A MODIFIED WATER MODEL TO CONTROL THE IRRIGATION SUPPLY IN SOILLESS SYSTEMS

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ABSTRACT

This paper presents the implementation, calibration and validation of a water model that can be used both for simulation and prediction purposes within a control strategy aimed at determining the ideal irrigation schedule (quantity and frequency) for crop growth in greenhouse using rockwool substrate. One of the main advantages of the model is that model-based irrigation can be performed using online measurements obtained from a relative water content in the substrate sensor as feedback signals, instead of irrigating only using the users' experience or other kind of (expensive) sensors like lisymeters.

INTRODUCTION

Water management is an essential task in soilless systems to supply adequate quantities without affecting yield but reducing lixiviates emitted to the environment. Furthermore, the fresh fruit horticultural products are constituted by high levels of water content, ascending to more than 90% of the weight of the ripe tomato fruits (Ho et al., 1987), which need to complete quality characteristics for the market. There are two main approaches in order to manage water supply: 1) to use physical or mathematical models relating the plant with its environment, or 2) to use measurements obtained with electronic transducers, such as stem "sap flow" devices or machine vision (Giacomelli, 1994). Typical models have been applied within the field of water supply in sand (Heinen, 1997), nutrient film systems (Hamer, 1998; Gieling, 2001), or rockwool medium (Heinen *et al*., 2002). In (Sigrimis *et al*, 2001), a hybrid approach is applied, where a simplified crop transpiration model is used to predict the necessary supply of water. At the same time, drain water flow from the crop is measured using an appropriate flow sensor. Using the error between drain measurement and the model estimate, the coefficients of the model are adapted iteratively. These models can be useful to obtain crop irrigation patterns indicating optimum quantities and adequate irrigation times. In order to control the amount and frequency of water supply in soilless systems a mechanistic water model (Thornley, 1996) has been implemented, calibrated and validated for the pool water in the substrate on greenhouse tomato crop in the Southeast of Spain conditions.

The underlying ideas in the work presented in this paper are based in the fact that the water balance model takes into account the quantity of water in (1) the vegetative part, (2) the roots and (3) the substrate in which the crop growths. Considering that the vegetative part is constituted by stems, leaves and fruits, it is possible to use the model for predicting the production of fresh matter of the commercialized part (fruits), requiring the knowledge of the fractions destined to each organ of the plant and it also makes possible to analyze the potential use of an integral model, although this aspect lies out of the scope of this paper. The main feature of the model exploited in this work in conjunction with a crop growth model is its capability to predict the amount of water in the substrate, as this information is of capital relevance to perform irrigation tasks. In synthesis, the model includes the dynamics of the water balance of the system composed by the substrate-plant-environment and the biomass production.

Considering that it is difficult and of greater cost to evaluate the water flows between the soil-root, root-canopy or even the water potentials in each one of the components of the system in a continuous way during the day, the main measured variables considered in this work have been the transpiration and the relative quantity of water in the substrate, as these variables allow us to know the distribution of water in the system and more precisely, to validate the developed model to be used for irrigation tasks for crop growth in greenhouse using rockwool substrate.

MATERIAL AND METHODS

The original water model was designed to be integrated with plant growth simulators for crops and plants ecosystems where internal plant substrates and variable shoot:root partitioning are represented (Thornley, 1996). This model is an integrated and mechanistic one with the following main features:

- It is composed by three state variables: mass of water in the root, in the shoot and in the substrate.
- It is based on a single soil compartment and two compartments for the plant.
- It calculates water flow from substrate to root, root to shoot, and shoot to the atmosphere via transpiration.
- The main driving forces to calculate water movement are the water potential differences divided by resistances.
- The main crop variables required by the water model are: shoot and root structural dry masses, shoot and root storage dry masses, leaf area index and root density and the substrate is treated as a single layer.

Table 1 shows only the main equations because the full model has about 35 algebraic and differential equations and more than 30 parameters (therefore it is not possible to include it here). The meaning of the variables and parameters of the model are also included in Table 1.

This original model has been modified in this work in order to adapt it to artificial substrate (instead of soil), eliminate some physical processes and adjust it to the greenhouse tomato crop:

1) The rain was substituted by high frequency irrigation supply.
2) The evaporation was eliminated because in the soilless system used the crop was grown on rockwool bags and then the evaporation is negligible.
3) In the shoot-atmosphere water flow the original equation (Table 1 eq. 7) was changed by the equation proposed for tomato crop from Stanghellini (1987) (Table 1 Eq. 8) which has been widely used and adjusted for greenhouse crops.
4) Substrate water potential was estimated with the equations 9-10 based on the relationship with the water characteristic retention curve using the function proposed by van Genutchen (1980); the main factor for the osmotic water potential is electrical conductivity of the nutrient solution; the gravitation potential is considered negligible.
5) The substrate hydraulic conductivity was calculated with the function proposed by Mualem (1976) (eq. 11); the parameters used were those obtained in Da Silva et al., (1994), for rockwool substrate.
6) Because the hydraulic resistance of the root is variable and at high rates of transpiration will be low allowing for a rapid uptake of water (Steudle and Peterson, 1998) the hydraulic resistance function has been modified by a factor shown in equation 12, in which more transpiration induce less resistance to water flow.

7) The model has been coupled with a tomato crop growth model (TOMGRO) based on climatic conditions (Jones *et al*., 1999), which was calibrated and validated for the local semiarid conditions (Ramírez-Arias *et al*., 2003) and was adjusted to estimate structural and non-structural dry mass using data obtained for tomato crop (Pressman *et al*., 1997).

The model was implemented in Matlab-Simulink (Matworks Co.). Several experiments with tomato crop *Lycopersicon esculentum* 'Boludo', grown in Rockwool® substrate at 2 (plants m^{-2}) of plant density were carried out in a greenhouse with roof plastic cover. The data of substrate water content, water supply, amount of lixiviates, electrical conductivity of the substrate, leaf temperature, inside and outside global radiation, photosynthetic photon flux density, ambient humidity, CO_2 and air temperature were recorded each minute using a computer-based data acquisition system. The loss of water in plants was measured with an electronic weight. The model was tested with some periods composed by data sets of four or five days corresponding to different climatic conditions. A numerical sensitivity analysis of the optimal values obtained in the calibration and validation processes was also performed.

RESULTS AND DISCUSSION

An important flow is that of the shoot to atmosphere or transpiration. Fig. 1A shows both measured and simulated transpiration for three days and as can be seen, the model behaves adequately, the absolute mean error being $1.7 \cdot 10^{-4}$ kg m^{-2} min^{-1}, the absolute maximum error $2.6 \cdot 10^{-3}$ kg m^{-2} min^{-1} and the standard deviation $3.5 \cdot 10^{-4}$ kg m^{-2} min^{-1}. This flow is the main driving force to generate sink of water, which in this type of systems is important as the water must be frequently replaced to avoid stress to the greenhouse crop.

The simulated water potentials (substrate, root and shoot) reach the equilibrium at predawn, but the dynamics of the last two ones is such that these become more negative at noon and less negative at predawn, their values being in the range between -0.07 and -0.5 MPa, lying within the range reported on tomato crops grown on rockwool substrate (Li et al., 2004). The root mean square error in the estimation of substrate water content was 0.02 kg m^{-2} which represents the 0.4% of the mean water content in the substrate, the mean absolute error was 0.016 kg m^{-2} and the standard deviation 0.012 kg m^{-2}, using a data set of 5760 records. Fig. 1B shows both the measured and simulated dynamics of the relative water content in the substrate; the simulation can be considered acceptable considering that the model is going to be used for control purposes, however the model is unable to represent the dynamics of the water content in the last moments preceding the irrigation supply, when the transpiration is very low and there is minimum substrate water content. Simulations of pool water content in the shoot and root are shown in Fig. 1C and 1D. The shoot water mass shows normal loss of water due to transpiration flux, but increases every day due to the accumulation of water. The pool of water in roots shows the transference of water from the root tissue to the shoot during the day, when the mass water is decremented, but is recovered at night. The pool is stable every day because the root system does not growth or its growing is very low when the crop is mature (Pressman et al., 1997).

The main modifications on the model have been to adapt the dynamics of the substrate water potential and hydraulic conductivity of the substrate, because the soil in this application has a different behaviour than that of the original model. The modifications carried out on the substrate-root resistance helps the model to simulate better the flow of water between the substrate and roots, as can be seen in figure 2A, where the effect of including/not including the parameter (Ck_{rth}) to affect hydraulic resistance is shown, in which an important input is the transpiration (see Eq. 12).

The main parameters affecting the model performance are shown in fig. 2B, where the parameters related with water potentials and the substrate-root hydraulic resistance are presented in descending order: parameter affecting the pressure component in the shoot (*Cprv*), cell wall rigidity parameter (*Cee*), parameter on the relationship fraction of storage mass that is osmotically active/molar mass storage in the shoot (*CFFv*), parameter affecting the pressure component in the root (*Cprr*), plant water conductivity (*Ccw*), parameter on the relationship fraction of storage mass that is osmotically active/molar mass storage in the root (*CFFr*) , parameters on the substrate-root resistance affecting root structural dry mass (*Ckwrsrt* and *Crsr*). The three formers have the most important effect on the pool water substrate estimation. The initial conditions (Fig. 2C) have important effect on the behavior of the dynamic of the water in the soil-root system, mainly the initial water content in the substrate and the initial water content in the shoot, as can be seen on the scale magnitude in figures 2B-2C.

One interesting feature of the model is that it can be used for automatic control purposes, as it is shown in Fig. 3B and 3C in which, the model is used as a simulator to test irrigation control strategies, using as set-point the relative water content and applying both an on-off control strategy and a proportional control strategy, that are compared with the actual irrigation water supply used by the grower (Fig. 3A). Model-based control (that has been used by other authors in this context, e.g. Sigrimis *et al*., 1999) can be useful to maintain an appropriate relative water content level in the substrate. Obviously, in the examples shown in this paper the proportional control is better than on-off control because it maintains the water level very close to the set-point; however at present is not a feasible solution in commercial production. Fig. 3D shows the control signals provided by the on-off and proportional controllers applied in the mentioned simulations. The model-based on-off control algorithm saves 20% with respect to the actual control system.

CONCLUDING REMARKS

The main concluding remarks are that we agree with the sentence “although the model attempts to be mechanistic at a simple level and our knowledge of the mechanisms is incomplete and in some cases probably wrong (Thorn96)”, however the model describes the water dynamics in a understandable way, thus it is possible to use it for controlling irrigation in greenhouse crops. The model can be used within model-based control schema including predictions on transpiration in open loop or using predictions on water content in the substrate in closed loop, which also includes the estimation on the transpiration; it is also possible to use it for controlling taking into account the amount of lixiviates, although this issue it is being validated now. The simulations encourage us to apply this model with a simple on-off control or other more complex control strategies like model predictive control ones.

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REFERENCES

[1] Da Silva F.F., Wallach R., Chen Y. 1995. Hydraulic properties of rockwool slabs used as substrates in horticulture. Acta Hort. 401: 71-75.

[2] Giacomelli G.A. 1998. Monitoring plant water requirements within integrated crop production systems. Act. Hort. 458:21-28.

[3] Gieling, Th. 2001. Control of water supply and specific nutrient application in closed growing systems. PhD Thesis. Wageningen Agric. Univ. The Netherlands. 176 p.

[4] Hamer, P.J.C. 1998. Validation of a model used for irrigation control of a greenhouse crop. Act. Hort. 458: 75-82.

[5] Heinen, M. 1997. Dynamics of water and nutrients in closed, recirculating cropping systems in glasshouse horticulture. With special attention to lettuce growth in irrigated sand beds. PhD Thesis. Wageningen Agric. Univ. The Netherlands. 270 p.

[6] Heinen M., Marcelis L.F.M., Elings A., Figueroa R., del Amor F.M.. 2002. Effects of EC and fertigation strategy on water and nutrient uptake of tomato plants. Act Hort. 593: 101-107.

[7] Ho, L.C., Grange, R.I., Picken, A.J. 1987. An analysis of the accumulation of water and dry matter in tomato fruit. Plant, Cell Environ. 10: 157-162.

[8] Jones, J.W., Kening, A., Vallejos, C.E., 1999. Reduced state-variable tomato growth model. Trans. of the ASAE, 42(1): 255-265.

[9] Li L.Y., Marcelis L.F.M., Stanghellini C. 2004. Plant water relations as affected by osmotic potential of the nutrient solution and potential transpiration in tomato (Lycopersicon esculentum Mill). J. Horticultural Science and Biotechnology 79: 211-218.

[10] Mualem Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12: 513-522.

[11] Pressman E., Bar-Tal A., Shaked R., Rosenfeld K. 1997. The development of tomato root system in relation to the carbohydrate status of the whole plant. Annals of Botany 80, 533-538.

[12] Ramírez Arias, A., Rodríguez F., Berenguel, M., Heuvelink, E. 2003. Proc. of Int. Workshop on Models for Plant Growth and Control of Product Quality in Horticultural Production. Postdam, Germany 25-28 agust 2003.

[13] Sigrimis, N., Arvanitis, K.G., Pasgianos, G.D., Ferentinos, K. 2001. Hydroponics water management using adaptive scheduling with an on-line optimiser. Computers and Electronics in Agriculture, 31:31-46.

[14] Stanghellini, C. 1987. Transpiration of greenhouse crops: an aid to climate management. Ph. D. dissertation. Wageningen agricultural University, Wageningen, The Neederlands.

[15] Steudle E. and Peterson. 1998. How does water get through roots? J. of Experimental Botany. 322: 775-778.

[16] Thornley J.H.M. 1996. Modelling water in crops and plant ecosystems. Annals of Botany 77, 261-275.

[17] van Genutchen, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44:892-989.

Table 1. Main equations of the water model

Equation		Description	Units
$\frac{dM_{W,sh}}{dt} = F_{W,rt-sh} - F_{W,sh-atm}$	(1)	$M_{W,sh}$ – Shoot water pool	Kg water m^{-2}
		$M_{W,rt}$ – Root water pool	Kg water m^{-2}
$\frac{dM_{W,rt}}{dt} = F_{W,so-rt} - F_{W,rt-sh}$	(2)	$M_{W,so}$ – Substrate water pool	Kg water m^{-2}
		c –Nutritive solution concentration	Mol m^{-3}
If [$(F_{W,so} > 0)$ and $(\theta_{so} \geq \theta_{so,\max})$]		C_{prv} – Parameter affecting pressure component in shoot	kg struct. DM (kg water)$^{-1}$
$\frac{dM_{W,so}}{dt} = 0$, $F_{w,drain} = F_{w,so}$		C_{prr} – Parameter affecting pressure component in root	kg struc. DM (kg water)$^{-1}$
else:		C_{rsrt} – Parameter affecting resistance between soil-root	m s^{-1}
$\frac{dM_{W,so}}{dt} = F_{W,so}$	(3)	C_{cw} – Parameter of plant water conductivity	m^{-2} d
$F_{W,so} = \rho_W r_{ain} - F_{W,rain-atm} - F_{W,so-rt}$	(4)	C_{kwrsrt} – Parameter of soil-root resistance	kg struct. DM m^{-2}
		Ck_{rht} - Parameter to affect resistance substrate-root	-
$F_{W,so-rt} = \frac{Ct(\psi_{so} - \psi_{rt})}{r_{W,so-rt}}$	(5)	$F_{W,so}$ – Water flow into the substrate water pool	Kg water m^{-2} min^{-1}
		$F_{W,so-rt}$ – Water flow from soil to root	Kg water m^{-2} min^{-1}
$F_{W,rt-sh} = g_{W,rt-sh}(\psi_{rt} - \psi_{sh})$	(6)	$F_{W,rt-sh}$ – Water flow from root to shoot	Kg water m^{-2} min^{-1}
		$F_{W,sh-atm}$ – Water flux from transpiration	Kg water m^{-2} min^{-1}
		$F_{W,drain}$ – Water flow from lixiviates	Kg water m^{-2} min^{-}
$F_{W,sh-atm} = \frac{sJ_{nr,a,c} + Ct\lambda\gamma g_a(\rho_{swv} - \rho_{wv})}{\lambda(s + \gamma(1 + g_a / g_c))}$	(7)	$f_{osrt\ (sh)}$ – fraction of storage mass that is osmotically active in root (shoot)	-
		$g_{W,rt,sh}$ hydraulic conductance root-shoot	$Kg^{-1}m^4$ min^{-1}
$F_{W,sh-atmSt} = g_{tr}(\chi_{eff} - \chi_a)$	(8)	g_{tr}- Conductance of transpiration	Kg m^4 min^{-1}
		$K(S_e)$ - Hydraulic conductivity of the substrate	Kg m^{-3} s^{-1}
$\psi_{so} = \psi_g + \psi_o + \psi_m$; $\psi_o = -cRT$	(9)		
$S_e = \frac{1}{(1 + \lvert \alpha\psi_m \rvert^n)^m}$	(10)	$r_{Th,so,rt}$ - Resistance substrate-root in original model	Kg m^4 min^{-1}
		$r_{W,so,rt}$ – hydraulic resistance substrate-root	m s^{-1}
$K(S_e) = S_e^{1/2}\left(1 - (1 - S_e^{1/m})^m\right)^2$	(11)	R – Universal gas constant	J $K^{-1}mol^{-1}$
$r_{W,so.rt} = r_{Th,so-rt} * (1 - Ck_{rht} * F_{W,sh-atmSt})$	(12)	T – Temperature of substrate	K
		T_{air} – Air temperature	ºC
$r_{Th,so-rt} = \frac{c_{sors}\rho_{root}}{K_{so}M_{G,rt}} + \frac{c_{rsrt}}{\rho_{root}}(\frac{M_{G,rt} + C_{KWrsrt}}{M_{G,rt}})$	(13)	S_e - Effective water content in the substrate	m^3 water m^{-3}subst.
		α,m,n - shape parameters in curve water retention	-
$g_{W,rt-sh} = c_{cw}\frac{M_{W,rt}M_{W,sh}}{M_{W,rt} + M_{W,sh}}$	(14)		
		Ψ_{so} - Substrate water potential	J (kg water)$^{-1}$
		Ψ_{rt} - Root water potential	J (kg water)$^{-1}$
$\psi_{rt,os} = -\frac{R(T_{air} + 273)M_{S,rt}}{M_{W,rt}}(C_{FFr})$	(15)	Ψ_{sh} - Shoot water potential	J (kg water)$^{-1}$
		$\Psi_{rt,os}$ - Osmotic potential in root	J (kg water)$^{-1}$
		$\Psi_{rt,pr}$ - Pressure potential in root	J (kg water)$^{-1}$
$\psi_{rt,pr} = C_{ee}\left(\frac{c_{prr}M_{W,rt}}{M_{G,rt}} - 1\right)\Big/\rho_W$	(16)	$\Psi_{sh,os}$ - Osmotic potential in shoot	J (kg water)$^{-1}$
		$\Psi_{sh,os}$ - Pressure potential in shoot	J (kg water)$^{-1}$
		Ψ_o - Osmotic water potential in the substrate	J (kg water)$^{-1}$
$\psi_{sh,os} = -\frac{R(T_{air} + 273)M_{S,rt}}{M_{W,rt}}(C_{FFv})$	(17)		
		Ψ_g - Gravitational water potential in the substrate	J (kg water)$^{-1}$
$\psi_{sh,pr} = C_{ee}\left(\frac{c_{prv}M_{W,rt}}{M_{G,rt}} - 1\right)\Big/\rho_W$	(18)	Ψ_m - Matric water potential in the substrate	J (kg water)$^{-1}$
		ρ_W- Water density	Kg m^{-3}
$C_{FFv} = f_{os,rt} / \mu_s$	(19)	χ_{eff} – Effective absolute humidity of the “big leaf”	Kg m^{-3}
$C_{FFv} = f_{os,sh} / \mu_s$	(20)	χ_a – Absolute humidity in the air	Kg m^{-3}
		μ_s – Molar mass of storage	Kg mol^{-1}

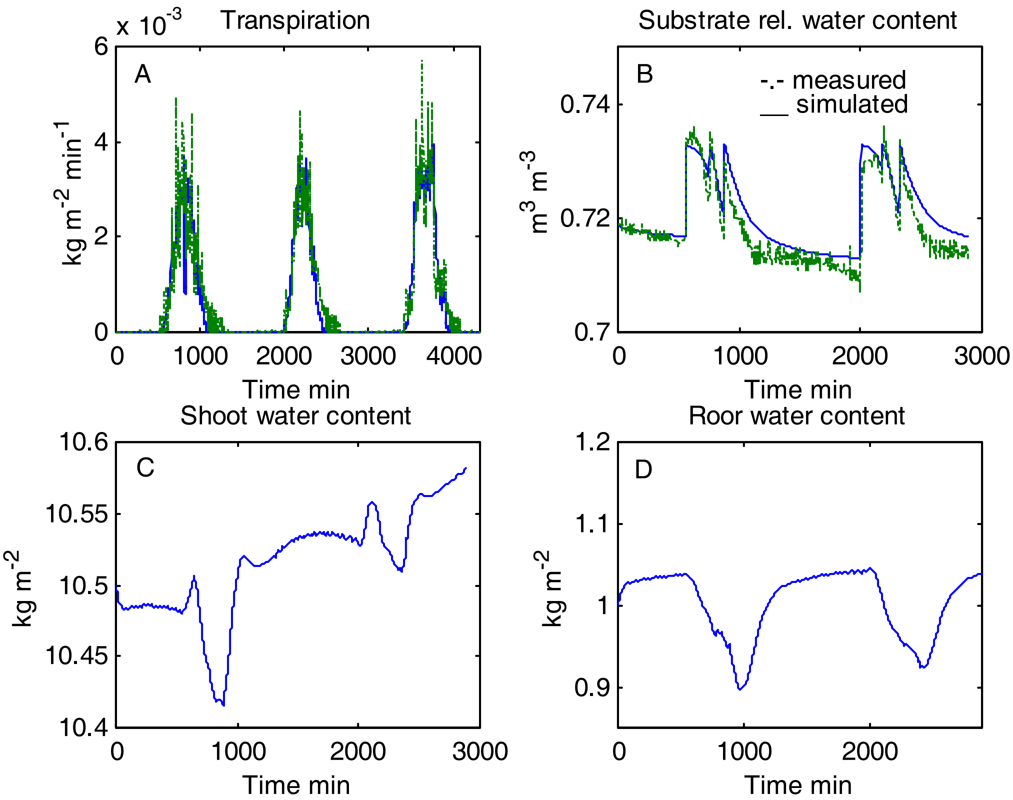


Fig. 1. A) Transpiration measured and simulated during three days. Water simulations in two days: B) Measured and simulated relative water content in substrate. C) Simulated water content in shoot. D) Simulated water content in root.

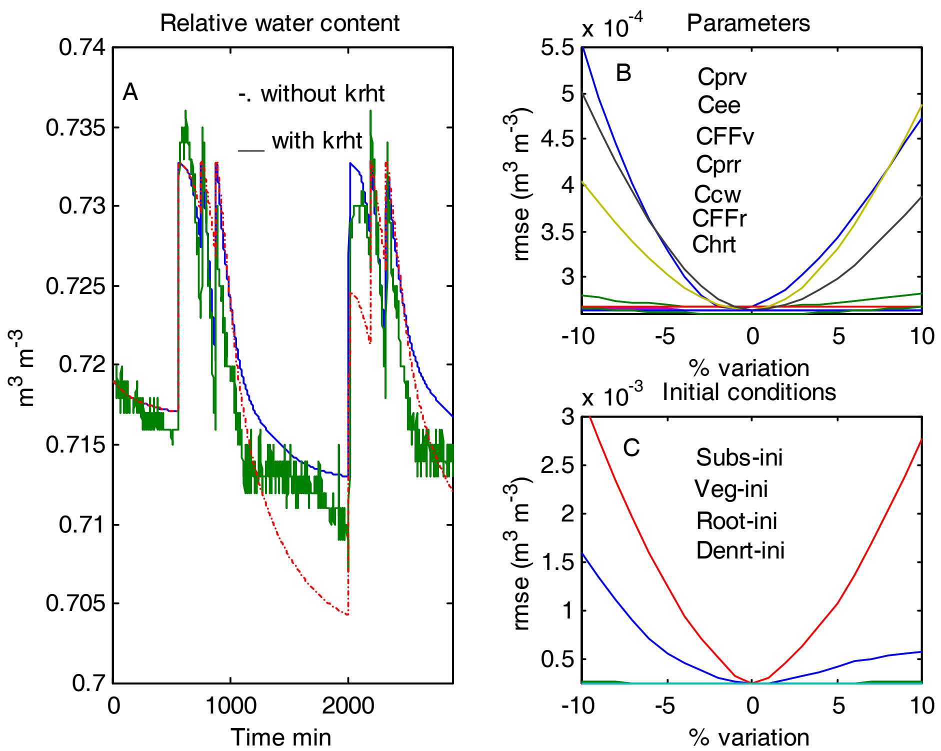
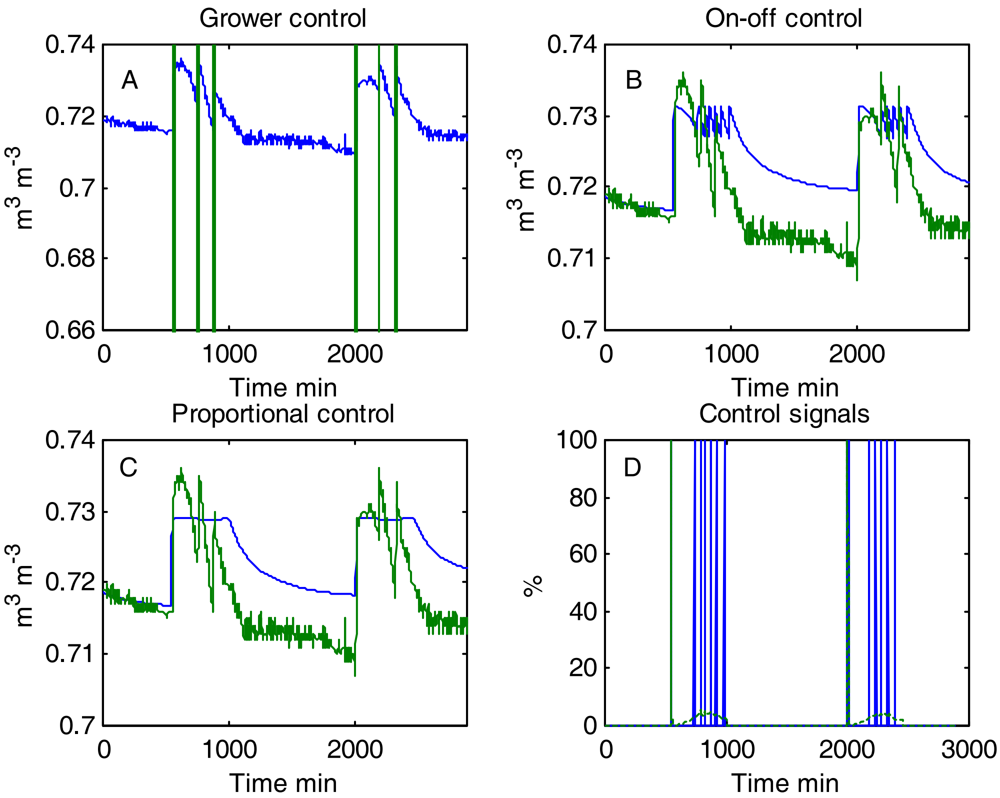


Fig. 2. A. Relative water content with and without parameter modifying substrate-root resistance. B. Sensitivity to the parameters ordered by importance, variation from the optimum value vs. root mean square error. C. Sensitivity to the initial conditions.



__ on-off --- proportional

Fig. 3. Water supply. A) Actual grower control system. B) Model-based on-off control. C) Model-based proportional control. D) Control signals of both proportional and on-off control.