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Assessing salinity leaching efficiency in three soils by the HYDRUS-1D and -2D simulations

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ABSTRACT

Salinity leaching is necessary to sustain agricultural production in irrigated croplands. Improving salinity leaching efficiency not only conserves water but also reduces groundwater contamination. Current leaching requirement (*LR*) calculations are based on steady-state and one-dimensional (1D) approaches, and consequently, this *LR* concept may not be applicable to drip irrigation (approximately 2D), which is becoming more common due to its higher water use efficiency. The aims of this study were to assess the salinity leaching fraction (*LF*) in clay, loam, and sand soils under 1D (to mimic sprinkler irrigation) and 2D (to mimic drip irrigation) transient conditions with a numerical model (HYDRUS). Water applications used the actual irrigation scheme in an almond orchard located in central California without considering precipitation. Model simulations showed that soil salinity at the lower boundary (depth of 150 cm) reached steady-state in 10 years in HYDRUS-1D simulations. The leaching fractions calculated from the ratio of drainage-water depth to irrigation-water depth ($LF_w = D_{dw}/D_{iw}$) and irrigation-water salinity to drainage-water salinity ($LF_{EC} = EC_{iw}/EC_{dw}$) from HYDRUS-1D were similar among different textured soils. However, they were much higher under drip irrigation (2D) than under sprinkler irrigation (1D) when the same amount of water was applied, and LF_{EC} values were much greater than the LF_w values under 2D simulations. Salt balance (*SB*) and leaching efficiency (*LE*) indicated that sprinkler irrigation (1D) is more effective for salinity leaching than drip irrigation (2D). To improve salinity leaching efficiency, further evaluation of *LRs* under drip irrigation is needed.

1. Introduction

The level and distribution of salinity in irrigated cropland soils are the result of time-dependent interactions of rainfall, irrigation, evapotranspiration, leaching, and drainage. These interactions involve crop growth and yield, root water extraction, soil salinity, irrigation, salt-loading, leaching, and drainage are complicated and are not fully understood or quantified (Corwin et al., 2007). In irrigated soils, salts will remain behind and concentrate on the crop root zone because crops take up nearly pure water for transpiration. Thus, periodic leaching is required to move excessive salts downward to minimize crop yield reduction (Letey et al., 2011).

The ratio of the water depth that drains beyond the root zone relative to the depth of applied irrigation water is defined as a leaching fraction (*LF*). The minimum *LF* that will adequately leach salts out of the root zone to prevent soil salinity from exceeding a specified value over a growing season, for the water of a particular quality, is defined as the leaching requirement (*LR*) (U.S. Salinity Lab, 1954). A soil profile that has been irrigated over a long period will reach steady-state conditions with regard to salt accumulation and distribution, and the *LF* can be estimated using the ratio of the electrical conductivities of irrigation water (EC_{iw}, dS/m) and drainage water (EC_{dw}, dS/m), $LF = EC_{iw}/EC_{dw}$ (dS/m) or the ratio of drainage water depth (D_{dw}) to irrigation water depth (D_{iw}) (Letey and Feng, 2007).

In recent years, the appropriateness of the traditional method related to the steady-state assumption has been discussed. A comprehensive evaluation of steady-state approaches and transient model evaluations indicated that there exist substantial differences among different methods in estimating *LRs* (Letey et al., 2011). Hoffman (1985) also compared 5 different steady-state *LR* calculation methods using the field and plot experimental data based on the mass balance of both water and salts, and found that the highest correlation coefficient

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between measured and predicted values was 0.67, indicating that none of the methods was completely satisfactory. Gonçalves et al. (2006) analyzed transient water flow and solute transport in three soil lysimeters irrigated with waters of different *ECs* over a period of 4 years using the HYDRUS-1D model (Šimůnek et al., 2008, 2016) with major ion chemistry subroutines from UNSATCHEM, indicating that HYDRUS-1D with UNSATCHEM can successfully simulate the water regime, as well as the effects of different irrigation water on the geochemistry of the test soil. *LRs* based on steady-state, one-dimensional (1D) and water balance approaches often overestimate those observed values under field conditions (Oster et al., 2012). Another question is related to the fact that surface and sprinkler irrigated fields have been largely converted to drip or micro-spray systems for regions in California, South Africa, Israel, and some other areas. Consequently, the 1D water balance approach for calculating field-scale *LFs* is considered to be inappropriate for drip irrigation (Ayars et al., 1999; Dhawan, 2000; Benouniche et al., 2016).

The temporal pattern of soil water and salinity in cropland soils is often transient instead of steady-state. It appears that a single *LR* value is not sufficient for describing inherently transient and non-uniform systems. Many studies have investigated the movement and distribution of water and salts in soils under drip irrigation. Nightingale et al. (1991) estimated the apparent *LFs* for drip irrigation in a silt/clay loam soil using chloride concentrations under three water application rates at 50%, 100%, 150% of crop evapotranspiration rates (ET_c). They estimated that the *LFs* in the 1-m space drip line system was 0.05, 0.22, and 0.36, respectively, for 50% ET_c, 100% ET_c and 150% ET_c, and was 0.06 to 0.34, respectively, in the 1.6 m space drip line system for the 100% and 150% of ET_c treatments. It was observed that the *LFs* decreased with distance from the drip line for the 100% and 150% of the ET_c treatment, and increasing the water volume to 100% and 150% of ET_c moved the zone of salt accumulation farther from the drip line.

Hanson et al. (2008) defined the localized leaching fraction (*LLF*) as the actual leaching fraction representative of the local irrigated root domain near the drip line. They found that higher salinity accumulated on the edges of the wetted zone, and localized salt leaching around/below the drip line occurred even under deficit irrigation. Raij et al. (2016) used drip-irrigated lysimeter to calibrate the HYDRUS 2D/3D coupled with UNSATCHEM module and evaluated *LFs* using drainage water fluxes, chloride concentrations and overall salinity of the drainage water. Their results showed that, over the long term, *LFs* calculated from electrical conductivity (*EC*) were affected by the pressure head at the lower boundary conditions of the soil profile, while *LFs* calculated from chloride concentrations and drainage fluxes were not affected.

The evaluation of *LFs* whether using steady-state or transient models is still a controversial topic (Corwin et al., 2007; Letey and Feng, 2007; Dudley et al., 2008; Letey et al., 2011). There has been wide interest in the concept of *LFs* under both steady-state and transient state. Nevertheless, application of the traditional *LF* approach to new irrigation systems such as drip irrigation can lead to erroneous conclusions, which would directly affect irrigation decision making. Improving leaching efficiency can minimize salt accumulation in the root zone and sustain crop production with less water. However, few studies have been published to consider the effects of multidimensionality of flow and solute patterns, root water uptake, and soil texture on *LF* calculation and leaching efficiency, especially at the field scale.

The objectives of this study were to use the HYDRUS-1D and HYDRUS-2D models to (1) predict salinity leaching in three soils of different textures (clay, loam, and sand) under sprinkler (1D) and drip (2D) irrigation based on the actual irrigation scheme of an almond orchard in central California, (2) reveal differences in soil water and salinity distributions in the three test soils with two different root water uptake functions and their associated *LFs* under drip (2D) and sprinkler (1D) irrigation systems, and (3) evaluate leaching efficiency under different soil types, irrigation methods, and root water uptake functions.

2. Materials and methods

2.1. Water flow modeling

To simulate water flow, the Richards equation [Eq. (1)] subject to appropriate initial and boundary conditions is numerically solved in both HYDRUS-1D and HYDRUS-2D models using the Galerkin finite element method based on the mass conservative iterative scheme proposed by Celia et al. (1990):

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

where θ is the volumetric water content ($cm^3\,cm^{-3}$), h is the matric pressure head (cm H_2O), $K(h)$ is the soil unsaturated hydraulic conductivity (cm day^{-1}), x is the horizontal coordinate (cm), z is the vertical coordinate (cm), and $S(h)$ is the root water uptake term ($cm^3\,cm^{-3}\,day^{-1}$).

The relationship between θ and h is represented in the HYDRUS models using the following equation (van Genuchten, 1980v):

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

where θ_s is the saturated volumetric water content ($cm^3\,cm^{-3}$), θ_r is the residual volumetric water content ($cm^3\,cm^{-3}$), α, n, and m are empirical parameters (m = 1-1/n).

The unsaturated hydraulic conductivity $K(h)$ is defined as a function of h (van Genuchten, 1980):

$$K(h)=K_sS_e^{0.5}[1-(1-S_e^{1/m})^m]^2 \tag{3}$$

where K_s is the saturated hydraulic conductivity (cm day^{-1}), and S_e is the effective saturation.

The root water uptake model is based on the sink term in the Richards equation, $S(h)$, representing the volume of water removed from a unit volume of soil per unit time due to plant water uptake (Feddes et al., 1978):

$$S(h)=\beta(h)S_p \tag{4}$$

where S_p is the potential water uptake rate (day^{-1}), which is reduced using the water stress response function $\beta(h)$ that is a prescribed dimensionless function of the soil water pressure head ($0<\beta<1$). To simplify the analysis of the leaching performance under different dimensions, the osmotic stress was not considered in this study.

In a 1D system, the potential root water uptake S_p is described by Feddes et al.(1978):

$$S_p(z)=\frac{b(z)T_p}{\int_0^{Z_m}b(z)dz} \tag{5}$$

where $b(z)$ is a function (cm^{-1}) describing the root distribution with depth, T_p is the potential transpiration rate (cm day^{-1}), and Z_m is the maximum rooting depth (cm). The 1D root-depth distribution model was proposed by Vrugt et al. (2001), based on the model by Raats (1974):

$$b(z)=\left(1-\frac{z}{z_m}\right)e^{-(p_z/Z_m)|z^*-z|} \tag{6}$$

where p_z and z^* are empirical parameters.

In an axially symmetrical system, the two-dimensional (2D) root water uptake model is used (Vrugt et al., 2001):

$$S_p(x,z)=\frac{X_mb(x,z)T_p}{\int_0^{X_m}\int_0^{z_m}b(x,z)dxdz} \tag{7}$$

where X_m is the maximum root radius (cm). The root spatial distribution in 2D

$$b(x, z) = \left(1 - \frac{z}{Z_m}\right)\left(1 - \frac{x}{X_m}\right)e^{-[(p_z/Z_m)|z^* - z| + (p_x/X_m)|x^* - x|]} \quad (8)$$

where Z_m and X_m are the maximum rooting depth and length in z and x directions, respectively, z and x are the distances from the origin of the tree in the z and x directions, respectively, and p_z, z^*, p_x, and x^* are empirical parameters.

Potential transpiration T_p and evaporation E_p fluxes can be calculated from potential evapotranspiration using Beer's law that partitions the solar radiation component of the energy budget via interception by the canopy (Ritchie, 1972) as follows:

$$T_p = ET_0(1 - e^{-kLAI}) \quad (9)$$

$$E_p = ET_0 e^{-kLAI} \quad (10)$$

where ET_O, T_p, and E_p are reference evapotranspiration, potential transpiration, and potential evaporation fluxes (cm/day), respectively; *LAI* is leaf area index (-), and k is a constant governing the radiation extinction by the canopy (-) as a function of sun angle, the distribution of plants, and the arrangement of leaves (between 0.35-0.75). For almond trees in this study, k was taken as 0.463, and *LAI* was 0–3.351 (Zarate-Valdez et al., 2012).

2.2. Solute transport model

The convection dispersion equation (*CDE*) representing non-sorbing, conservative solute transport is numerically solved in both HYDRUS-1D and -2D as follows:

For HYDRUS-1D:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial C}{\partial z}\right) - \frac{\partial}{\partial z}(q_w C) \quad (11)$$

For HYDRUS-2D:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x}\left(\theta D\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(\theta D\frac{\partial C}{\partial z}\right) - \frac{\partial}{\partial z}(q_w C) \quad (12)$$

where C is the solute concentration (g cm^{-3}), θ is the volumetric water content (cm^3 cm^{-3}), D is the dispersion coefficient (cm^2 day^{-1}), q_w is water flux (cm day^{-1}). The dispersion coefficient is defined as (ignoring molecular diffusion):

$$D = \lambda\ |v| \quad (13)$$

where λ is the dispersivity (cm), and v is obtained from the numerical solution of the water flow model (the water flux q_w (cm day^{-1}) divided by θ)

2.3. Model parameters and input data

2.3.1. Irrigation salinity and soil hydraulic properties

The electrical conductivity (*EC*) of irrigation water (EC_{iw}) in the orchard ranged from 0.9 to 1.1 dS/m during the experimental period. Undisturbed soil core samples were collected in the field to measure hydraulic properties of the clay soil from Holtville, loam soil from Kern County and sand soil from Irvine, CA. The soil water retention curves of the three test soils (drying) were determined in the laboratory using the pressure plate apparatus for pressures of 0.01, 0.03, 0.10, 0.50, and 1.50 MPa (Klute, 1986). Another set of undisturbed soil-core samples was used to determine the saturated hydraulic conductivities (K_s) using the constant-head method (Klute and Dirksen, 1986), as well as the soil bulk densities. Other parameters, such as the residual water content (θ_r) are empirical parameter, (α and n) in Eq. (2) were optimized using both the water retention and hydraulic conductivity data. The hydraulic parameters for the three soils used in the numerical simulations in this study are listed in Table 1. Solute transport parameters used the default values provided by the HYDRUS model. For simplicity, the soil profile was considered as a uniform soil layer between depths of 0 and 150 cm.

Table 1
Hydraulic parameters of the three soils representing different textures.

	Q_r [-]	Q_s [-]	*Alpha* [1/cm]	n [-]	K_s [cm/day]	l [-]
Clay soil	0.068	0.38	0.018	1.04	28.8	0.5
Loam soil	0.048	0.51	0.09	1.14	225.27	0.5
Sand soil	0.045	0.43	0.1	1.24	300	0.5

The same hydraulic parameters and field irrigation scheme were used both in the HYDRUS-1D and HYDRUS-2D models to predict water movement and salinity leaching in the three soils (Table 1).

2.3.2. Initial and time-variable boundary conditions

HYDRUS-1D simulations were used to mimic sprinkler irrigation. The vertical soil profile was discretized into 101 equidistant finite elements in HYDRUS-1D simulations. The initial soil water pressure head was set to a uniform value of -100 cm throughout the soil profiles. The initial soil solute concentrations were specified in terms of EC_{sw}, which was set to 0 dS/m at the beginning of the simulations. The same initial conditions were applied in HYDRUS-2D to simulate drip irrigation, where the soil profiles were discretized using triangular finite elements with grid sizes of about 3.3 cm near the drippers and 10 cm elsewhere (Fig. 1).

The surface boundary condition used the variable flux boundary condition of the once a week water application rate, evaporation (*E*) and transpiration (*T*) rates, and *EC* of the applied irrigation water. Variable flux upper boundary conditions were specified using the weekly irrigation data of an almond orchard in the Kern County, CA. The average annual precipitation in the area is about 16 cm, but it was not considered for the simulations. The reference evapotranspiration fluxes (ET_O) were calculated using the Penman-Monteith equation from the local meteorological data (Allen et al., 1998). The crop potential transpiration and evaporation fluxes were then calculated from Eqs. (9) and (10).

The lower boundary condition used the free drainage boundary condition (Fig. 1). The solute transport bottom boundary condition was set as the third-type (or Cauchy, mixed, or solute flux). The seasonal change of the crop evapotranspiration ($ET_c = k_c \times ET_O$) and irrigation scheme are shown in Fig. 2. The annual irrigation depth was 141.8 cm, and the ET_c was 126.2 cm/yr, so that the ratio of D_{iw}/ET_c was 1.12.

2.3.3. Root distribution and root-water uptake

The almond root depth was set to 122 cm (4 ft, based on field observations, constant over time) for *1D* simulations. The depth of maximum root density was 50 cm and the shape parameter of *Pz* was 1. For 2D simulations, the root depth was set to 122 cm (4 ft), the width of the root zone was set to 152.4 cm (5 ft), the radius of the maximum intensity was 76.2 cm, and the shape parameters of P_z and P_x were 1 (Fig. 1). The soil water pressure head parameters in the Feddes et al. (1978) model were set as follows: h_1 = -10, h_2 = -25, h_3 = -500, and h_4 = -8000 cm. For simplicity, no salinity stress and no active solute uptake were considered in this study.

2.4. Leaching efficiency evaluation

Leaching fraction (*LF*) is a measure of the proportion of the water supposedly dedicated to leaching salts from the root zone. Root water uptake leads to a corresponding increase in soil salt concentrations (salinity) as the leaching fraction (*LF*) decreases with depth (Ayers and Westcot, 1985). The effect of *LF* on soil salinity (measured using soil water electrical conductivity, EC_{sw}) is more evident at the bottom of the root zone. *LFs* can be calculated annually and independently for water fluxes (LF_w) and *EC* (LF_{EC}) for each soil type (Ayers and Westcot, 1994):

$$LF_w = \frac{D_{dw}}{D_{iw}} \quad (14)$$

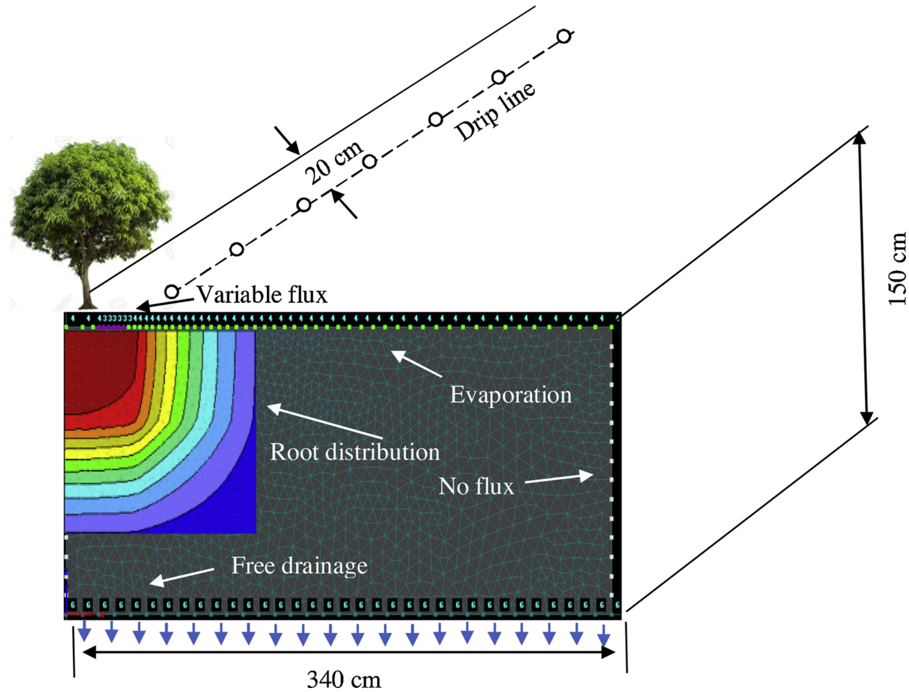

Fig. 1. The HYDRUS-2D model setup showing the *FE*-Mesh, boundary conditions for water flow, and two-dimensional root water uptake in the soil profile.

$$LF_{EC} = \frac{EC_{iw}}{EC_{dw}} \tag{15}$$

where EC_{iw} is the EC of irrigation water, EC_{dw} is the EC of drainage water at the bottom of the root zone (dS/m), and D_{iw} and D_{dw} are the depths of irrigation water and drainage water (cm), respectively.

The traditional approach to estimate the LF is based on an assumption that the salt concentration of the soil solution at any point in the soil profile (1D) is constant at all times (steady-state). Steady-state does not actually exist in the field, but if a given irrigation regime is followed for an extended period of time, the salt concentration below the root zone will be constant with time; such conditions can be taken as quasi-steady-state (Letey et al., 2011; Tripler et al., 2012). Under quasi-steady-state, LF below the root zone can be calculated by assuming no appreciable contribution of salts from the dissolution of soil minerals or salts, or loss of soluble salts by the precipitation process and crop removal, and uniform areal application of water in the field, where LF_w equals to LF_{EC}.

A salt-balance evaluation involves measuring the depth and salinity of irrigation water diverted into the soil and the depth and salinity of drainage discharged from the soil. The salt-balance (SB) is then calculated from the cumulative data by the equation (Wilcox and Resch, 1963):

$$SB = D_{dw}EC_{dw} - D_{iw}EC_{iw} = D_{iw}EC_{iw}\left(\frac{LF_w}{LF_{EC}} - 1\right) \tag{16}$$

where SB can be expressed with the ratio of LF_w/LF_{EC}. When $LF_w > LF_{EC}$, then $SB > 0$, which means drainage water carries more salts than salts applied from irrigation water; when $LF_w = LF_{EC}$, $SB = 0$, which means steady-state, the amount of salts in drainage equals the amount of applied salts from irrigation; and when $LF_w < LF_{EC}$, $SB < 0$, drainage water can only remove part of salts from the total amount of input salts by irrigation water.

Leaching efficiency can be determined from the ratio of the collected drained salt mass to the applied salt mass (Grismer, 1990), which

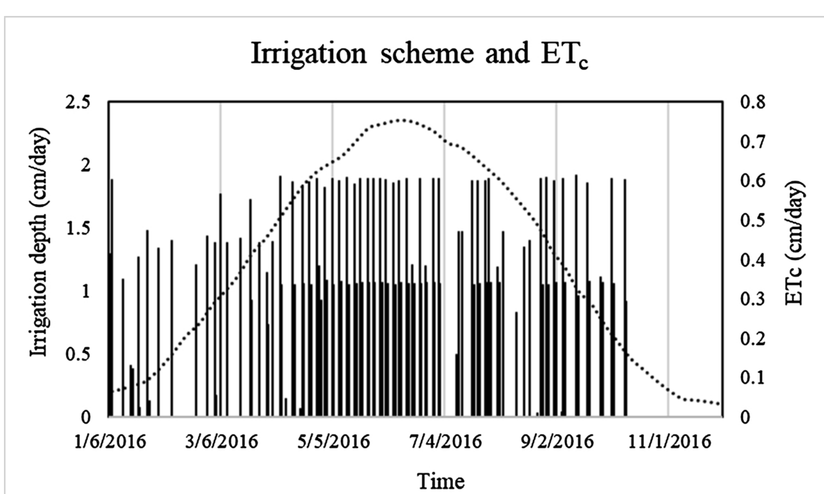

Fig. 2. Seasonal variation of crop evapotranspiration (ET_c) and irrigation scheme.

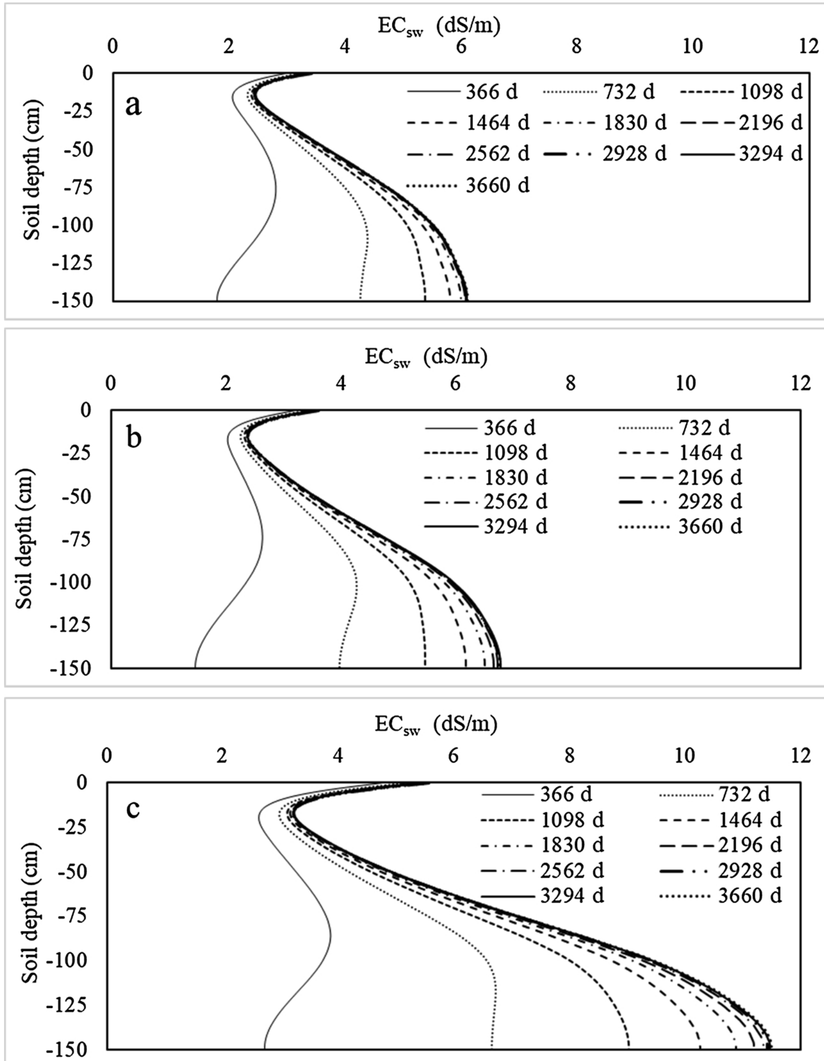

Fig. 3. The salinity distribution along the soil profile at different time simulated using HYDRUS-1D for (a)-clay soil, (b)-loam soil and (c)-sand soil.

can be expressed by LF_w and LF_{EC}:

$$LE = \frac{D_{dw}EC_{dw}}{D_{iw}EC_{iw}} = \frac{LF_w}{LF_{EC}} \tag{17}$$

3. Results and discussion

3.1. Comparison of LF_w under one- and two- dimensional simulations

To evaluate the traditional *LF* values, the HYDRUS-1D and -2D models were used to simulate soil salinity leaching using meteorological data at the almond orchard in Kern County, CA and measured hydraulic parameters of three soils representing different textures for a period of 10 years (3660 days) to ensure the EC_{sw} at the bottom of the root zone in the three test soils reached approximately steady state. The annual soil water salinity profiles (EC_{sw}) for the clay, loam, and sand soils from HYDRUS-1D simulations are shown in Fig. 3. Soil salinity distributions in the clay soil profile in years 1 to 10 are shown in Fig. 3a. The initial condition (time = 0) when EC_{sw} = 0 is not shown. As the simulation time increased, the *EC* of drainage water at the bottom of the soil profile (EC_{dw}) continued to increase until it reached the highest value, and then it became nearly constant with time. Similar trends were also observed in the loam and sand soils (Figs. 3b and c, respectively). In contrast, salinity distribution in drip-irrigated soils based on HYDRUS-2D simulations was not uniform, and it varied with time, depth and location, which agrees with the observation by Hanson et al. (2008).

The water balances at the 10th year of simulations for the three soils using HYDRUS-1D and -2D simulation are shown in Table 2. Based on the yearly applied water and crop potential evapotranspiration rates, the traditional *LF* is 0.11 ($LF = (D_{iw} - ET_c)/ D_{iw} = 0.11$), and it is expected that steady-state would be reached for both water and solutes (Letey et al., 2011; Tripler et al., 2012). The time series (daily and yearly) of LF_w for the three soils calculated from both HYDRUS-1D and -2D simulated values of D_{dw}/D_{iw} (LF_w) in Eq. (14) are shown in Fig. 4.

Table 2
Cumulative depths of irrigation, root water uptake, evaporation and drainage water in the 10th year of simulation.

Soil types		Cum. Irrigation water [cm]	Cum. Root water uptake [cm]	Cum. Evaporation [cm]	Cum. Drainage water [cm]
1D	clay soil	141.86	94.29	23.66	22.69
	loam soil	141.89	91.70	24.09	26.49
	sand soil	141.88	102.79	23.98	15.12
2D	clay soil	141.82	77.47	16.27	42.88
	loam soil	141.84	98.38	13.7	30.46
	sand soil	141.84	97.23	9.23	35.56

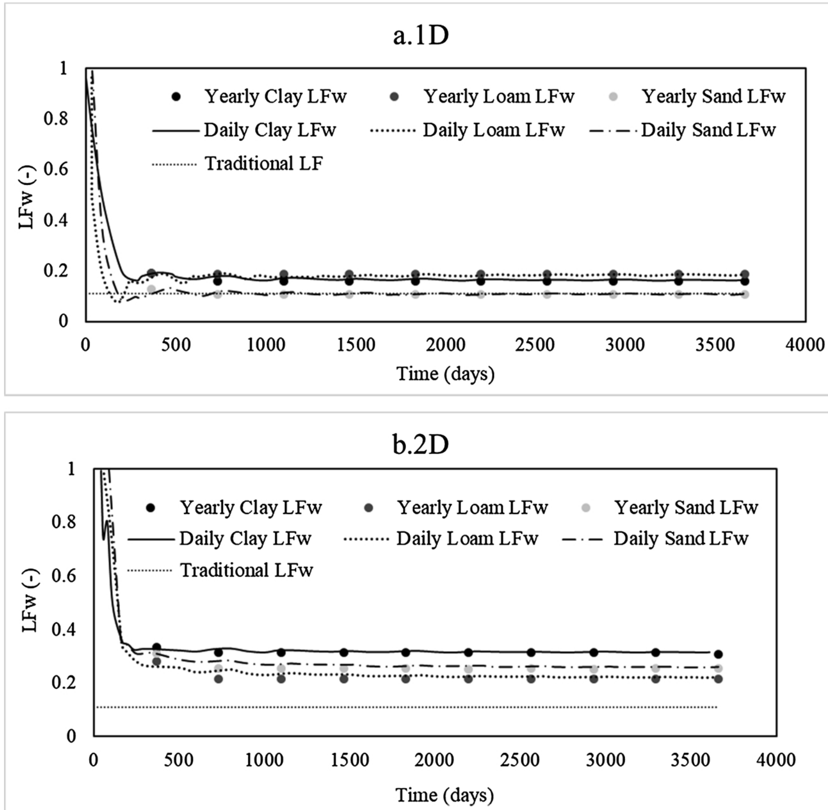

Fig. 4. Time series of leaching fractions (LF_w) calculated from HYDRUS-1D (a) and *-2D* (b) simulations for the three test soils.

The daily data represent the dynamic nature of soil water and salinity in the field; while the yearly averaged data provide a basis for comparison between the *LF* based on a traditional steady-state model and on transient models such as HYDRUS over a crop rotation period (Corwin et al., 2007).

The LF_w of the daily time series from HYDRUS-1D decreased sharply at the beginning of the simulations, while the yearly averaged LF_w values were much smoother. Both daily and yearly LF_w values approached a constant leaching fraction at the end of the 10-year simulations, which were 0.16, 0.19 and 0.11, respectively, for the clay, loam and sand soil (Fig. 4a). The LF_w for the sand soil in 1D simulation is close to the traditional *LF* of 0.11. While, for the clay and loam soils, the 1D simulated LF_w values were higher than those of the traditionally estimated LF_w, indicating that soil texture indeed influences the simulated LF_w values. Coarse soils normally have larger continuous pores and thus it is easier for a coarse soil to reach quasi-steady-state.

Compared with 1D simulation, 2D simulations had higher drainage and lower evapotranspiration (Table 2), and greater leaching below the root zone. As shown in Fig. 4b, the daily and yearly LF_w values in 2D simulations were similar to those in 1D simulations during early time stages. However, 2D simulations resulted in very different LF_w (Fig. 4b) in Year 10, which were 0.3 for the clay, 0.22 for the loam and 0.25 for the sand soil. These LF_w values were greater than that of the traditional *LF* (0.11) and those of 1D simulations (0.16, 0.19 and 0.11 respectively, for the clay, loam and sand soil). The higher LF_w from transient 2D simulations than that of the traditional *LF* as well as those of 1D simulations are attributed to the fact that drip-irrigation systems typically wet only part of the soil surface, and field-wide application of traditional *LF* to drip system leads to underestimation of actual LF_w (Hanson et al., 2009; Letey et al., 2011), especially for drip irrigation.

Water application and root distribution can also affect water distribution and crop water uptake in the soil profile, and consequently, LF_w. With the same amount of water application and ET_c, water and salt fluxes behaved similarly in different parts of the field in 1D simulations that mimic sprinkler irrigation, while 2D simulations representing drip irrigation wet only part of the soil surface, inducing differences in water and salt movement in the wetted and dry or less wetted area (particular in the wetting edge) (Burt and Isbell, 2005). Furthermore, in 1D simulations, root distribution and water uptake only consider the vertical direction, whereas, in 2D simulations, root distribution considers both vertical and horizontal directions. Because drip irrigation wets only part of the root zone, it is difficult for roots to extract water from the dry soil, which may effectively reduce the evapotranspiration. In addition, as the same amount of water is applied to only a small portion of the surface area, it is not surprising to see higher leaching (higher LF_w) in 2D simulations when the potential root water uptake was the same as in 1D simulations, which led to the concept of *localized leaching fraction* for drip irrigation (Hanson et al., 2008).

3.2. Evaluation of LF_{EC} under one- and two-dimensional simulations

To evaluate the salinity leaching efficiency by the same amount of water, the EC_{dw} change with pore volume (dimensionless time) for the three test soils are presented in Fig. 5. For HYDRUS-1D, the EC_{dw} values were 8.58, 4.89 and 5.47 *dS/m* for the sand, loam, and clay soil, respectively, at the pore volumes of 2.1, 3.61, 3.14 when they reached quasi-steady-state (Fig. 5a). For HYDRUS-2D, the average EC_{dw} values were 3.03, 2.63 and 1.72 *dS/m*, respectively, at pore volumes of 4.95, 4.23 and 6.03 for the sand, loam and clay soil (Fig. 5b). In the meantime, salts appeared in the drainage water much earlier (at about 0.1 pore volume) in 2D simulations than it did in 1D simulations (at about 0.3 pore volume). The early appearance of salts in the drainage water and lower EC_{dw} values in 2D simulations are largely attributed to the fact that in drip irrigation, soil salts near the drip line move much faster, and consequently more salts were leached downward by relatively larger amounts of localized drainage water near the drip lines.

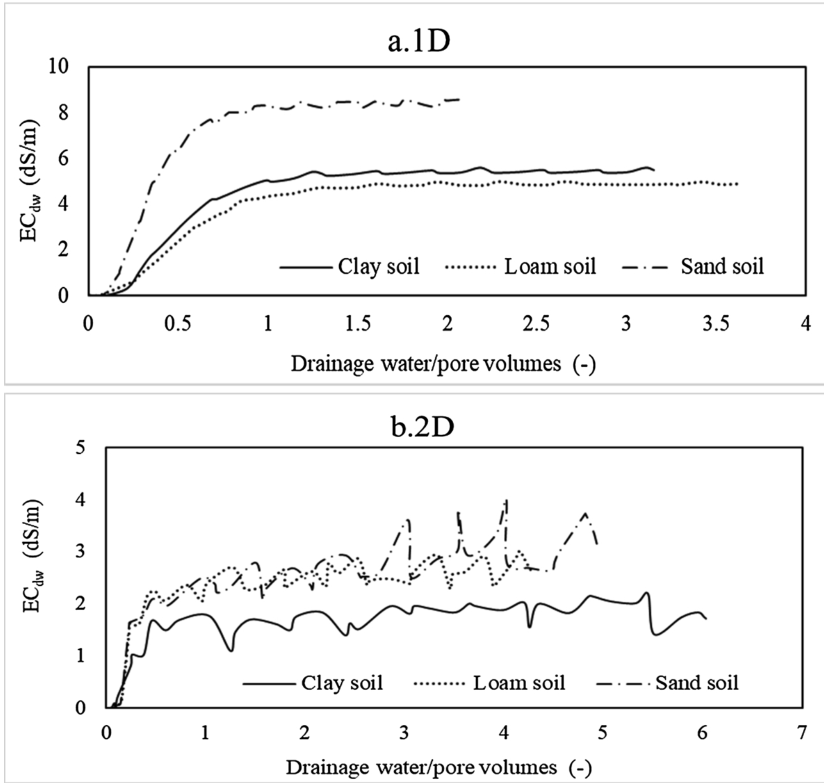

Fig. 5. Changes of electrical conductivities of the drainage waters (EC_{dw}) in the three soils with pore volumes (representing 10 years) from HYDRUS-1D (a) and HYDRUS-2D (b) simulations.

The EC_{sw} distributions in the profiles of the three test soils at the end of the 10-year simulation period are shown in Fig. 6. EC_{sw} near the drip lines (emitters) was low so osmotic stress was not considered as in this study. Fig. 6 clearly showed that sprinkler irrigation (1D) was more effective in leaching salts out of the crop root zone than drip irrigation (2D), and more salts moved below the root zone in the sand soil than in the clay and loam soils.

Under transient-state, the salt concentration continually changes as water is added, drained, and extracted by roots. According to previous studies, soil salinity distribution is sensitive to root water extraction patterns (Gardner, 1983; Rhoades, 1999) and a large amount of water is extracted from the upper part of the root zone where soil salinity (LF_w) is low (Letey et al., 2011). To assess the root distribution effect on water uptake and salinity leaching, the time series (daily and yearly) of simulated LF_{EC} for the three soils from both HYDRUS-1D and -2D using Eq. (14) are shown in Fig. 7. The yearly LF_{EC} calculated from 1D simulations decreased with time and then became nearly constant values (0.18, 0.20, and 0.12, respectively, for the clay, loam, and sand soils). In the 10th year, the LF_{EC} values for the three test soils calculated from the simulations were very close to their respective LF_w for each soil type from HYDRUS-1D simulations (Table 3).

It is well recognized that water and solute fluxes under 1D transient-state conditions can approach quasi-steady state below the root zone after a long period of leaching (Letey and Feng, 2007; Letey et al., 2011). However, the behaviors of water and salinity leaching under drip irrigation (2D, transient) in the three soils were different from those under 1D. Under 2D transient conditions, the daily water and salt fluxes never reached quasi-steady state, and the LF_{EC} values at the end of the 10-year simulations were 0.58, 0.38 and 0.33, respectively, in the clay, loam, and sand soils, which were much greater than those from 1D simulations, especially for the clay soil.

Furthermore, the LF_{EC} values were greater than the LF_w values in all the three soils, even though they were both based on the data from HYDRUS-2D simulations. Apparently, the equality between LF_w and LF_{EC} after a long period of leaching cannot be applied to drip irrigation (2D transient condition).

The higher LF_{EC} in 2D simulations can be explained by the transverse dispersion phenomenon as well as by lower ET (more drainage), which results in lower EC_{dw} than that in 1D simulations. The relationship between LF_{EC} and the parameter *Disp.T* (dispersion in the transverse direction) for the sand soil is depicted in Fig. 8. When *Disp.T* is between 2–10 cm, there is no significant difference in LF_{EC} (roughly around 0.35 for the three of them). However, when *Disp.T* is 0 cm, the LF_{EC} is higher than the LF_{EC} values for *Disp.T* = 2–10 cm in the sand soil for the initial 3 years; after that, it decreased sharply and became lower than the LF_{EC} values for *Disp.T* = 2–10 cm. At the end of the 10-year simulation, the LF_{EC} reached 0.12 for *Disp.T* = 0, which is closest to the results of LF_{EC} of the sand soil in 1D simulation and it is an indication that *Disp.T*, not lower *ET*, is the major factor for the higher LF_{EC} in *2D* simulations.

In addition, drip irrigation can cause edge effects through accumulate salts near the wetting edge. Thus, proportionally large water application and drainage near the drip lines (2D) effectively reduce the total salinity leaching, even when the same amount of water as that of sprinkler irrigation (1D) is applied, leading to a higher value of LF_{EC} in drip irrigation than in sprinkler irrigation.

Furthermore, root uptake patterns and chemical factors such as precipitation and dissolution of calcite and gypsum in the root zone can cause an increase or decrease in EC_{sw} in the root zone (Raviv and Lieth, 2007). Rainfall (Isidoro and Grattan, 2011) and drainage boundary conditions (Raij et al., 2016) can also influence the soil salinity distribution, as well as *LF*. Thus, *LF* under drip irrigation varies with soil water content, soil salinity, root distribution, and distance from and depth to the drip line.

3.3. Salt balance (SB) and leaching efficiency (LE) under 1D and 2D

It is well known that micro-irrigation has higher water use

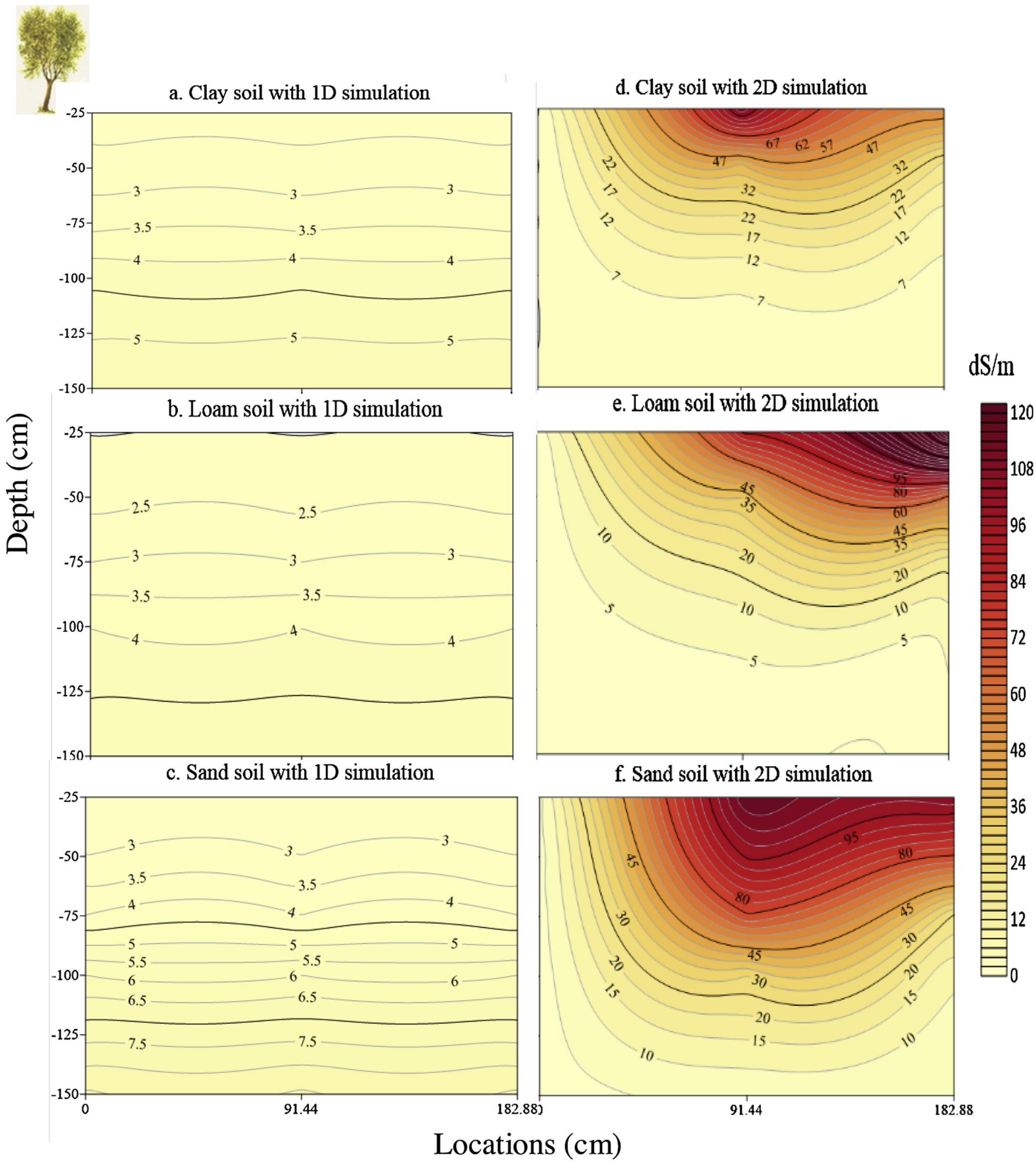

Fig. 6. Contour maps of EC_{sw} at the end of 10-year simulations by HYDRUS-1D (Left) and HYDRUS-2D (Right) for the clay a, d), loam (b, e) and sand (c, f) soils. The three locations of 0 cm (Drip line), 91.4 cm and 182.9 cm from the drip line resemble the soil sampling sites.

efficiency than flood irrigation. However, evaluating leaching efficiency in micro-irrigation systems still remains a challenge. The relative leaching efficiency proposed by Burt and Isbell (2005) for micro-irrigation systems, expressed by the ratio of the salt reduction to the equivalent leaching depth curve, indicates that the amount of salt removed per unit depth of leaching water decreases as more leaching water is applied.

As illustrated earlier, a positive *SB* represents a net removal of salts in the soil. Based on the HYDRUS-1D simulations, the calculated *SB* values were -10.1, -4.5 and -9.8 mg ($SB < 0$, indicating net increase in soil salinity), respectively, accounting for 11.1%, 4.9% and 10.8% of the total applied salts (90.75 mg cm^{-2} yr^{-1} land surface) for the clay, loam and sand soil in the 10th year. This means drainage water carried 90–95% of the salts in the irrigation water out of the root zone under 1D conditions.

For 2D simulations, the *SB* values were -43.8, -38.2 and -19.2 mg ($SB < 0$), respectively, for the clay, loam and sand soils, which implies that 48% (clay), 42% (loam) and 21% (sand) of the total input salts (90.75 mg) remained in the soils. The large *SB* values from 2D simulations are mainly the results of concentrated leaching under or near the drip lines where EC_{dw} is relatively low in the drainage water. Leaching under drip irrigation is not as effective as that of sprinkler irrigation (1D), because the edges of the wetted area are not fully leached.

Based on the definition of leaching efficiency (*LE*) [Eq. (17)], when *LE* is greater than 1, the *SB* is positive (removal of salts in drainage water is greater than that of irrigation input). In 1D simulations, *LE* was 88.9%, 95% and 92%, respectively, for the clay, loam and sand soils; while in 2D simulations, *LE* was 51.7%, 57.9% and 78.8% for the clay, loam and sand soils, which is considerably lower than the *LE* values in 1D.

4. Conclusion

Analyses of leaching fractions (*LF*) and leaching efficiency (*LE*) by

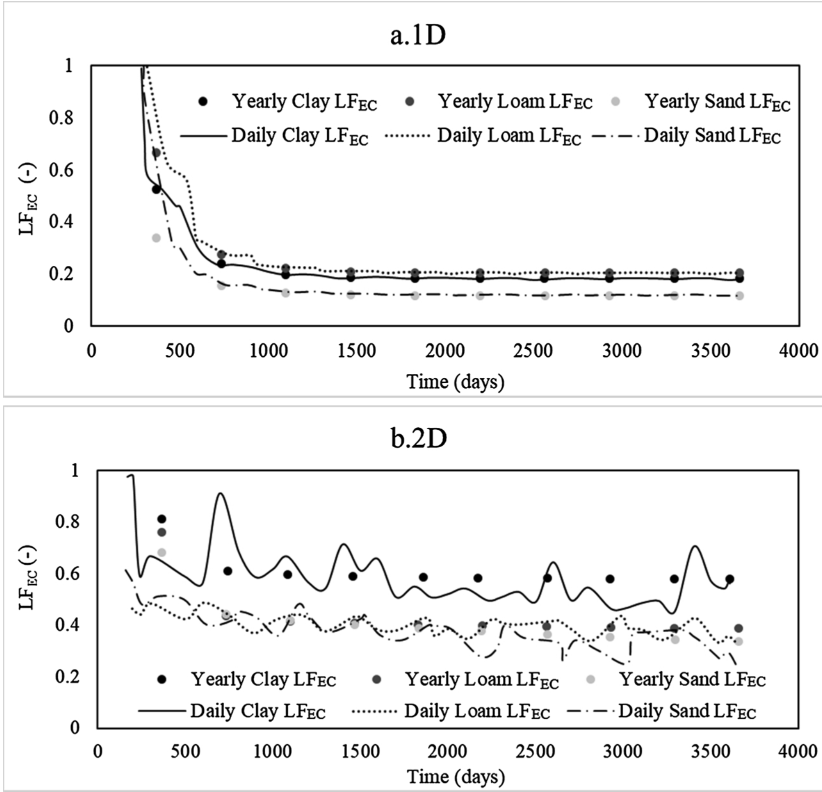

Fig. 7. Time series of leaching fractions (LF_{EC}) based on irrigation water EC (EC_{iw}) and drainage water EC (EC_{dw}) simulated by HYDRUS-1D (a) and HYDRUS-2D (b) for the three soils.

Table 3
Leaching fractions (*LF*) of the three test soils based on HYDRUS-1D and -2D simulations.

		Clay soil	Loam soil	Sand soil
1D	LF_w	0.16	0.19	0.11
	LF_{EC}	0.18	0.20	0.12
2D	LF_w	0.30	0.22	0.25
	LF_{EC}	0.58	0.38	0.33

steady-state, one-dimensional (1D) and two dimensional (2D) transient models are valuable in developing salinity management guidelines in irrigated cropland. Real steady-state condition rarely exists in the field, and new irrigation systems such as drip and micro-irrigation further violate the assumption of $LF_w = LF_{EC}$ under 1D and steady-state conditions. This study used the HYDRUS-1D and -2D models to simulate water and salinity dynamics with the same irrigation scheme in three soils of different textures. The calculated *LFs* based on model simulations were then compared with the traditional *LFs*.

Our results indicate that in 1D simulations salinity leaching reached quasi-steady-state at the end of 10-year simulations, and the LF_w values were close to LF_{EC} values for each of the three soils representing different textures based on the simulated drainage water depths and ECs. While in 2D simulations, the daily water and solute fluxes never attained such "steady-state" condition, but the annual average of *LFs* approached quasi-steady-state in the 10th year, although the LF_w values did not equal to the LF_{EC} values in each of the three test soils.

Under transient-state, leaching efficiencies (*LE*) were 88.9%, 95%, and 92%, respectively, based on HYDRUS-1D simulations; and *LE* calculated from HYDRUS-2D were 51.7%, 57.9% and 78.8%, respectively, for the clay, loam and sand soil. Thus, we conclude that considering the overall efficiency of salt leaching out of the root zone, sprinkler irrigation (1D) is more effective than drip irrigation systems (2D), and in drip irrigation systems the current *LR* guideline is not appropriate.

The main purpose of the study was to compare the *LFs* estimated from 1D and 2D simulations with the traditional *LF* (1D steady-state), thus we employed HYDRUS-1D and -2D to estimate salinity leaching without more complex modeling approaches. Our future work will

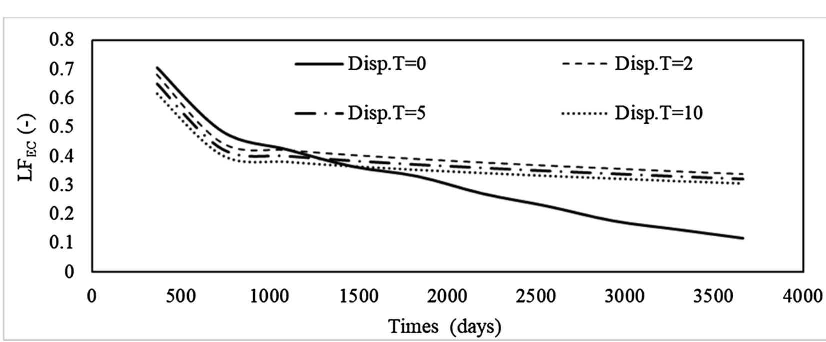

Fig. 8. Change of leaching fraction based on electrical conductivities (LF_{EC}) with transverse dispersivity (Disp. T) in the sandy soil based on HYDRUS-2D simulations.

further evaluate how ion interactions and crop salinity stress may affect *LF* estimation.

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