Determination of irrigation depths using a numerical model and quantitative weather forecast

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Abstract
A method of determination of irrigation depth using a numerical model of crop response to irrigation and weather forecast was presented. To optimize each irrigation depth, a concept of virtual income, which is proportional to an increment in transpiration amount during an irrigation interval, is introduced. A numerical model that simulates water, solute, and heat transport and crop response is used in a numerical experiment. Results indicated that the optimized irrigation depth can be smaller than the value which attains maximum yield.

Key Words
Irrigation, weather forecast, transpiration, net return

Introduction
Soaring food price and intensified scarcity of water resources bring a new emphasis on efficient use of water in irrigation. The determination of irrigation depth has still widely relied on experience (i.e. fixed amount) or intuition of farmers even in industrialized countries. Such conventional irrigation may cause yield reduction or waste water. To precisely meet crop water requirements and respond to water/salinity stresses quickly, automatic irrigation systems using sensors have been developed. Such "water stat" systems, however, require high initial investment and have difficulty in adjusting irrigation depth to weather forecasts. For example, it is obviously wasteful to apply a full irrigation when rain is forecast on next day. "Water stat" systems may nevertheless do this if currently monitored value reaches its threshold value. Expensive monitoring using sensors can be altered by numerical simulation of water, solute, and heat transport in soil and crop response to them. High-spec personal computers are getting affordable even for farmers in developing countries. Not only monitoring current status, a numerical model can predict near future conditions. Numerical prediction requires knowledge of atmospheric boundary condition: quantitative weather forecast. Today, freely accessible quantitative weather forecasts, whose accuracy is improving, have been provided on the web (e.g. wetherunderground.com). These progresses have enabled the optimization of irrigation depths using quantitative weather forecast as input data for numerical models such that net return is maximized. This paper presents a procedure for the determination of irrigation depths using quantitative weather forecast. We also demonstrate its effectiveness with a numerical experiment.

Methods
Maximization of virtual net return
Like other inputs such as labour or fertilizer, the purpose of irrigation is not necessarily to obtain the highest yields, nor even water use efficiency, but to maximize the net returns. Timing of irrigation is generally restricted to social factors such as rotation or availability of labour. In contrast, irrigators have more discretion with regard to the amount of irrigation. Thus, we focus on the optimization of the amount.
If we can calculate net return until the next irrigation, the irrigation depth can be optimized such that net return is maximized. Although in reality income is realized when harvest is sold, we assume that a farmer can obtain virtual income, which is proportional to an increment of dry matter attained during an interval. Also, water must be priced high enough to give irrigators incentive to save water. Net return, N_r (\$ a^{-1}), during a period is then defined as:

$$N_r = P_c \varepsilon \tau - P_w W - C_{ot} \quad (1)$$

where P_c is the price of crop (\$ /kgDM), ε is water use efficiency of the crop, τ is cumulative transpiration (1 cm =10^7 kg/ha), P_w is the price of water (\$ /kg), W: irrigation depth (kg/ha), and C_{ot} is the other costs (\$ ha^{-1}). The amount of valuable part (fruit, grain etc.) of the crop is assumed to be proportional to dry matter production, which is well known to be approximately proportional to cumulative transpiration. Under given conditions, N_r is thus a function of W. The problem is thus a simple one-dimensional search.

To estimate transpiration amount, τ, which dynamically responds to matric and osmotic potential in soil and therefore, irrigation, a sophisticated model of the response of crop to irrigation is required. Numerical models developed in the realm of soil physics can be such ones.

Procedure

First, using the records of climatic condition, numerical simulation is performed to estimate the current status. Then, download quantitative weather forecast as input data and repeat simulations changing irrigation depth until maximum anticipated N_r is obtained. Then perform irrigation. On the early morning of the next irrigation day, current status is estimated by simulation using the actual records of irrigation depth and climatic condition from the last irrigation until the moment. This cycle continues until the last irrigation.

Numerical model

Algorithm and user interface described above was incorporated into a numerical model, WASH_1D, which solves governing equations for one-dimensional movement of water, solute and heat in soils with the finite difference method. The one-dimensional maximization was implemented with the golden section method with searching range 0 to 10cm. Governing equation of water flow is Richards equation including water vapor movement. Solute and heat transport are described with the convection-dispersion equation. It can be applied to layered soil, and consider thermal vapor diffusion and hysteresis.

Root water uptake and crop growth sub-models

A widely used macrospopic root water uptake (RWU) model (Feddes and Raats 2004) was used in calculating root water uptake and transpiration rate, T(cm/s) . The crop growth model describes the growth of the each plant part as a function of cumulative transpiration amount. In WASH_1D, root activity distribution, β(/cm), is given as

$$\beta = (b + 1)d_{rt}^{-b-1}(d_{rt} - z)^b \tag{2}$$

where b is plant-specific parameter, d_{rt} is the depth of lower boundary of the root zone(cm), and z is the depth(cm). The d_{rt} is described as a function of cumulative transpiration amount, ΣT(cm):

$$d_{rt} = a_{drt}[1 - \exp(b_{drt}\Sigma T)] + c_{drt} \tag{3}$$

where a_{drt}, b_{drt} , and c_{drt} are plant-specific parameters.

Leaf area index, I, which affects both radiation and wind, is also handled as a function of ΣT.

$$I = a_{LAI}[1 - \exp(b_{LAI}\,\Sigma\mathrm{T})] \tag{4}$$

where a_{LAI}, and b_{LAI} are plant-specific parameters.

The potential transpiration rate, T_p, which is used in the RWU model, is given by multiplying potential evapotranspiration, E_p(cm/s), from Penman equation by crop coefficient, K_c:

$$T_p = E_p\,K_c \tag{5}$$

The K_c is also assumed to be a function of □T.

$$K_c = a_{kc}[1 - \exp(b_{kc}\Sigma\mathrm{T})] + c_{kc} \tag{6}$$

where a_{kc}, b_{kc} , and c_{kc} are plant-specific parameters.

The evaporation rate is calculated with the bulk transfer equation (Daamen and Simmonds 1996; Noborio *et al.* 1996; Yakirevich *et al.* 1997):

$$E = \frac{\rho^*_{vs} h_{rs} - \rho^*_{va} h_{ra}}{r_a} \tag{7}$$

where ρ_v^* is the saturated water vapor density (g cm^{-3}), h_r is the relative humidity, r_a is the aerodynamic resistance (s /cm), and where the subscripts s and a denote the soil surface and air at the reference height, respectively. Since ρ_{vs}^* is a function of surface temperature, heat movement also must be analysed. The main energy input, solar radiation, is absorbed and reflected by leaves. Such attenuation is commonly described as (e.g. Campbell 1985)

$$R_s = R_{s0}\exp(-a_{rs}\,I) \tag{8}$$

where R_{s0} is R_s(W m^{-2}) above canopy and a_{rs} is plant-specific parameter. As crops grow, r_a is increased as leaves restrict water vapor transport. Such an additional resistance is expressed as a function of leaf area index, I:

$$r_a = r_{a0}(1 + a_{ra}I) \tag{9}$$

where r_{a0} is r_a from bare soil surface, and a_{ra} is plant-specific parameter.

Numerical experiment of the proposed procedure

A numerical experiment was performed from August 7 to October 26, 2009. We assumed the experiment using upland rice, Toyohatamochi, in Tsukuba, Japan. Irrigation interval was two days. The records of climatic condition were downloaded from the website of Japan Meteorological Agency (www.kishou.go.jp/) and quantitative weather forecasts were downloaded from the website of Yahoo! JAPAN (www.yahoo.co.jp).

Soil properties of Tottori sand were used in the simulation. Lower boundary was set at the depth of 40cm. Initial cumulative transpiration amount and initial pressure head were set at 1.4cm and -5cm, respectively. Pressure head at the bottom and temperature at the lower boundary were assumed to be constant at -30cm and 23 ^{o}C, respectively. Supposed parameter values in the net return equation are listed in Table 1. Irrigation was started 9:00 of August 9 at an intensity of 5 cm/h.

Table 1. Assumed parameter values in the net return equation.

Parameter	Value	Unit
P_c	0.33	$ /kg
P_w	0.0001	$ /kg
E	0.001	
C_{ot}	0	$

Numerical experiment of an automatic irrigation system

Experimental period and condition were same as the experiment of the proposed procedure. The records of climatic condition from August 7 to October 26 were downloaded, and numerical simulation was performed to estimate the change of status and when irrigation was occurred. The automatic irrigation system was set to apply irrigated 5cm water when volumetric water content at the depth of 5cm was lower than 0.02.

Results

Table 2 shows the cumulative irrigation depth, transpiration amount and net income of the proposed procedure and automatic irrigation system. Automatic irrigation system irrigated more water than the proposed procedure and cumulative transpiration amount of automatic irrigation system was more than that of the proposed procedure. However, net return of automatic irrigation system was less than that of the other because of the greater irrigation cost.

Table 2. Cumulative irrigation depth, transpiration amount and net income of the proposed procedure and automatic irrigation system.

	Irrigation depth (cm)	Transpiration amount (cm)	Net return ($/a)
The proposed procedure	34.6	39.9	9.7
Automatic irrigation system	63.9	45.2	8.5

Figure 1 shows the temporal change of soil water content at the depth of 5 cm for the proposed procedure and automatic irrigation system. On September 29, automatic irrigation system applied 2 cm while the proposed procedure applied far less because of the climatic condition on next two days and volumetric water content of automatic irrigation system was higher than that of the proposed procedure after the irrigation.

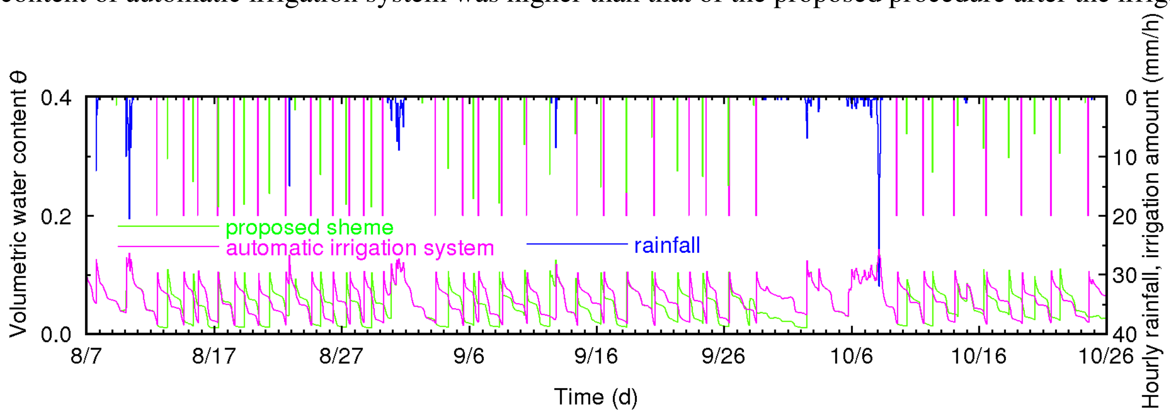

Figure 1. Temporal change of soil water content at a depth of 5cm of the proposed procedure and automatic irrigation system.

Figure 2 displays the temporal change of net return of the proposed procedure and automatic irrigation system. When rainy or non-rainy days continued, difference in net return was small.

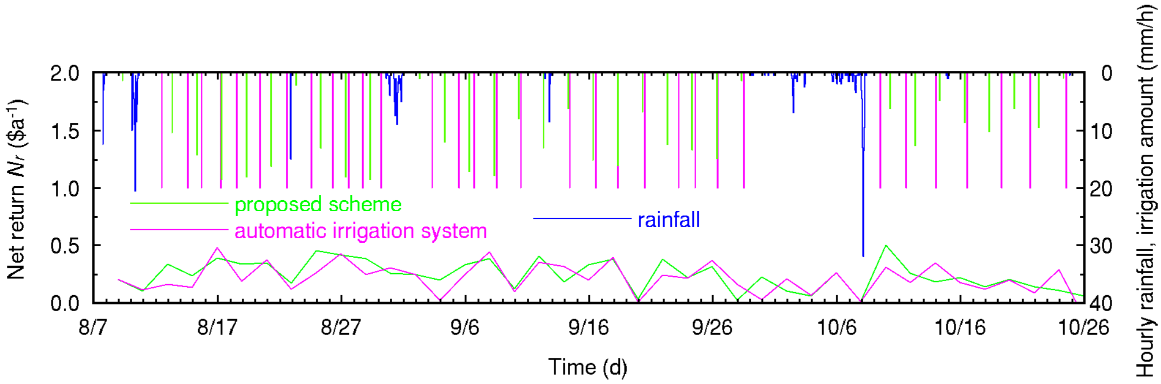

Figure 2. Temporal change of net return of the proposed procedure and automatic irrigation system.

Figure 3 shows net return and cumulative transpiration over 48h hours from 0:00 on September 28 as a function of irrigation depth, *W*. Plots interpolated with spline curves were the trajectory of optimization, and points are realized values determined by the actual climatic condition. Predicted N_r and ΣT increased with *W*, with diminishing gradients, and N_r reached to the peak at $W = 0.15$ cm, beyond which the N_r decreased with *W*. Note that maximum cumulative transpiration (i.e. yield) is achieved at larger irrigation depth. According to the actual value, irrigation depth of automatic irrigation system was larger than that of the proposed procedure while the difference in transpiration amount between the two was small. As a result, net income of the proposed procedure was higher than that of the other. In addition, the differences in both net return and cumulative transpiration between optimization and actual values were small during the period.

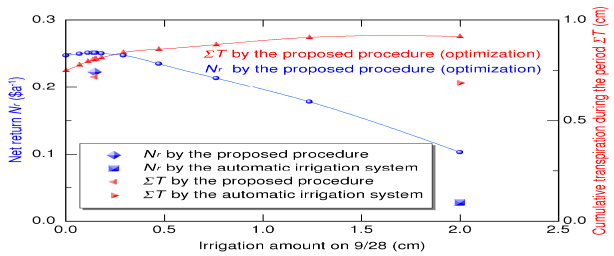

Figure 3. Net return and cumulative transpiration from September 28 to 29 as a function of irrigation depth.

Conclusion

In this study, a method of determination of irrigation depth using a numerical model of crop response to irrigation and weather forecast was outlined. The numerical experiment showed encouraging results. Still, some of the employed plant specific parameter values were hypothetical. We are performing an experiment to determine these parameter values and test the effectiveness of this method by comparing with an automatic irrigation system.

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