

TRANSIENT WATER FLOW MODEL IN A SOIL-PLANT SYSTEM FOR SUBSURFACE PRECISION IRRIGATION

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ABSTRACT

The spatial and temporal variability of plant-water characteristics in the soil is still unclear due to the limitation of measuring method. This limits the attempt to model the soil-plant-atmosphere system with this factor. Understanding the non-steady water flow along the soil-plant component is essential to understand their variability. An experimental set-up was designed to collect the data needed to develop more realistic and dynamic model, incorporating the dynamic water flow. The set-up was built using a modified subsurface irrigation system that allows the determination of soil water content for irrigation. The plant-water responses were measured for their evapotranspiration activity based on water usage, mass change, soil water potential and soil moisture content. The data has shown the real dynamic of the plant-water relation such as time lag between the water uptake by root and the water loss from evapotranspiration. It has also shown the water storage capacity of the soil-plant and the charge and discharge of the internal water reservoirs. A dynamic model for the transient water flow in the soil-plant system was developed based on the analogy of resistance-capacitance relations from the modified subsurface irrigation system. The result has shown the significant of the proposed method to model the water flow in a soil-plant system.

Keywords: Spatial-temporal variability, Soil-plant system, SPAC model, Evapotranspiration, Water uptake, Subsurface irrigation, Precision irrigation.

INTRODUCTION

Water uptake by plant largely influences the transport of water in the soil-plant system. The process has critical effect on crop yield thus irrigation play a very important role for high quality yield. The concern of water shortage for industry

and daily life has also affected agricultural sector. Thus water saving management is a key technology for precision irrigation (Smith and Baillie, 2009). This was the motivation for our project to develop a site-specific irrigation system to meet the water demand for plant growth by applying precise control.

A successful irrigation practice requires comprehensive understanding of the dynamic water flow in the soil-plant-atmosphere continuum (SPAC) system. Progresses have been made for irrigation management based on SPAC model that generalized the spatial and temporal variability of individual plant water requirement (James, 1988 and Camp, 1998). In new measurement paradigm of plant-based water sensing (Jones, 2004), the measurement of the plant water requirement can be made to individual plant in real time. This approach can be used to incorporate the variability of water requirement for individual plant into the model.

Our project has been developed for a plant-based water-sensing system which enables the measurement of dynamic water flow by using a modified subsurface irrigation system (Ohaba et. al, 2010 and M.Shukri et. al, 2011). The modified subsurface irrigation system is a plant-based water sensing and self irrigation system. It combines the irrigation system and a measuring device for water need by plant which allows the real time measurement of spatial and temporal variability of the soil-plant water need.

This paper investigates the attempt to develop a transient water flow model for the soil-plant system using the modified subsurface irrigation system. The approach is based on empirical model (Van Pee, 1999) and the result is validated with real data to conform the significant of the proposed method.

MATERIALS AND METHODS

The soil-plant system model

The physical system used to describe the water flow in the soil-plant system for the modified subsurface irrigation is shown in Fig. 1(a). Water flow in soil-plant system is based on water potential gradient (Slatyer, 1967). In the system, the driving force of evapotranspiration is the pressure gradient between leaf and atmosphere. The evapotranspiration demand is known as potential evapotranspiration ET_O and can be estimated by FAO Penman-Monteith equation (Allen, 1998). The potential gradient causes root water uptake from the soil. Water uptake Q and crop evapotranspiration ET_C is based on simplified soil water balance model (Yuan et al. 2001). The experimental setup is designed to allow precipitation and irrigation only from the subsurface irrigation system while the drainage and percolation is negligible.

The analogy model for the physical system is shown in Fig. 1(b). For the model, the soil-plant system consist of a single pathway of constant hydraulic conductivity of plant R_p and soil R_s associated with discharge and recharge of the plant tissue C_p and soil capacitance C_s (Philips et. al, 1997). The hydraulic conductivity of the fibrous interface is represented by $R_{\Delta h}$. The potential gradient of plant canopy Ψ_C and soil Ψ_S defined by the potential evapotranspiration ET_O is the climatic input to the system. The potential gradient of soil Ψ_S and water in the reservoir Ψ_W defined by Δh is the soil potential input to the system. The soil-plant

response from the crop evapotranspiration ET_C is defined as the output of the system. The proposed model is shown in Eq. (1)

$$G(s) = \frac{As + B}{Cs^2 + Ds + 1} \quad (1)$$

where, $A=R_{sh}C_sR_p$, $B=R_{sh}+R_p$, $C=R_{sh}C_sR_pC_p$ and $D=R_{sh}C_p + R_{sh}C_s + R_pC_p$. In the equation, $R_{sh}=R_s+R_{\Delta h}$. Derived variables are the combination of the resistive and capacitive elements in the network. From the analogy model, the plant-water need is indicated by the water uptake Q .

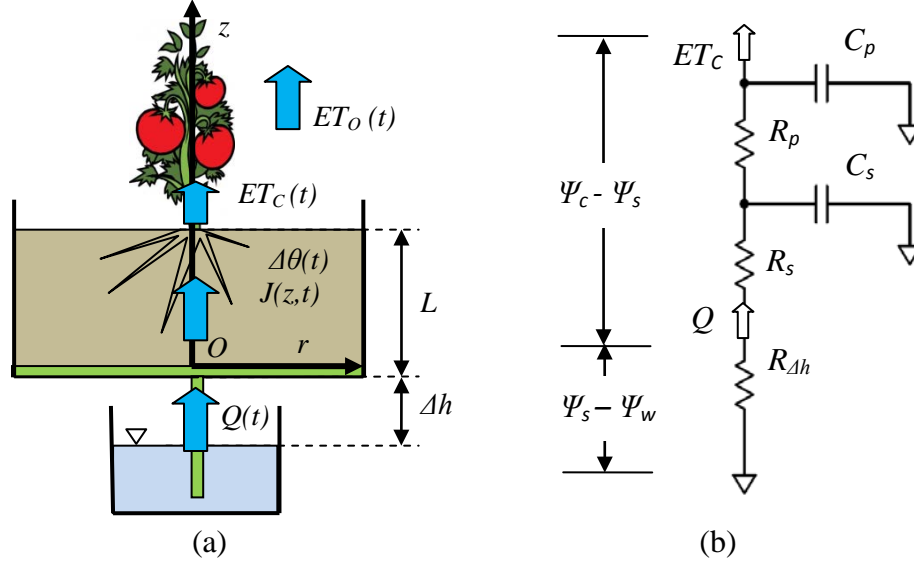


Fig. 1. The physical system (a) and analogy model (b) for the modified subsurface irrigation system.

For simplicity the model is determined by using ARX model (Ljung, 1987) as in Eq. (2)

$$A(q) y(t) = B(q) u(t - nk) + e(t) \quad (2)$$

where $A(q) = 1 + a_1q^{-1} + \dots + a_{na}q^{-na}$, $B(q) = b_1q^{-1} + \dots + b_{nb}q^{-nb+1}$. a_i , b_j are model parameters, $u(t)$, $y(t)$ are input and output signal respectively at time t and $e(t)$ is disturbance. Step input method is used to estimate the parameters (Boonen et. al, 2000). The developed model is evaluated by comparing the model response of crop evaporation with the measured crop evapotranspiration. This is quantified by using the coefficient of determination r^2 as in Eq. (3)

$$r^2 = \frac{\sum_{k=1}^N [y(k) - y_{sim}(k)]^2}{\sum_{k=1}^N [y(k) - y_{mean}]^2} \quad (3)$$

where N number of sample, $y(k)$ measured output at time k , $y_{sim}(k)$ simulated output at time k and y_{mean} mean value of y for N sample. Second-order ARX model was used in the experiment to represent the model in Eq. (1).

Experimental Setup and Procedure

Figure 2 shows the actual experimental setup. A modified subsurface irrigation system was built for a plant pot containing compost soil (1) (Masaki, RF-7). A small reservoir (2) is positioned under the pot and water rises up to a horizontal fibrous interface (3) (Toyobo 7210s) through a fibrous string (4) (Toyobo A-1). Infiltration of water to the soil above the fibrous interface is achieved by capillary rise. The soil water content was determined by setting a suitable water height Δh (5) using an adjustable platform (6) below a level regulator water tank (7). The water height was set at 0 cm throughout the experiment for maximum water uptake. The pot, with a horizontal fibrous interface of 20 cm in diameter was used. The compost soil in the pot was well mixed and the packing bulk density was 0.40 g/cm^3 . A tomato was transplanted into the pot and used as the test plant. Nutrient was supplied through mixture of liquid fertilizer of 5-5-5 (Hyponex) into the water supply tank (12) with ratio of 1:1000.

The plant was grown in a phytotron for 30 days. The phytotron uses glass roof and walls to allow entry of direct sunlight. The air humidity in the phytotron was set at 70% and the air temperature was set at 25°C from 06:00 to 18:00 and 15°C from 18:00 to 06:00. The phytotron is located at the Faculty of Agriculture, Tokyo University of Agriculture and Technology in Fuchu, Tokyo. The experiment was conducted from January to February, 2012. At day 31 after transplant, the pot was transferred to a growth chamber for the step input experiment.

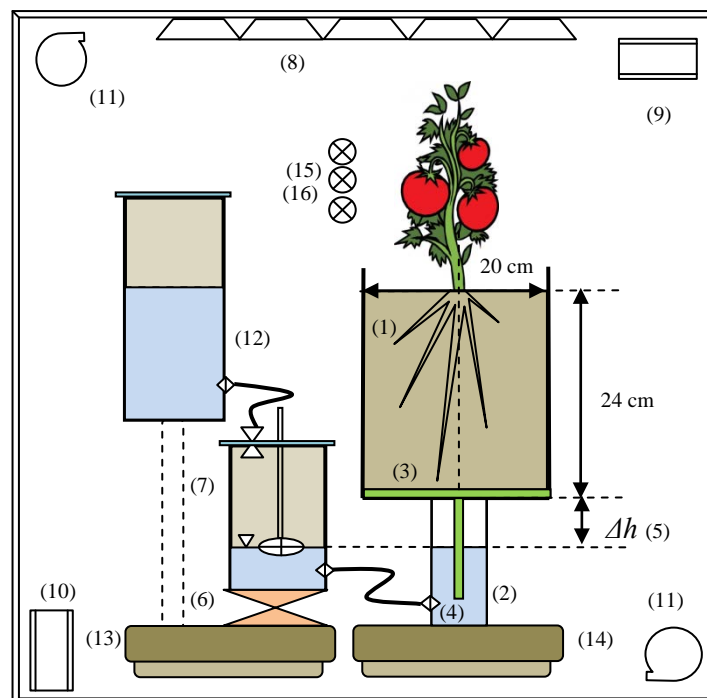


Fig. 2. The experimental setup for the modified subsurface irrigation system in the growth chamber.

The step experiment was conducted in the growth chamber (NK-System, KCLP-1500LED-NCS) with dimension of 1512 mm height, 1200 mm width and 800 mm length. The chamber uses florescent lamp (8) for artificial lighting, an air conditioner (9) and a humidifier (10) for the air temperature-humidity system. The air inside the chamber was circulated by centrifugal fans (11). The air temperature and humidity was set at 25°C and 70% respectively throughout the experiment. The water used by the soil and plant was determined from the change in water mass in the water supply tank. The mass change was measured with an electronic balance (13) (AND, GP32KS) and denoted as “water uptake”. A second electronic balance (14) was used to measure the mass of the potted soil-plant. The mass change indicated the evapotranspiration rate and denoted as “crop evapotranspiration”. The micro-climate parameters inside the growth chamber were measured using an air temperature-humidity sensor (15) (Vaisala, HMP155) and a solar radiation sensor (16) (Li Cor, LI-190). A data logger system (Graphtech, GL820), was used to measure data from the sensors and the sampling time was 1 minute. The step input was made by increasing the radiation level from 0 to 400 $\mu\text{molm}^{-2}\text{s}^{-1}$.

RESULT AND DISCUSSION

Figure 3 shows the result of crop evapotranspiration ET_C from the step input of radiation. It is indicated that the ET_C has an under-damped second order system response which is expected from the model proposed in Fig. 1(b). The increase of radiation causes the stomata to open and release high water vapour into the air. The release of water vapour increases the potential gradient between leaf and atmosphere thus increases the water flow in the soil-plant system (Larcher, 1997). The discharge and recharge of water capacitance in the soil-plant system during the step response is shown by overshoot and damped frequency of the ET_C data. The radiation and the ET_C data are used to estimate the model parameters and the result is shown in Table 1. The simulated output of crop evapotranspiration from the model is shown in Fig. 3.

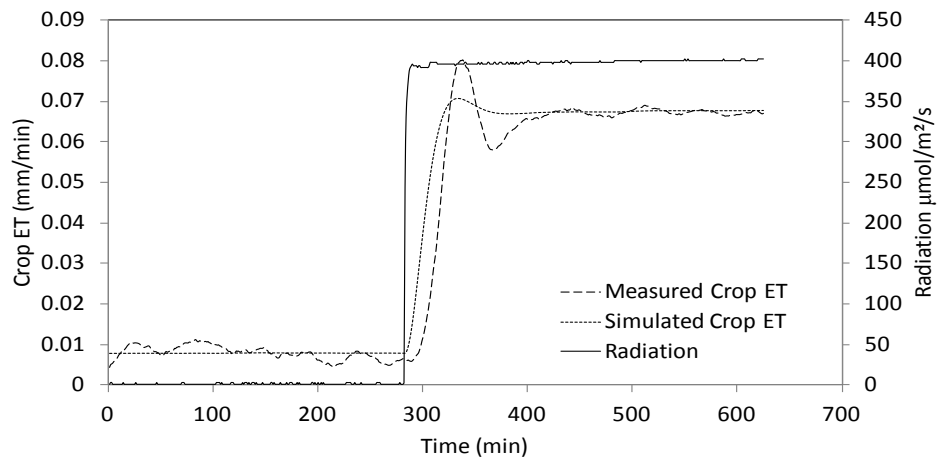


Fig. 3. Measured and simulated crop evapotranspiration response from the step input of radiation.

Table 1. Estimated ARX model for crop evapotranspiration from the radiation step input.

a_1	a_2	b_1	b_2	r^2
-1.889	0.8956	1.044×10^{-6}	-5.601×10^{-8}	0.95

Figure 4 shows the response of water uptake based on the step input radiation. The result indicated that the water uptake has similar response to over-damped second order system. The response is caused by the increase of ET_C when the radiation step started. During high ET_C , water uptake is mainly caused by the demand from plant evapotranspiration which is supplied by the subsurface irrigation system. This can be observed from the water uptake level at 0.065 mm/min which is similar to the ET_C level shown in Fig. 3 during the step response. Small water uptake at 0.02 mm/min is observed before the radiation step. This is caused by the upward water flow into the soil by the potential gradient in the soil. Based on the radiation and water uptake data the model parameters is estimated and the result is shown in Table 2. The simulated output of the water uptake model is shown in Fig. 4.

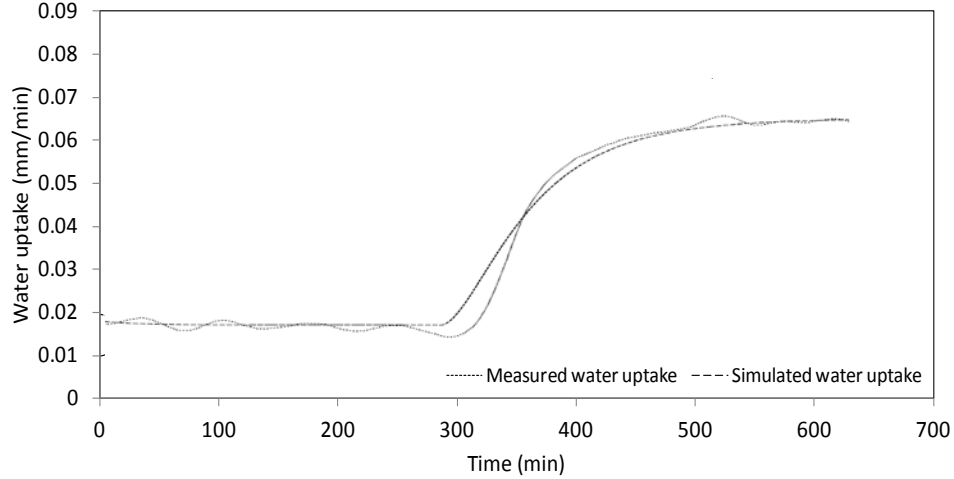


Fig. 4. Measured and simulated water uptake response from the step input of radiation.

Table 2. Estimated ARX model for water uptake from the radiation step input.

a_1	a_2	b_1	b_2	r^2
-1.923	0.9237	1.877×10^{-7}	-5.853×10^{-8}	0.89

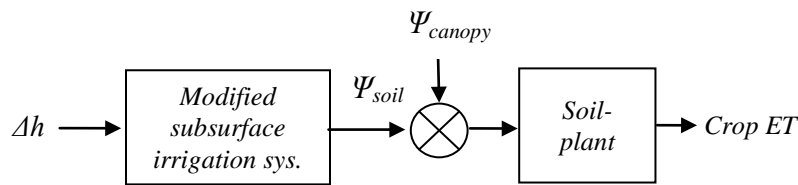


Fig. 5. Block diagram of the soil-plant and the irrigation system.

The parameters identified in Tables 1 and 2, represent the soil-plant characteristic which assumed constant during the experiment. However these parameters vary over time and directly related the soil-plant status such as hydraulic conductivity and water capacitance in the soil-plant system. Variations of these parameters during growth period may provide early status of physiological change and plant water stress (Larcher, 1997). The relationship of the soil-plant model and the modified subsurface irrigation system is shown in Fig. 5. In this experiment the soil water potential is kept constant by selecting the water height Δh to 0 cm and the radiation step is used as input to model the response of the soil-plant system.

CONCLUSION

The study has shown the significant of the modified subsurface irrigation system for understanding the variability of water flow in the soil-plant system. The result has shown the dynamics response of water flow in the soil-plant system from a continuous subsurface irrigation supply. The proposed model of analogy network based on resistance and capacitance has been proven to have similar characteristic with water flow in the soil-plant system which has a second order system response. The parameters estimated base on the proposed model is directly related to the soil-plant characteristic and condition which is very useful for our water saving irrigation management for precision irrigation. In future we will focus on understanding the variability in soil-plant characteristic based on the identified parameters in order to include the soil-plant variability factor into the model.

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