Model development for prediction of soil water dynamics in plant production

Zhengfeng Hu, Huixia Jin and Kefeng Zhang*
Ningbo Institute of Technology, Zhejiang University, Ningbo, China

Abstract: Optimizing water use in agriculture and medicinal plants is crucially important worldwide. Soil sensor-controlled irrigation systems are increasingly becoming available. However it is questionable whether irrigation scheduling based on soil measurements in the topsoil could make best use of water for deep-rooted crops. In this study a mechanistic model was employed to investigate water extraction by a deep-rooted cabbage crop from the soil profile throughout crop growth. The model accounts all key processes governing water dynamics in the soil-plant-atmosphere system. Results show that the subsoil provides a significant proportion of the seasonal transpiration, about a third of water transpired over the whole growing season. This suggests that soil water in the entire root zone should be taken into consideration in irrigation scheduling, and for sensor-controlled irrigation systems sensors in the subsoil are essential for detecting soil water status for deep-rooted crops.

Keywords: subsoil water, soil-crop system, irrigation scheduling, water dynamics, numerical simulations.

INTRODUCTION

Agriculture is the largest water consumer in the world and uses 70% of the world's accessible water (Clay, 2004). With increase in food production and medical treatment demand to keep pace with a growing global population and climate changes, a greater irrigated plants and irrigation amount could be expected in the future. It is therefore crucially important to optimize irrigation scheduling to optimize water use in agriculture and medicinal plant production (Greenwood *et al*., 2010; Mirshekari and Farahvash, 2011).

It is well documented on the response of water on yield for a wide range of herbaceous and arable crops (Steduto *et al*., 2012). Efforts have also made to optimize water use in medicinal plant production (Liang *et al*., 2014; Chen *et al*., 2014; Mirshekari and Farahvash, 2011; Mohamed *et al*., 2014). Liang *et al*. (2014) experimentally investigated the effects of soil moisture condition on both photosynthesis and saponin content of *Paris polyphylla*, and found that there was a strong correlation between the total saponin content in rootstalk and soil water content. Mohamed *et al*. (2014) carried out a study on the effects of irrigation intervals on growth, yield of rhizomes and content of chemical composition of both *Curcuma* aromatica and *Curcuma* domestica medicinal plants. The plants were irrigated at the time intervals of one, two and three weeks, respectively. It was clear that long irrigation intervals led to significant reduction in plant growth and chemical composition. It was also indicated that C. aromatica grew better and had higher values of chemical composition, compared with those from C. domestica regardless of irrigation treatments. Clearly, soil water content has a great impact on both plant growth and content of chemical composition.

Currently, there are three approaches commonly used in practice for irrigation scheduling (Greenwood *et al*., 2010). They are: Experience-based judgements guided by the visual appearance of plant and soil; based on water balance approach; and based on soil moisture monitoring at a specific depth (irrigation is applied when soil water content reaches a threshold). The experienced-based approaches are non-scientific, and often lead to over irrigation (Greenwood *et al*., 2010). A weakness associated with the water balance approach for estimating water loss over substantial periods is that errors are cumulative and so added irrigation water can become out of step with requirement (Jones, 2004). The sensor-controlled irrigation systems, which are able to detect soil water status in real time, are more advanced, compared with the other two approaches. With the availability of wireless data acquisition technology and affordable and accurate soil sensors, such systems are increasingly adopted. However, a literature review of irrigation scheduling controlled by soil water sensors reveals that irrigation decisions are principally made based on sensor readings at a specific depth in the topsoil, ignoring water stored in the subsoil (Boote and Ketring 1990; Stanley and Maynard 1990; Wright and Stark 1990; Kang and Wan 2005; Munoz-Carpena *et al*. 2005; Wang *et al*. 2007). It is adequate to use such systems for growing crops that penetrate to only a shallow depth. But it would be questionable to use the systems for crops with roots that penetrate to a deep depth, if the soil conditions are satisfactory and extract water to that depth.

The main purpose of this study was therefore to provide quantitative evidence to highlight the importance of water

---

**Corresponding author:* e-mail: kfzhang@hotmail.com stored in the subsoil in meeting water demand for the maximum growth of deep-rooted crops using a numerical approach and thus efforts should be made to account for subsoil water in irrigation scheduling.

MATERIALS AND METHODS

Brief description of the model

To simulate soil water dynamics in the soil-crop system, the model proposed by Yang *et al*. (2009) was used in this study. It has been proven that the model is capable of making reasonable predictions for water dynamics in the soil-crop system if the model parameter values are given with precision (Yang *et al*., 2009; Zhang *et al*., 2011). The brief description of the model in this section is mainly based on Yang *et al*. (2009) and Zhang *et al*. (2011).

The Richards' equation with sink terms for water movement within the soil profile can be expressed as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[K(\theta)(\frac{\partial h}{\partial z}+1)] - \beta(h)S_{\max}(z) \tag{1}$$

where q is the soil water content, h is the soil water pressure head, K (cm d^{-1}) is the soil hydraulic conductivity, b is the root water stress reduction factor, and S_{max} (d^{-1}) is the maximum root water uptake.

The soil hydraulic functions are (Genuchten, 1980):

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [\frac{1}{1+|\alpha h|^n}]^m \tag{2}$$

$$K(\theta) = K_s \Theta^{0.5}[1-(1-\Theta^{1/m})^m]^2 \tag{3}$$

Where Θ is the relative saturation, θ_s and θ_r (cm^3 cm^{-3}) are the saturated and residual soil water contents, a (cm^{-1}) and n are the shape parameters of the retention and conductivity functions, m = 1-1/n and K_s (cm d^{-1}) is the saturated hydraulic conductivity.

S_{max} and b can be calculated using the following equations (Feddes *et al*., 1978):

$$S_{\max}(z) = L_r(z)K_{cb}ET_0 / \Sigma L_r(z) \tag{4}$$

$$\beta(h) = \begin{cases} 0 & h \le h_3\ ,\ h \ge h_1 \\ (h-h_3)/(h_2-h_3) & h_3 < h < h_2 \\ 1 & h_2 \le h < h_1 \end{cases} \tag{5}$$

where L_r(z) is the relative root length distribution at z, K_{cb} is the basal crop coefficient for transpiration from the FAO56 (Allen *et al*., 1998), ET_0 (mm) is the reference evapotranspiration, h_3 is the soil water pressure head at the permanent wilting point, h_1 is the soil water pressure head near saturation above which water uptake is prohibited, and h_2 is the threshold soil water pressure head below which the transpiration is reduced (Sonnleitner *et al*., 2003; Yang *et al*., 2009, Zhang *et al*., 2011).

ET_0 can be calculated using the Penman-Monteith equation at a daily interval according to the FAO56:

$$ET_0 = \frac{0.408\Delta(R_n - G) + 900\gamma/(T+273)u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \tag{6}$$

where R_n (MJ m^{-2} d^{-1}) is the net radiation at the crop surface, G (MJ m^{-2} d^{-1}) is the soil heat flux density, u_2 (m s^{-1}) is the 24 h average wind speed at 2 m height, e_s (kPa) is the saturation vapour pressure, e_a (kPa) is the actual vapor pressure, Δ (kPa°C^{-1}) is the slope of the vapour pressure curve, and γ (kPa°C^{-1}) is the psychrometric constant. The procedures of computing G, e_s, e_a, d and γ are given in the FAO56.

Rooting depth growth is estimated according to Greenwood *et al*. (1982):

$$R_z = R_{z0} + \max[0,10(\mathrm{W}-2)] \tag{7}$$

where R_z (cm) is the rooting depth, R_{z0} is the rooting depth at planting, W (t ha^{-1}) is the above ground plant dry weight, which is estimated using the equation by Greenwood *et al*. (1977).

The root length density is assumed to decline exponentially from the soil surface downwards (Gerwitz and Page, 1974; Pedersen *et al*., 2010):

$$L_r(z) = e^{-a_z z} \qquad z \le R_z \tag{8}$$

Where a_z (cm^{-1}) is the shape parameter controlling root distribution down the soil profile.

Daily potential soil evaporation and crop transpiration, based on the information of weather variables and crop growth stages, is calculated using the dual crop coefficient method proposed by the FAO56 (Allen *et al*., 1998).

The procedure used to solve the equations stated the above and a detailed description of the algorithm is given in Yang *et al*. (2009).

Experiments

An experiment was carried out on a Dutch white cabbage in the UK (latitude: 52°12' N, longitude: 1°37' W). The detailed description of the experiment is reported in Zhang *et al* (2011). Here only a brief description of the experiment is outlined.

The soil was classified as a sandy loam. Soils were found to be generally uniform in both the topsoil of 30 cm and the subsoil with the physical properties shown in table 1. Also shown in the Table are the soil hydraulic properties, which were derived using the pedo-transfer functions (PTFs) proposed by Wösten *et al*. (1999). The experimental design was a fully randomised block, with five replicates. The crop was transplanted on 29 April 2009 and harvested on 8 September 2009. The plots were 5.0 x 2.0m. Plants were spaced 0.50m between and within rows. The adequate fertilisers were applied and pests, diseases and weeds were effectively controlled throughout growth.

The amounts of irrigation of 6.4, 6.4, 9.6, 3.1 and 30.7mm were applied on 5 May, 6 May, 12 May, 2 June and 7 July, respectively. Soil water potential was measured at the depths of 10, 30, 50, 70 and 90cm using granular matrix Watermark 200SS-v soil sensors (Irrometer Company, USA). A set of 6 sensors were installed in each replicate plot. Readings were taken hourly and the replicate sensor measurements at each depth were averaged.

Meteorological data were recorded using an on-site station, situated approximately 100m from the experimental site. The measured weather variables included maximum, mean and minimum air temperatures, total solar radiation, relative humidity, wind speed and precipitation. All the measurements were taken at a daily interval and some of them are given in fig. 1.

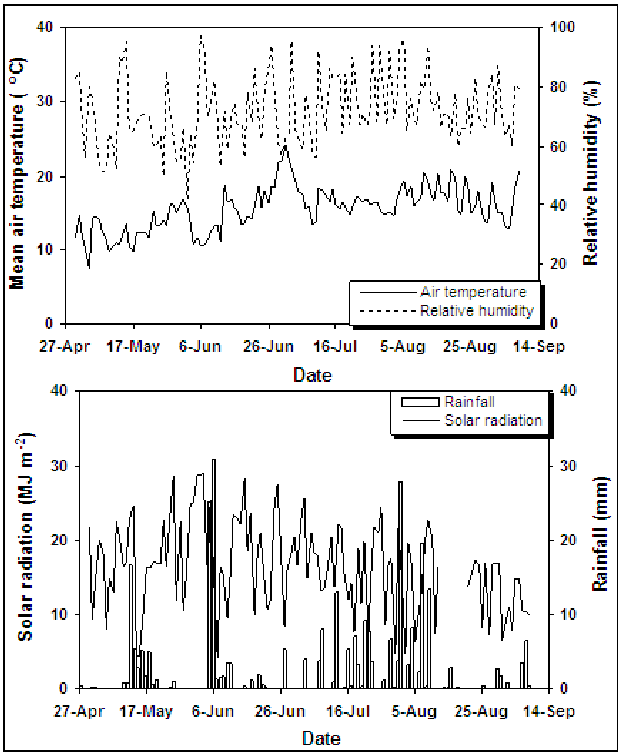

Fig. 1: Measured daily mean air temperature and relative humidity (a) and solar radiation and rainfall (b) during the experiment

RESULTS

Soil hydraulic properties, derived using the PTFs proposed by Wösten *et al*. (1999) and shown in table 1, were used for the topsoil and the subsoil. Other model parameter values were determined according to Zhang *et al*. (2011). The overall comparison of simulated and measured soil water potential at various depths was satisfactory. Statistical analyses reveal that the simulated values are highly correlated with the measurements with the value of coefficient of determination (R^2) of 0.814. The value of Nash-Sutcliffe efficiency (NSE), commonly used for model assessment, is fairly high (0.78), and the root of the mean squared errors (RMSE) is relatively low (15.3 kPa) (Zhang *et al*., 2011). The detailed comparison of the simulated and measured soil water potential at each of individual soil depths can also be seen in Zhang *et al*. (2011).

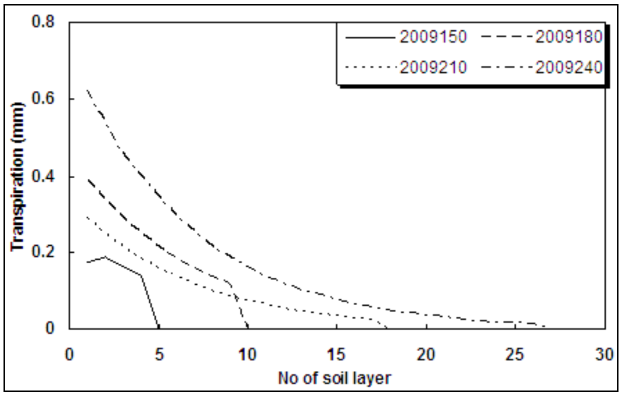

Fig. 2: Simulated transpiration from various soil layers (each layer having 5cm thickness) on DOYs of 150, 180, 210 and 240 respectively.

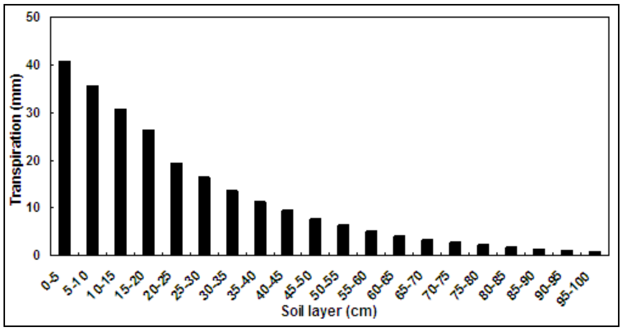

Fig. 3: Simulated seasonal transpiration from different soil layers

The simulations of soil evaporation and crop transpiration from the soil were carried out throughout the entire crop growth. The total simulated soil evaporation and crop transpiration were 106.8 and 242.5mm, respectively. fig. 2 shows, as examples, the simulated crop transpiration from 5cm soil layers down the profile on the DOYs (day of year) of 150, 180, 210 and 240. fig. 3 shows the seasonal crop transpiration from various soil layers. The overall pattern of transpiration down the soil profile followed the root length distribution. fig. 4 illustrates the percentage of seasonal transpiration from the soil below the 30, 40, 50 and 60cm depths. It can be seen that a significant proportion of seasonal transpiration was met by water from the subsoil. Soil water from the 30cm depth below accounted for about 30% of the total transpiration over the season. For the soil below the 50 cm depth, it provided some 13% of total transpiration. These fig. were even higher in the percentage of transpiration after the roots reaching the 30cm depth (see fig. 5). The corresponding values were 35% and 15%, respectively.

DISCUSSION

Statistical indices calculated for water content in various soil layers showed that the model reproduced the measured values fairly accurately. The calculated values of soil water content could, therefore, be used for further discussion. While it was generally the case that water extraction by roots declined with increasing soil depth due to the root length distribution, water uptake from a deeper layer could be greater than that in the above layer, when soil water supply in a particular layer was limited (see DOY of 150). Also the results indicated that root water uptake was approximately proportional to the root length distribution. This could be explained by the fact that in this study the total rainfall and irrigation of 405.2mm exceeded the potential evapotranpiration of 350mm, resulting in that the potential transpiration assigned in each soil layer according to the root length density distribution was met for most of the growing season.

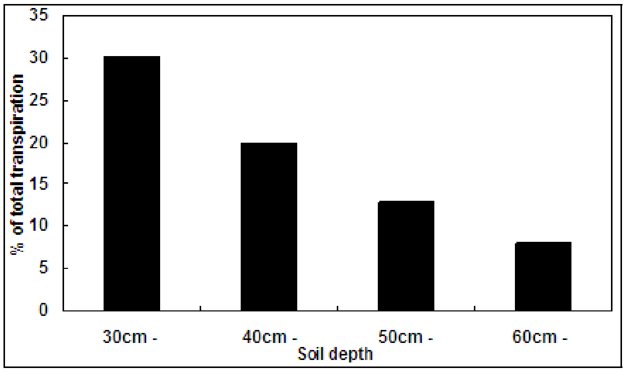

Fig. 4: Percentage of total transpiration from the soil below the 30, 40, 50 and 60 cm depths

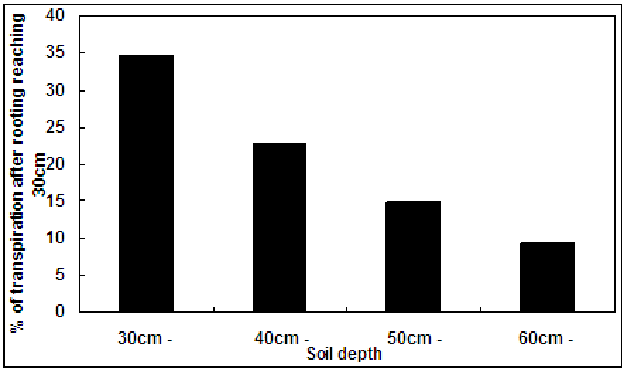

Fig. 5: Percentage of transpiration after the rooting reaching the 30cm depth from the soil below the 30, 40, 50 and 60cm depths

It is clear from this study that subsoil water plays an important role in meeting crop water demand for the maximum growth. Subsoil water supplied some 30% of the total seasonal transpiration in the case studied. To save water for deep-rooted crop production, it is essential to take into consideration of water contained in subsoil for irrigation decisions. This also suggests that multi-sensor systems with sensors in the subsoil are more favorable for sensor-controlled irrigation scheduling, in agreement with the argument put forward by Greenwood *et al.* (2010).

Nowadays, water use in crop production is mainly based on visual inspection of soil. Over application of irrigation is very common. This has led to the increase of cost resulting from waste of irrigated water and caused great impacts on the environment and ecological systems (Wright and Stark, 1990; Stalham *et al.*, 2007). The reason for the above mentioned problem was largely due to the unknown of water distribution in the soil profile in crop production. This study showed that the prediction of soil water dynamics was not only possible, but also could be done with reasonable accuracy. With the model proposed in this study both root growth and soil water content could be simulated on any given day, and the results could directly be used for irrigation decisions. In this way water use in crop production could be optimized and crop yield could be increased. The importance of using innovative models such as the one proposed in this study for irrigation decision-making has highly been recommended by Bastiaanssen *et al.* (2007) and by Greenwood *et al.* (2010).

Numerous studies have been conducted to investigate the importance of soil water content in controlling growth and content of chemical compositions of medicinal plants (Liang *et al.*, 2014; Mirshekari and Farahvash, 2011; Mohamed *et al.*, 2014). Liang *et al.* (2014) found that the total saponin content in rootstalk varied with soil water content, and water stress was not conductive to the photosynthesis of *Paris polyphylla*. Mirshekari and Farahvash (2011) conducted experiments on how irrigation affects the growth of Fennel (*Foeniculum Vulgare Mill.*) as a medicinal plant under semi-arid conditions. The results revealed that with delaying in irrigation time from 90 to 120mm evaporation from pan, the number of umbels per plant of fennel decreased up to 22.5%. The highest seed yield and essence percentage obtained from treatment of irrigation of 150mm evaporation from pan. Clearly, soil water content played an important role in medicinal plant production. For different medicinal plants there was an optimal soil water regime in order to achieve a high plant yield and high content of chemical compositions. Currently, such a soil water regime was obtained based on experimental trials. Experiments are both labor intensive and cost ineffective. Further, there are various soil textures and climatic conditions. It is, therefore, not realistic to conduct experiments for all different scenarios. This study provided an alternative to maintain optimal soil water regime for growing medicinal plants. During the growing season of medicinal plants, the proposed model could be run on a daily basis with soil and weather information. The model output soil water content, which could be compared with the specified soil water content.

Table 1: Soil physical and hydraulic properties (Zhang *et al*., 2011)

	Clay (%) (<0.002mm)	Silt (%) (0.002-0.05mm)	Organic matter (%)	Bulk density (g cm-3)	s (cm3 cm-3)	r (cm3 cm-3)	(cm-1)	N	Ks (cm d-1)
Topsoil (0-30-cm)	13.0	11.5	1.7	1.55	0.374	0.025	0.07119	1.283	73.0
Subsoil (30cm-)	11.0	10.0	0.8	1.65	0.342	0.025	0.06173	1.346	174.8

Consequently the decisions for irrigation could be made. In case of irrigation requirement, the model predictions could also used to estimate the amount of water addition. Thus the model as such has a potential to be applied not only for studying soil-plant water relations, but also for optimizing water use in the production of medicinal plants and herbal industry.

CONCLUSIONS

The simulations of water dynamics in the soil-cabbage system were successfully carried out. It reveals that the subsoil provides about a third of water transpired over the whole growing season in this study. It is therefore essential to take into consideration of subsoil water in irrigation decision making for deep-rooted crops. It also suggests that for sensor-controlled irrigation systems it would be desirable to have multi-sensor systems with sensors in subsoil detecting soil water status for accurate irrigation scheduling for deep-rooted crops.

ACKNOWLEDGEMENTS

The authors are grateful to the financial support from National Science Foundation of China (No. 51379187) and the Seventh Framework Programme of the European Community for research, technological development and demonstration activities (2007-2013) under the Specific Programme “Capacities” (Research for the Benefit of SMEs) through the Water Bee project (Grant Agreement Number: 222440).

REFERENCES

Allen RG, Pereira LS, Raes D and Smith M (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and drainage. FAO, Rome. P.56.

Bastiaanssen WGM, Allen RG, Droogers P, D’Urso G and Steduto P (2007). Twenty-five years modelling irrigated and drained soils: State of the art. *Agr. Water Manage.*, **92**: 111-125.

Boote KJ and Ketring DL (1990). Peanut. In Irrigation of Agricultural Crops (Eds B.A Stewart & D.R Nielsen), Madison, WI: ASA CSSA SSSA. Pp.675-717.

Chen P, Men P, Zhang JS, He CX, Jia CR and Li JZ (2014). Effect of drought stress on growth and water use efficiency of two medicinal plants. *Chin. J. Appl. Ecol.,* **25**: 1300-1306.

Clay J (2004). World Agriculture and the Environment: A Commodity-by-Commodity Guide to Impacts and Practices. Washington, DC: Island Press.

Feddes RA, Kowalik PJ and Zaradny H (1978). Water uptake by plant roots. In: Feddes RA, Kowalik PJ, Zaradny, H. (Eds.), Simulation of Field Water Use and Crop Yield. John Wiley & Sons, Inc., New York.

Gerwitz A and Page ER (1974). Empirical mathematical model to describe plant root systems 1. *J. Appl. Ecol.,* **11**: 773-781.

Greenwood DJ, Cleaver TJ, Loquens SHM and Niendorf KB (1977). Relationships between plant weight and growing period for vegetable crops in the UK. *Ann. Bot.,* **41**: 987-997.

Greenwood DJ, Gerwitz A, Stone DA and Barnes A (1982). Root development of vegetable crops in the UK. *Plant Soil,* **68**: 75-92.

Greenwood DJ, Zhang K, Hilton H and Thompson A (2010). Opportunities for improving irrigation efficiency with quantitative models, soil water sensors and wireless technology. *J. Agr. Sci.,* **148**: 1-16.

Jones HG (2004). Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Exp. Bot.,* **55**: 2427-2436.

Kang YH and Wan SQ (2005). Effect of soil water potential on radish (Raphanus sativus L.) growth and water use under drip irrigation. *Scientia Horticulturae.,* **106**: 275-292.

Liang J, Guo ZY and Ye Y (2014). Effect of different soil moisture conditions on photosynthetic characteristics and effects content of saponin of paris polyphylla. *Plant Physiol. J.*, **50**: 56-60.

Mirshekari B and Farahvash F (2011). Management of irrigation and nitrogen fertilizing in Fennel (*Foeniculum Vulgare Mill.*) as a medicinal plant under semi-arid conditions. *Iranian J. Med. Aromat. Plants,* **27**: 541-550.

Mohamed MA, Wahba HE, Ibrahim ME and Yousef AEA (2014). Effect of irrigation intervals on growth and chemical composition of some *Curcuma* spp. plants. *Nusantara Biosci.*, **6**: 140-145.

Munoz-Carpena R, Dukes MD, Li YC and Klassen W (2005). Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. *Horttechnology*, **15**: 584-590.

Pedersen A, Zhang K, Thorup-Kristensen K and Jensen LS (2010). Modelling diverse root density dynamics and deep nitrogen uptake A simple approach. *Plant Soil*, **326**: 493-510.

Sonnleitner MA, Abbaspour KC and Schulin R (2003). Hydraulic and transport properties of the plant soil systems estimated by inverse modelling. *Eur. J. Soil Sci.*, **54**: 127-138.

Stalham MA, Allen EJ, Rosenfeld AB and Herry FX (2007). Effects of soil compaction in potato (Solanum tuberosum) crops. *J. Agr. Sci.*, **145**: 295-312.

Stanley CD and Maynard DN (1990). Vegetables. In irrigation of Agricultural crops (Eds B. A. Stewart & D. R. Nielsen), Madison, WI: ASA CSSA SSSA. Pp.921-950.

Steduto P, Hsiao. T, Fereres E and Raes D (2012). Crop yield response to water. FAO Irrigation and Drainage. FAO, Rome, p.66.

van Genuchten MTh (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.*, **44**: 892-898.

Wang FX, Kang Y, Liu SP and Hou XY (2007). Effects of soil matric potential on potato growth under drip irrigation in the North China Plain. *Agr. Water Manage.*, **88**: 34-42.

Wösten JHM, Lilly A, Nemes A and Le Bas C (1999). Development and use of a database of hydraulic properties of European soils. *Geoderma*, **90**: 169-185.

Wright JL and Stark JC (1990). Potato. In Irrigation of Agricultural Crops (Eds B.A Stewart & D.R Nielsen). Madison, WI: ASA CSSA SSSA. Pp.859-888.

Yang D, Zhang T, Zhang K, Greenwood DJ, Hammond J and White PJ (2009). An easily implemented agro-hydrological procedure with dynamic root simulation for water transfer in the crop-soil system: Validation and application. *J. Hydrol.*, **370**: 177-190.

Zhang K, Hilton HW, Greenwood DJ and Thompson AJ (2011). A rigorous approach of determining FAO56 dual crop coefficient using soil sensor measurements and inverse modeling techniques. *Agr. Water Manage.*, **98**: 1081-1090.