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Numerical analysis of soil water dynamics in a soil column with an artificial capillary barrier growing leaf vegetables

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Abstract

An artificial capillary barrier (CB), which consists of two layers of gravel and coarse sand, was used to improve the soil water retention capacity of the root zone of sandy soil for the cultivation of Japanese spinach (*Brassica rapa* var. *perviridis*). The performance of a CB under specific conditions can be evaluated using numerical simulations. However, there have been relatively few numerical studies analyzing soil water dynamics in CB systems during crop growth. The objectives of this study were (i) to evaluate the performance of a CB during the cultivation of Japanese spinach irrigated at different rates and (ii) to investigate the effect of the irrigation schedule on root water uptake. Numerical analysis was performed using HYDRUS-1D after the soil hydraulic properties of the CB materials were determined. In most cases, the HYDRUS-1D results agreed well with the experimental soil water content data without any calibration when the dual-porosity model describing soil hydraulic properties was used for gravel and coarse sand. We found that the dual-porosity model was able to attenuate the unrealistically steep reduction in the unsaturated hydraulic conductivity predicted by the single-porosity model. The numerical simulations also showed that the CB played an important role in maintaining plant-available water in the root zone while maximizing the water use efficiency. The numerical simulations revealed that the irrigation frequency could be reduced by half during the early growth stage, and the water use efficiency could be greatly improved with the CB layer installed.

Keywords: Capillary barrier, HYDRUS-1D, irrigation efficiency, drought

Introduction

A capillary barrier (CB) is a layered soil system, which consists of two layers with contrasting hydraulic characteristics. A layer of a finer material usually overlays a layer of a coarser material. Depending upon the difference in capillary forces, vertical movement of infiltrated water is either slowed down or temporally paused in the fine layer at the interface with the coarse layer, as long as the capillary forces in the fine layer are significantly stronger than those in the coarse layer, mainly because of the difference in pore sizes. CB systems are recognized as alternative systems that not only control water percolation in landfill covers (Berger *et al*., 2005; Abdolahzadeh *et al*., 2011) but also improve the root zone water retention capacity. A gravel layer installed below the root zone was found to both increase water contents by 20–70%, depending on the soil texture and the depth of the barrier (Ityel *et al*., 2011), and to prevent the capillary rise from an underlying saline soil layer (Rooney *et al*., 1998).

In order to improve the performance of a CB under specific conditions, numerical simulations can be used as they are recognized as a cost-effective tool to investigate soil water dynamics. The HYDRUS software package is one of the most complete packages for simulating soil water dynamics and has been utilized in a number of hydrological studies (Šimůnek *et al*., 2008, 2016). Ityel *et al*. (2011) successfully used HYDRUS-2D to simulate the soil water content in the root zone with an installed CB, without accounting for root water uptake. Cheng *et al*. (2013) also showed that HYDRUS-1D performed well in simulating the observed soil water contents in both homogeneous (sandy soil and silt loam soil) and layered soils (sand overlying silt loam soil) during *Caragana korshinkii* Kom cultivation.

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Previously, Miyake *et al*. (2015) conducted an experiment to evaluate the effects of a two-layered CB system on cultivating Japanese mustard spinach (*Brassica rapa* var. *perviridis*), a widely grown commercial leaf vegetable in Japan, known for its high nutrient contents. However, this genus is highly affected by drought and salinity during plant growth and development (Zhang *et al*., 2014; Zhu *et al*., 2016). The results of Miyake *et al*. (2015) showed the potential of the CB system to improve the water retentivity of the root zone as the average plant height was higher for the CB system than that for the no-CB standard system when the same amount of irrigation water was applied. To further improve the irrigation efficiency, it is necessary to understand soil water dynamics during the cultivation of Japanese spinach in the soil profile with a CB layer.

The objectives of this study were therefore twofold: (i) to investigate the applicability of HYDRUS-1D to predict observed soil moisture contents and (ii) to evaluate the effects of different irrigation schedules on root zone moisture conditions of the cultivation experiment of Miyake *et al*. (2015) using HYDRUS-1D.

Materials and methods

Cultivation experiment

The cultivation experiment was conducted and reported by Miyake *et al*. (2015). Japanese spinach was cultivated in four 24 × 36 × 23 cm containers. Three containers with a two-layered CB and one container without a CB (for reference) were used. The reference container was filled with Tottori Dune sand (referred to as dune sand in the remainder of the paper). The CB containers additionally included a 6-cm layer of the CB, which consisted of a 2-cm thick coarse sand layer and a 4-cm gravel layer between a 4-cm dune sand layer at the bottom and a 6-cm dune sand layer on top of the soil profile (Figure 1). Fertilizers were mixed into the upper sand layer before seeding and liquid fertilizers were applied with irrigation water twice a week.

During the experiment, three different amounts of water were sprinkled uniformly every day: 0.15, 0.30 and 0.45 cm (referred to as CB15, CB30 and CB45, respectively). The amount of water sprinkled on the reference container without a CB layer was 0.30 cm (referred to as REF). The results showed that the average main root lengths were 2.83, 4.33, 5.77 and 7.20 cm in CB15, CB30, CB45 and REF, respectively, and that the roots did not penetrate into the CB layers in any scenario. It was observed that the spinach in CB30, CB45 and REF grew continuously, while the growth in CB15 was significantly slower than in the other three scenarios (Figure 2). The average plant height in CB30 was the highest, while it was slightly smaller in C45 and REF at the end of the cultivation (the difference between CB30 and REF was not statistically significant; $P > 0.1$).

Soil hydraulic properties

Soil water retention curves of the materials used in the cultivation experiment were determined by measuring water contents at predetermined matric potential heads ranging from 0 to −100 cm using a modified suction table method (Dane & Hopmans, 2002). Common retention models were then fitted to the experimental curves to further evaluate the unsaturated hydraulic conductivity using the pore size distribution model of Mualem (1976). While the single-porosity (SP) model of van Genuchten (1980) was used for the dune sand, the dual-porosity (DP) model of Durner (1994) was used for the coarse sand and gravel. As the hydraulic conductivity evaluated with the SP model intrinsically accounts for capillary-type flow only, it might not be appropriate for relatively coarse materials, from which water discharges as film-type flow after capillary water is quickly drained. It is, therefore, necessary to use a model that can account for non-capillary type flow, such as film flow. Although the DP model was originally proposed to account for heterogeneity in pore structure, it can be used to mimic non-capillary flow by suppressing the sharp decrease in the hydraulic conductivity in the dry range. Brunetti *et al*. (2016) showed that the DP model outperformed the SP model in their simulations when the DP model was used for the hydraulic properties of the green roof substrate, which consisted mainly of gravel. When the SP model is used for coarse sand and gravel, the estimated hydraulic conductivity becomes extremely small even at relatively high pressure heads, resulting in unstable simulations.

The soil hydraulic properties for the SP model of van Genuchten (1980) were described as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + (\alpha h)^n)^m}, \quad m = 1 - \frac{1}{n} \tag{1}$$

$$K(h) = K_s S_e^{0.5}\left(1 - \left(1 - S_e^{1/m}\right)^m\right)^2, \tag{2}$$

where S_e is the effective degree of saturation [–], θ_r and θ_s are the residual and saturated water contents [cm^3/cm^3], respectively, α [1/cm > 0], n [-, $n > 1$] and m (=1–1/n, $0 < m < 1$) [–] are fitting parameters affecting the shape of the retention curve, and K_s is the saturated hydraulic conductivity [cm/day].

The soil hydraulic properties for the DP model of Durner (1994) were defined as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^{k} w_i \frac{1}{(1 + |\alpha_i h|^{n_i})m_i} \tag{3}$$

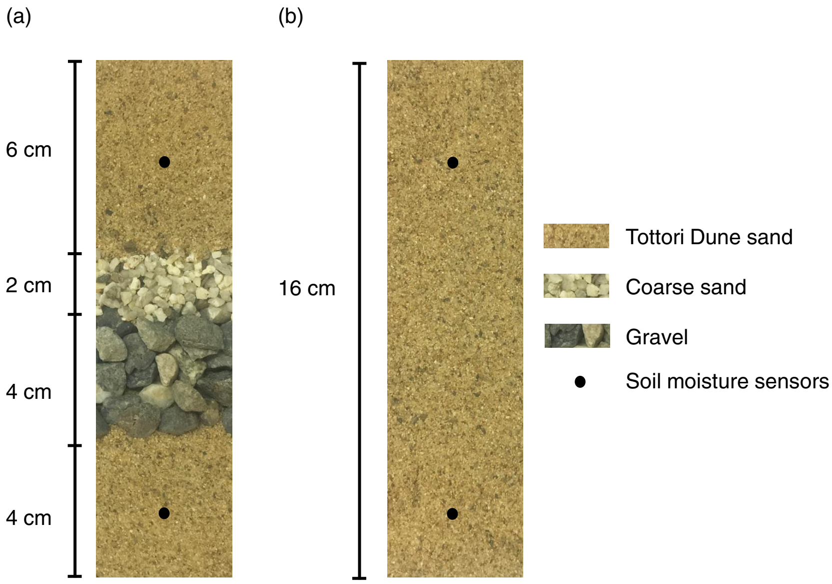

Figure 1 The soil profiles with (a) and without (b) a capillary barrier (CB) layer in the cultivation experiment (Miyake *et al*., 2015). [Colour figure can be viewed at wileyonlinelibrary.com]

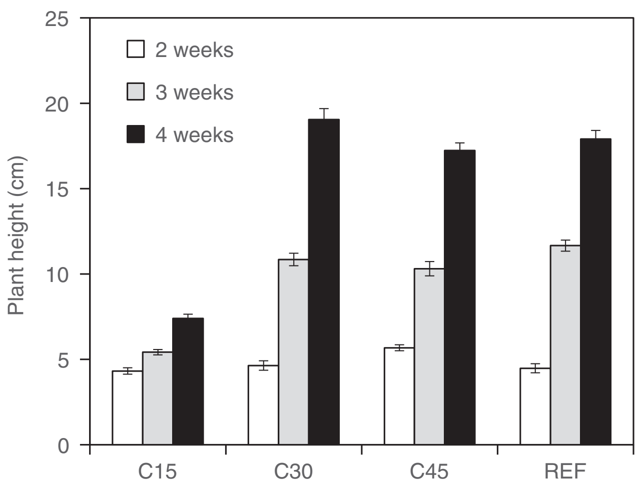

Figure 2 Average heights of Japanese spinach after 2, 3 and 4 weeks of cultivation in scenarios C15, C30, C45 and REF. Error bars indicate standard deviations of measurements (Miyake *et al*., 2015).

$$K(h) = K_s \frac{(w_1 S_{e_1} + w_2 S_{e_2})^l \left(w_1 \alpha_1 \left(1 - \left(1 - S_{e_1}^{1/m_1} \right)^{m_1} \right) + w_2 \alpha_2 \left(1 - \left(1 - S_{e_2}^{1/m_2} \right)^{m_2} \right) \right)^2}{(w_1 \alpha_1 + w_2 \alpha_2)^2}, \quad (4)$$

where w_i is the weighting factor for the overlapping regions, l is the pore-connectivity parameter (0.5), and α_i, n_i and m_i (=1–1/n_i) are fitting parameters of the sub-curves. While the SP model was fitted using the SWRC Fit program (Seki, 2007), the DP model was manually fitted in a trial-and-error fashion to the experimental retention curve. The fitting parameters of the DP model were determined so that the general shape of the measured soil water retention curve was well reproduced.

The saturated hydraulic conductivity (K_s) of dune sand and coarse sand was measured using the constant head method. In the case of gravel, the seepage rate was too high to measure K_s accurately using the constant head method; it was therefore estimated using available empirical models. The Kozeny (1927)-Carman (1937), Hazen (1892), Slichter (1899) and Terzaghi (1925) equations were compared to estimate K_s. The measured K_s of sand and coarse sand were compared with the K_s estimated using the above equations to find the best estimator for K_s. As the Hazen (1892) equation resulted in the minimum error for K_s of sand and coarse sand, it was also used to estimate K_s of gravel in this study.

According to the Hazen (1892) equation, K_s [cm/s] can be estimated as follows:

$$K_s = C_H {D_{10}}^2, \quad (5)$$

where C_H is an empirical coefficient [1/(cm/s)], which ranges from 1 to 1000 (Carrier, 2003) and D_{10} is the effective particle size in cm, for which 10% of the soil particles are finer. C_H was set to 1 because it is suitable for the estimation of K_s for uniformly graded soils from very fine sand to gravel. As a result of the particle size distribution analysis, the D_{10} of gravel used in this study was estimated to be between 0.475 cm and 0.485 cm. The K_s was then computed as a geometric mean of ten different D_{10} values ranging from 0.475 cm and 0.485 cm.

Numerical simulations

HYDRUS-1D (Šimůnek *et al.*, 2008, 2016) was used to simulate soil water contents in soil containers with a CB layer installed during the cultivation of Japanese spinach (Miyake *et al.*, 2015). In HYDRUS-1D, water flow in variably saturated soil is simulated by numerically solving the following Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S, \qquad (6)$$

where h is the soil water pressure head [cm], θ is the volumetric water content (VWC) [cm^3/cm^3], t is time [day], z is the vertical coordinate that is positive upward [cm], $K(h)$ is the unsaturated hydraulic conductivity [cm/day], and S is the source/sink term [cm^3/cm^3/day]. The sink term, S, is defined as the volume of water removed from a unit volume of soil per unit time because of plant water uptake. In HYDRUS-1D, a model proposed by Feddes *et al.* (1978) is used to evaluate S:

$$S = \alpha(h)R(z)T_p, \qquad (7)$$

where $R(z)$ is the normalized water uptake distribution function as a function of depth z [1/cm], T_p is the potential transpiration rate [cm/day] and $\alpha(h)$ is the stress response function [-], which is a prescribed dimensionless function of the soil water pressure head h ($0 \le \alpha \le 1$). The $\alpha(h)$ function is defined using a piecewise linear function introduced by Feddes *et al.* (1978):

$$\alpha(h) = \begin{cases} 0, & h \le h_4, h > h_1 \\ (h - h_1)/(h_2 - h_1), & h_2 \le h < h_1 \\ 1, & h_3 < h \le h_2 \\ (h - h_4)/(h_3 - h_4), & h_4 < h \le h_3 \end{cases} \qquad (8)$$

where h_1, h_2, h_3 and h_4 are the threshold parameters. Root water uptake is assumed to be zero when $h < h_4$ or $h > h_1$, to be at its potential value when the pressure head is between h_2 and h_3, and to increase (or decrease) linearly with h when $h_1 > h > h_2$ or $h_4 < h < h_3$. In this study, the Feddes parameters for lettuce, as morphology of this leafy vegetable was similar to Japanese spinach, were chosen from the database in HYDRUS-1D (Šimůnek *et al.*, 2008), and modified to stabilize numerical solutions as explained later. Although the wilting point h_4 is usually set in the range of −80 to −150 m, at which the water content of coarse soil is almost equal to the residual water content, h_4 should be selected so that the corresponding water content is at least 0.005 greater than the residual water content for a numerical reason. Table 1 lists the threshold pressure heads, h_1 to h_4, of the stress response function used in this study.

Because soil water dynamics were simulated from seeding to final cultivation, the root growth module implemented in HYDRUS was used to obtain the rooting depth, l_r [cm], at any given time. The rooting depth was assumed to be proportional to the Surface Cover Fraction (SCF). A linear interpolation was used to obtain l_r at a given time from the observed SCF. The trapezoidal function of Hoffman & van Genuchten (1983) that is implemented in HYDRUS was used as a normalized water uptake distribution function $R(z)$. The simulation domain was 16 cm deep and discretized into 120 finite elements of equal sizes. While the 6-cm-thick CB layer was positioned at a depth of 6 cm for the CB profiles, the reference profile consisted of a 16-cm dune sand layer without a CB layer. In all simulations, two observation points at depths of 3 and 14 cm were used to compare simulated and observed VWC.

A constant pressure head of −200 cm was assigned to the whole domain as an initial condition. The atmospheric boundary condition with surface run off was used as the upper boundary condition. This boundary condition requires potential evapotranspiration and irrigation fluxes as input. The actual evapotranspiration rate obtained from Miyake *et al.* (2015) was split into the potential transpiration and evaporation rates using SCF. SCF values during the cultivation period were proportional to the SCF values estimated at the end of the cultivation using photograph images taken from above. The irrigation fluxes were determined by assuming that irrigation water was applied over the duration of 30 min. The depth of the root zone was determined based on the root depth data obtained by Miyake *et al.* (2015). A no-flux boundary condition was assigned at the lower boundary. The simulation period was 28 days. In HYDRUS, the time step is automatically adjusted between the minimum and maximum time steps specified by the user. In this study, they were 10^{-7} and 10^{-3} days, respectively.

Table 1 The threshold parameters of the Feddes model used in the HYDRUS simulations for spinach

Threshold parameters of the Feddes model	Initial parameters (lettuce) (cm)	Modified parameters (cm)
h1	−10	−10
h2	−25	−25
h3	−400	−190
h4	−600	−200

Alternative irrigation schedule

Figure 2 shows the plant height of the Japanese spinach from the cultivation experiment of Miyake *et al.* (2015). The plant growth rate was 1.54, 7.21, 5.78 and 6.71 cm per week for CB15, CB30, CB45 and REF, respectively. This shows that the spinach growth was at maximum for CB30. However, it is not obvious whether the daily application of 0.3 cm of water indeed maximized root water uptake and the transpiration rate of the Japanese spinach under the application of a liquid fertilizer twice a week with a CB at a 6-cm depth. To investigate if the water use efficiency (WUE) could be improved during spinach cultivation in the CB profile, a numerical analysis was performed with different irrigation schedules for the same simulation setup used for CB30 in the previous section.

Two different irrigation schedules were compared. The same amount of water (0.5 cm) was applied during the first two days after seeding in both irrigation schedules. In the first irrigation schedule, 0.3 cm of water was applied every other day (every 2 days) during the first stage of plant growth (from day 4 to day 14) when only small leaves were grown, instead of irrigating every day. This resulted in 7 cm of irrigation water in total, which is 1.5 cm less than the 8.5 cm of water applied during the CB30 experiment. In the second irrigation schedule, the amount of applied water was reduced by irrigating every other day during the entire cultivation period. This resulted in the application of only 4.9 cm of water. The effect of the irrigation schedule was evaluated by comparing the actual root water uptake (RWU) rate.

Results and discussion

Soil hydraulic properties

Observed soil water retention curves for the materials used in this study are plotted along with the fitted water retention model curves in Figure 3. Figure 4 then shows the predicted unsaturated hydraulic conductivity functions that correspond to those retention curves. Both the SP and DP models were fitted to the coarse sand and gravel retention data. All three experimental retention curves clearly show the air-entry point (Figure 3). The SP model fits well with the dune sand retention data. The experimental retention data for coarse sand and gravel showed that the residual water content was already reached at pressure heads larger than −10 cm. Although the SP model fits well with the experimental retention curves of coarse sand and gravel, the corresponding unsaturated hydraulic conductivity functions shown in Figure 4 unrealistically predict small conductivity values at lower pressure heads.

The DP model was fitted in a trial-and-error fashion to the experimental retention curves of coarse sand and gravel. The hydraulic conductivity in the dry range was not as low

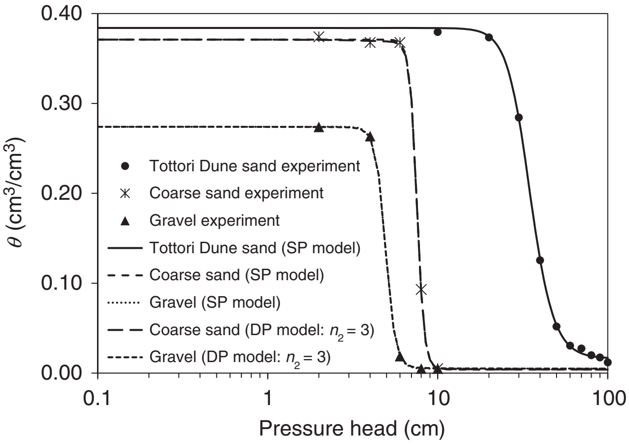

Figure 3 Measured and fitted retention curves of Tottori Dune sand, coarse sand and gravel. Single-porosity (SP) and dual-porosity (DP) models were used in fitting.

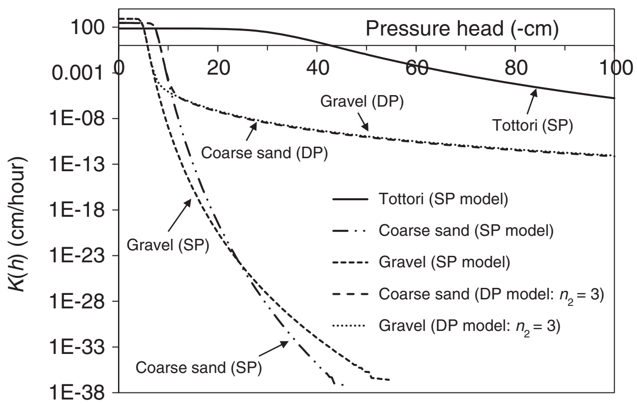

Figure 4 Estimated hydraulic conductivity functions of Tottori Dune sand, coarse sand and gravel calculated using the SP model and the DP model when n_2 was set to 3.

as predicted by the SP model, although it was still significantly lower than for dune sand. Parameters w_2, w_1, α_2 and n_2 were set to 0.01, 0.99, 0.25 and 3, respectively. The difference between the fitted SP and DP retention models was almost imperceptible because w_2 is very small (Figure 3). On the other hand, the $K(h)$ predicted by the DP model in the dry range was much larger than that predicted by the SP model. Table 2 lists the basic soil hydraulic parameters of the materials used in the following HYDRUS-1D simulations.

Numerical analysis

The observed VWCs (Figure 5) were averaged from hourly observed VWCs. The HYDRUS-1D simulation reproduced the soil water contents above (at a depth of 3 cm) and below (at a depth of 14 cm) the CB layer reasonably well for CB15

Table 2 Soil hydraulic parameters for the single-porosity (SP) and dual-porosity (DP) models for Tottori Dune sand, coarse sand and gravel used in HYDRUS-1D

Materials	θ_r	θ_s	α (1/cm)	n	K_s (cm/s)	w_1	w_2	α_2 (1/cm)	n_2
Tottori Dune sand	0.016	0.384	0.030	6.665	0.020				
Coarse sand	0.004	0.371	0.133	20.772	0.081	0.99	0.01	0.25	3
Gravel	0.005	0.274	0.204	15.524	0.230	0.99	0.01	0.25	3

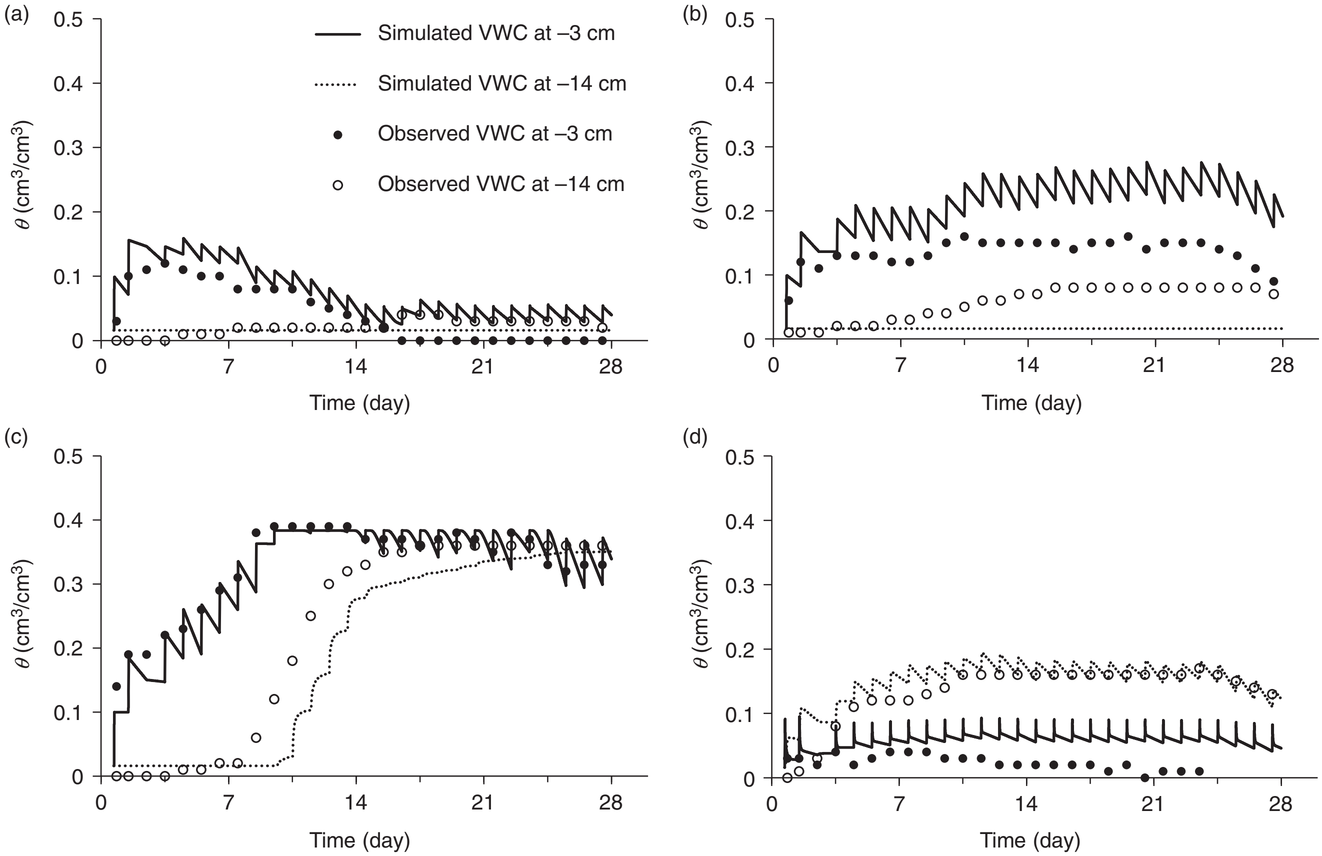

Figure 5 A comparison of observed (symbols) and simulated (lines) volumetric water contents (VWC) for experiments with different irrigation rates. Results for the soil containers with the CB and irrigation rates of 0.15, 0.30 and 0.45 cm/day are shown in (a), (b) and (c), respectively. Results for the soil container without a CB and the irrigation rate of 0.30 cm/day are in (d). It should be noted that the first values of VWC at a depth of 3 cm in (d) were observed after additional water was applied during the seedling day.

and CB45, although the timing of a sudden increase in the water content at a depth of 14 cm was not well reproduced for CB45 (Figure 5). In CB45, the simulated water contents of the top layer reached almost full saturation and water held above the interface leaked into the bottom layer through the CB layer. An accurate prediction of the break time may require detailed characterization of the spatial distribution of pore sizes at the interface, which is impractical. Also, it is more important to know whether the amount of applied water was too high for a CB to keep functioning than to know when the break occurs.

For CB30, the simulated values were higher than observed values at a depth of 3 cm and lower at a depth of 14 cm (Figure 5). Although the simulation results showed that vertically infiltrated water stopped at the interface, the water content in the bottom layer also increased continuously during the experiment. This may be caused by water reaching the bottom layer along the container walls during the experiment, which is common in lysimeter experiments (Corwin, 2000). In addition to sidewall flow, water vaporization and condensation may occur near the container walls because of changes in temperature between nighttime and daytime, although all containers were insulated with styrene foams.

For REF, while the simulated values overestimated the observed values at a depth of 3 cm, the observed and simulated VWCs corresponded well. Given that none of the soil hydraulic parameters were calibrated, the results give us confidence that the HYDRUS-1D model can be used to simulate soil VWCs in the CB profile during Japanese spinach cultivation.

The simulation results for CB15 and CB30 showed that water accumulated at the interface between dune sand and coarse sand (Figure 6a and b). For CB45, as the top layer almost reached full saturation, the first capillary barrier of coarse sand was broken after a few days and the second barrier of gravel after about a week (Figure 6c). Although the VWC in the gravel layer did not increase much, it was sufficient to conduct water from the coarse sand layer to the dune sand layer. As a result, the VWCs in all layers increased. The simulated profile for REF showed that without a CB, water infiltrated all the way to the bottom of the container.

This study shows that HYDRUS simulations with appropriate hydraulic models predict soil water dynamics well in a soil profile with a CB at a column scale. Similarly, Ityel *et al.* (2011) performed HYDRUS (2D/3D) simulations to investigate the soil water content in the root zone of a plot experiment with an installed CB. While they did not account for RWU, they found that HYDRUS (2D/3D) performed well in simulating soil water dynamics inside the CB system. Our results, taken together with those reported by Ityel *et al.* (2011) thus demonstrate that HYDRUS is a good tool to simulate the performance of the CB system. Additionally, HYDRUS has also been successfully used to simulate soil water dynamics in systems with other types of physical barriers (e.g. El-Nesr *et al.,* 2014; Guber *et al.,* 2015. El-Nesr *et al.* (2014) showed with the HYDRUS (2D/3D) model that the 1-cm-thick impermeable physical barrier significantly changed the wetting pattern and the distribution

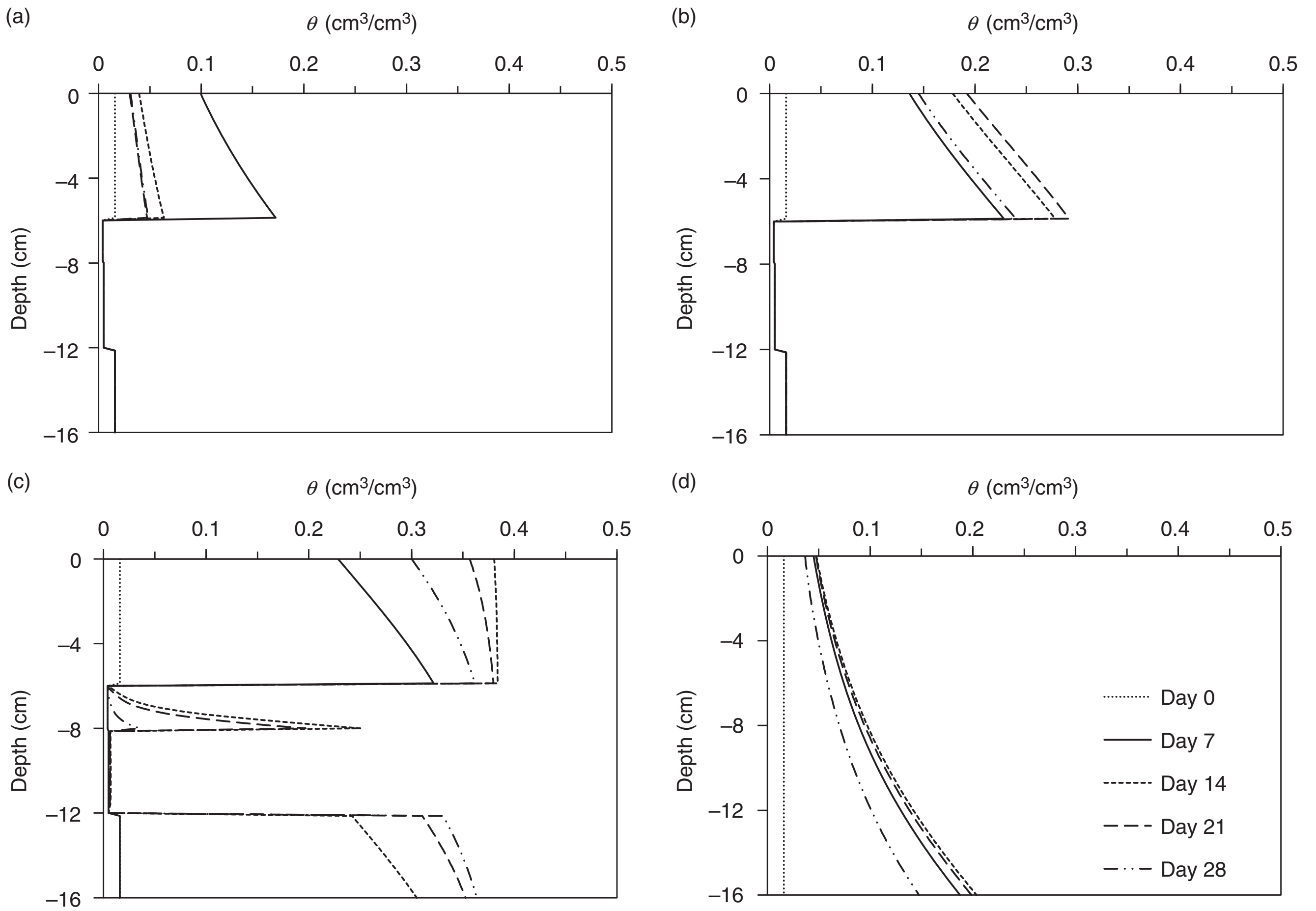

Figure 6 Simulated volumetric soil water contents at different times. Results for the soil containers with the CB and irrigation rates of 0.15, 0.30 and 0.45 cm/day are shown in (a), (b) and (c), respectively. Results for the soil container without a CB and the irrigation rate of 0.30 cm/day are in (d).

of nutrients in the root zone by preventing downward movement of water and nutrients. Guber *et al*. (2015) used the HYDRUS (2D/3D) model to evaluate the effects of the shape, installation depths and alignment of the polyethylene membrane barriers on reducing leaching water losses for different soil textures.

The role of CB on an increase in water use efficiency

Simulated cumulative RWUs for CB15, CB30, CB45 and REF were 0.13, 4.48, 6.03 and 4.76 cm, respectively, while simulated cumulative evaporations were 4.48, 2.98, 2.99 and 2.76 cm, respectively (Figure 7 and Table 3). These results reflect the fact that the spinach growth was similar for CB30, CB45 and REF. They also reveal that more than 90% of irrigated water in CB15 and more than 30% of irrigated water in CB30 and REF evaporated from the soil surface. Stormont & Morris (1998) also showed that a significant amount of water stored near the surface in the CB system could be lost by evaporation. This means that controlling the evaporation rate is also important for improving the WUE during spinach cultivation in the CB profile. For CB45, only about 25% of water was lost because of evaporation as a significant amount of water infiltrated below the CB layer.

Alternative irrigation schedules

Figure 8 shows computed cumulative RWU rates for different irrigation schedules during the cultivation with and without a CB. The one without a CB was obtained by using an 80-cm-long domain where the bottom boundary condition was set to free drainage (i.e. the pressure head gradient was forced to zero). The irrigation schedule for the non-CB profile was the same as for CB30. When the irrigation frequency was reduced by half during the initial stage of plant growth, the cumulative RWU was almost the same as for the original CB30 and much greater than for the non-CB profile. With a CB, the spinach roots can uptake water almost at the same rate as in CB30 even though the irrigation frequency is reduced during the early stage of the cultivation because applied water is stored in the root zone above a CB. This means that by reducing the irrigation frequency during the early growth stage, water loss by

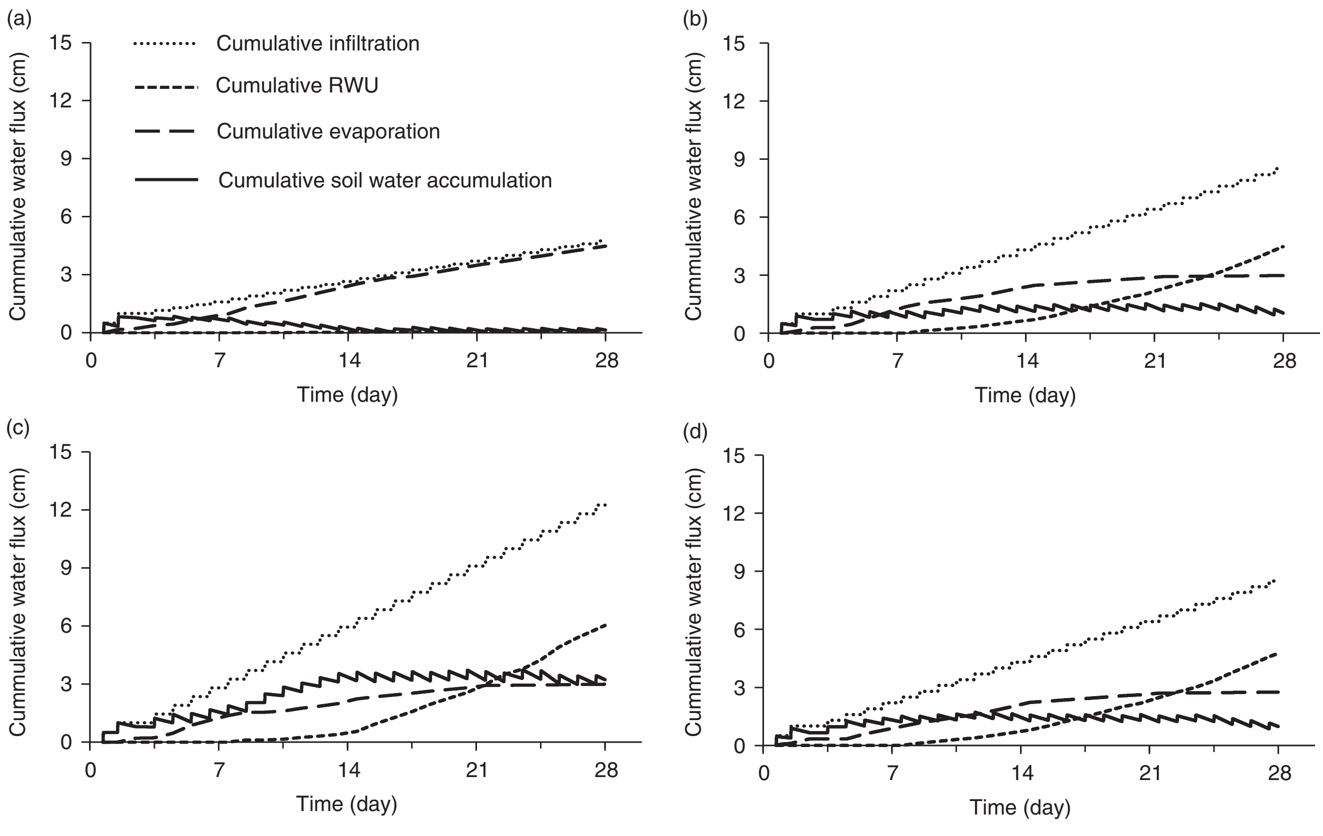

Figure 7 Simulated cumulative infiltration, root water uptake (RUW), evaporation and soil water accumulation at different times. Results for the soil containers with a CB and irrigation rates of 0.15, 0.30 and 0.45 cm/day are shown in (a), (b) and (c), respectively. Results for the soil container without a CB and the irrigation rate of 0.30 cm/day are displayed in (d).

Table 3 Simulated cumulative infiltration, root water uptake (RWU) and evaporation for each simulated scenario

Cumulative fluxes (cm)	CB15	CB30	CB45	REF
Infiltration	4.75	8.50	12.25	8.50
Root water uptake (RWU)	0.13	4.48	6.03	4.76
Evaporation	4.48	2.98	2.99	2.76
Water storage	0.14	1.04	3.23	0.98

evaporation can be greatly reduced. In other words, the water use efficiency can be improved without sacrificing root water uptake much.

The irrigation frequency during the later stage was also further reduced by half. Cumulative RWU, in this case, could not keep up with that of CB30, especially after day 14 (Figure 8). It was shown that the amount of irrigation water could be reduced by half during the early growth stage. However, during the later stage when plant growth is at its maximum, reducing the irrigation frequency by half may inhibit plant growth. Simulated cumulative evaporation for alternative irrigation scenarios was 2.64 and 2.48 cm, respectively, while that for CB30 was 2.99 cm. Although the amount of applied water was significantly reduced, the simulated amount of water evaporated from the soil surface did not decrease much. The water loss by evaporation needs to be taken into account when deciding the irrigation schedule even when the CB layer is installed to improve the water retention of the root zone. In addition to maximizing the water use efficiency, all possible irrigation schedules would have to be examined. That was, however, beyond the scope of this study.

This study numerically demonstrates the role of a CB in improving root zone conditions and maximizing the WUE. Semi-commercial scale experiments conducted in greenhouses during cultivation of a horticultural crop by Ityel *et al.* (2012) showed that the installation of a CB increased the soil water content by 60% and the fruit yield by 25% for green peppers, and increased the matric head by 80% and the biomass yield by 36% for lettuce. However, although the CB system can be installed on a large commercial field scale, there are some challenges associated with the maintenance of a CB. For example, soil management activities such as tillage and seedbed preparation can cause the movement of the top soil, during which finer soil particles can penetrate and fill the larger pores of the coarser layer, resulting in a break of a CB layer. To minimize such risk, Ityel *et al.* (2011) installed a sheet material to keep the gravel layer separate from the layer above. Alternatively, Miyake *et al.* (2015) proposed a two-layered CB system where a thin 2-cm coarse sand layer was installed between the top sand layer and the lower gravel layer. The 2-cm coarse sand layer intercepts fine sand particles penetrating from the top sand layer so that pores of the gravel layer are kept open. However, a shallow CB layer can be easily damaged by machinery, which is necessary in large-scale farming. The installation of a CB system of the design used in this study in a large-scale field thus may not be appropriate. The CB system needs to be carefully designed for large-scale farming.

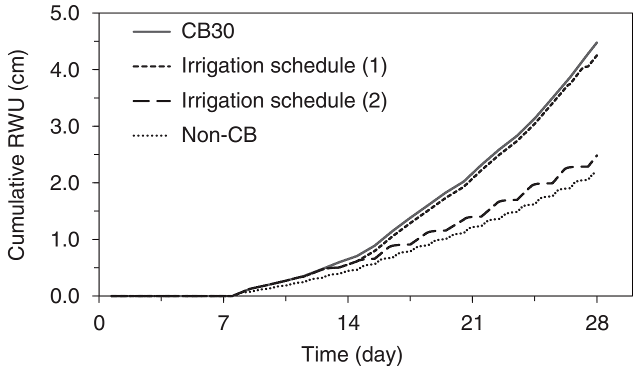

Figure 8 Cumulative root water uptake (RWU) for different irrigation strategies based on CB30. The irrigation schedule (1) involves the soil container with a CB in which 0.30 cm of water was applied every other day during the first stage of plant growth (from day 4 to day 14). The irrigation schedule (2) involves the soil container with a CB where 0.30 cm of water was applied every 2 days during the entire growing period. The non-CB scenario represents the soil profile without a CB.

While the installation of a CB in the root zone can avoid excess nutrients or pesticides leaching to groundwater, it may result in accumulation in the root zone. Without appropriate treatment, such farmland can then be damaged for further cultivation. For the long-term utilization of CB systems for cultivation, a CB layer that can be directly installed in the root zone and easily displaced for soil maintenance needs to be further developed.

Conclusions

A numerical analysis of soil water dynamics in a dune sand profile with a capillary barrier layer installed at a depth of 6 cm during leaf vegetable cultivation was performed in this study using HYDRUS-1D. In most cases, the simulated soil volumetric water contents were in good agreement with the observed results when the dual-porosity model describing hydraulic properties was used for gravel and coarse sand. The numerical simulations of alternative irrigation schedules showed that when a CB is installed, the irrigation frequency can be reduced by half during the early growth stage and the water use efficiency can be improved. These results demonstrate that a CB system can be a practical tool for leafy vegetable cultivation in sandy soil.

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References

Abdolahzadeh, A.M., Lacroix Vachon, B. & Cabral, A.R. 2011. Evaluation of the effectiveness of a cover with capillary barrier effect to control percolation into a waste disposal facility. *Canadian Geotechnical Journal*, **48**, 996–1009.

Berger, J., Fornés, L.V., Ott, C., Jager, J., Wawra, B. & Zanke, U. 2005. Methane oxidation in a landfill cover with capillary barrier. *Waste Management*, **25**, 369–373.

Brunetti, G., Šimůnek, J. & Piro, P. 2016. A comprehensive analysis of the variably saturated hydraulic behavior of a green roof in a Mediterranean climate. *Vadose Zone Journal*, **15**, doi:10.2136/vzj2016.04.0032

Carman, P. 1937. Fluid flow through a granular bed. *Transactions of the Institution of Chemical Engineers*, **15**, 150–167.

Carrier, W.D. 2003. Goodbye, Hazen; Hello, Kozeny-Carman. *Journal of Geotechnical and Geoenvironmental Engineering*, **129**, 1054–1056.

Cheng, X., Huang, M., Si, B.C., Yu, M. & Shao, M. 2013. The differences of water balance components of *Caragana korshinkii* grown in homogeneous and layered soils in the desert–Loess Plateau transition zone. *Journal of Arid Environments*, **98**, 10–19.

Corwin, D.L. 2000. Evaluation of a simple lysimeter-design modification to minimize sidewall flow. *Journal of Contaminant Hydrology*, **42**, 35–49.

Dane, J.H. & Hopmans, J. 2002. *Methods of soil analysis, Part 4; Physical methods; Laboratory determination of water retention*. Soil Science Society of America, Inc., Madison, WI.

Durner, W. 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. *Water Resources Research*, **30**, 211–223.

El-Nesr, M.N., Alazba, A.A. & Šimůnek, J. 2014. HYDRUS simulations of the effects of dual-drip subsurface irrigation and a physical barrier on water movement and solute transport in soils. *Irrigation Science*, **32**, 111–125.

Feddes, R.A., Kowalik, P.J. & Zaradny, H. 1978. *Simulation of field water use and crop yield*. Wiley, New York.

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, **44**, 892–898.

Guber, A.K., Smucker, A.J.M., Berhanu, S. & Miller, J.M.L. 2015. Subsurface water retention technology improves root zone water storage for corn production on coarse-textured soils. *Vadose Zone Journal*, **14**, 2–13.

Hazen, A. 1892. Some physical properties of sands and gravels, with special reference to their use in filtration. In: *24th Annual Rep, Massachusetts State Board of Health. pp. 539–556*.

Hoffman, G.J. & van Genuchten, M.T. 1983. Soil properties and efficient water use: Water management for salinity control. In: *Limitations to efficient water use in crop production* (eds H.M. Taylor, W.R. Jordan & T.R. Sinclair), pp. 73–85. ASA-CSSA-SSSA, Madison, WI.

Ityel, E., Lazarovitch, N., Silberbush, M. & Ben-Gal, A. 2011. An artificial capillary barrier to improve root zone conditions for horticultural crops: physical effects on water content. *Irrigation Science*, **29**, 171–180.

Ityel, E., Lazarovitch, N., Silberbush, M. & Ben-Gal, A. 2012. An artificial capillary barrier to improve root-zone conditions for horticultural crops: response of pepper, lettuce, melon, and tomato. *Irrigation Science*, **30**, 293–301.

Kozeny, J. 1927. Uber kapillare leitung des wassers in boden. *Sitzungsber. Akad. Wiss. Wien*, **136**, 271–306.

Miyake, M., Otsuka, M., Fujimaki, H., Inoue, M. & Saito, H. 2015. Evaluation of an artificial capillary barrier to control infiltration and capillary rise to root zone areas. *Journal of Arid Land Studies*, **25**, 117–120.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, **12**, 513–522.

Rooney, D.J., Brown, K.W. & Thomas, J.C. 1998. The effectiveness of capillary barriers to hydraulically isolate salt contaminated soils. *Water, Air, and Soil Pollution*, **104**, 403–411.

Seki, K. 2007. SWRC fit – a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. *Hydrology and Earth System Sciences Discussions*, **4**, 407–437.

Šimůnek, J., van Genuchten, M.T. & Šejna, M. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal*, **7**, 587–600.

Šimůnek, J., van Genuchten, M.T. & Šejna, M. 2016. Recent developments and applications of the HYDRUS computer software package. *Vadose Zone Journal*, **15**, 1539–1663.

Slichter, C.S. 1899. Theoretical investigation of the motion of ground waters. In. US Geological Survey 19th Annual Report, pp. 322.

Stormont, J.C. & Morris, C.E. 1998. Method to estimate water storage capacity of capillary barriers. *Journal of Geotechnical and Geoenvironmental Engineering*, **124**, 297–302.

Terzaghi, C. 1925. *Principles of soil mechanics. Engineering News-Record*, **95**, 832.

Zhang, X., Lu, G., Long, W., Zou, X., Li, F. & Nishio, T. 2014. Recent progress in drought and salt tolerance studies in *Brassica* crops. *Breeding Science*, **64**, 60–73.

Zhu, M., Monroe, J.G., Suhail, Y., Villiers, F., Mullen, J., Pater, D., Hauser, F., Jeon, B.W., Bader, J.S., Kwak, J.M., Schroeder, J.I., McKay, J.K. & Assmann, S.M. 2016. Molecular and systems approaches towards drought-tolerant canola crops. *New Phytologist*, **210**, 1169–1189.