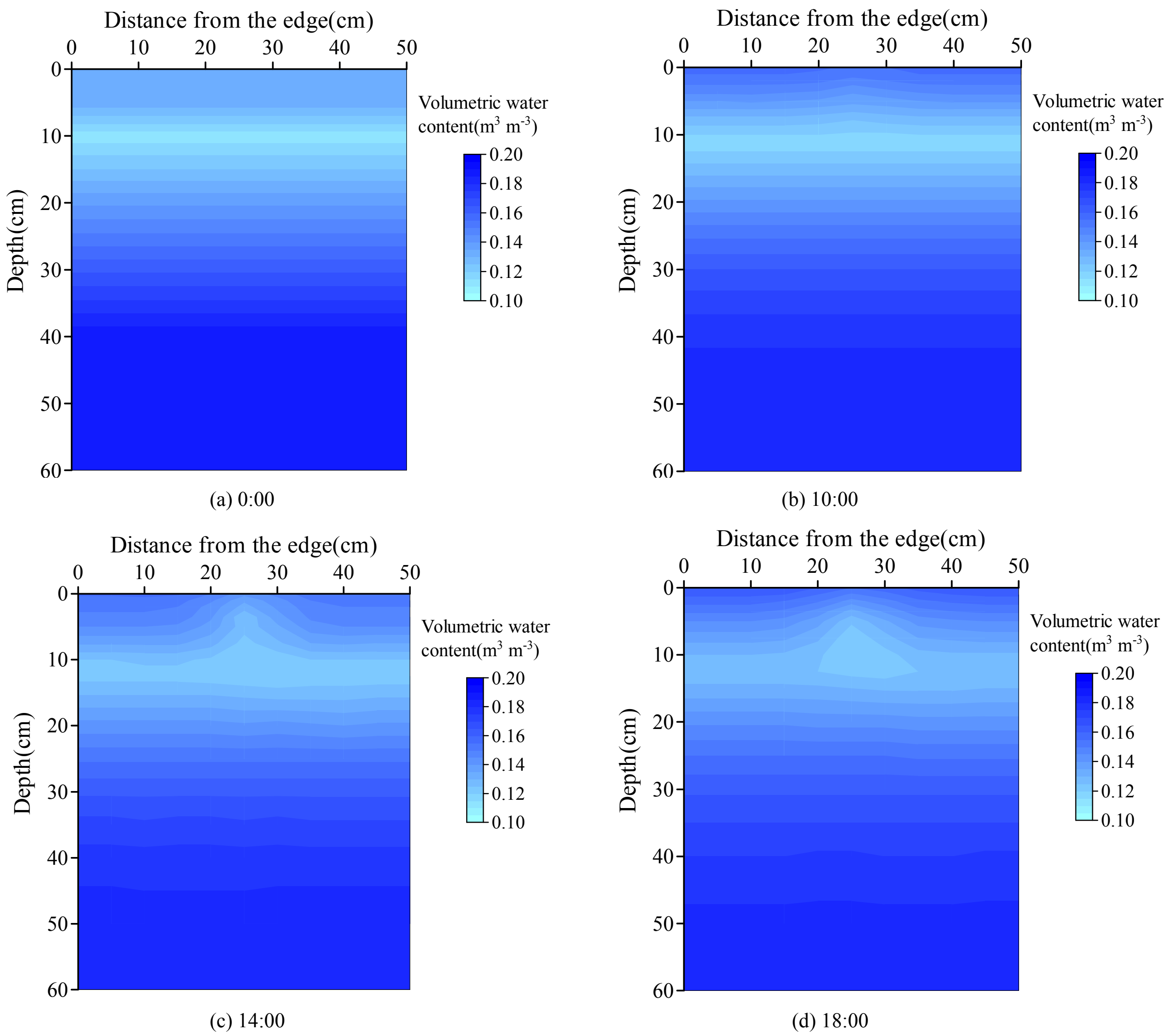

Figure 8. Comparison of simulated and observed soil temperature(continued).

every four hours. The distribution of the volumetric water content around root zone changed from 10 a.m. because of the soil water extraction by the crop root. The soil water condition of root zone was relatively high compared with the initial condition shown in **Figure 8(a)**. This result indicates that the volumetric water condition of root zone increased with the soil water extraction, and high soil water condition was maintained because the soil water retentivity of root zone increased with the root content.

5. Conclusion

To simulate soil water movement considering the crop root effect on soil water retentivity, a numerical model describing soil water and heat transfers was introduced. Cultivation experiments were conducted to clarify the effect of crop roots on soil water retentivity and to verify the accuracy of the numerical model. The relationship between soil water retentivity and root content was clarified by soil water retention curves. The soil water content was directly related to root content in the high volumetric water content zone. The differences in soil water retentivity decreased when the matric potential was over pF 1.5. Simulated volumetric water content and temperature of soil agreed with observed data. Using this model, spatial and temporal changes of soil water content were simulated. The soil water condition of the root zone was relatively high compared with initial conditions. This result indicates that the volumetric water condition of the root zone increased with soil water extraction, and high soil water condition was maintained because the soil water retentivity of root zone increased with the root content. The method introduced here is effective to estimate more accurately water consumption in crop fields. Considering the crop root effect on soil water conditions will allow scientists and farmers to correctly irrigate for crop growth and save irrigation water.

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