The effect of the top soil layer on moisture and evaporation dynamics

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Abstract
Understanding the effect of the top soil layer on surface evaporation and water distribution is critical to modeling hydrological systems. However, the dependency of near-surface soil moisture and fluxes on layering characteristics remains unclear. To address this uncertainty, we investigate how the arrangement of soil horizons affects the evaporation and soil moisture, specifically, the near-surface soil moisture, through the combination of numerical simulations and evaporation experiments. The characteristics of fluxes and moisture from different soil profiles are then used to understand the soil layering conditions. Results show that the top soil layer can significantly affect the evolution of soil moisture profiles and evaporation dynamics, the extent of which depends on the layering sequence, thickness, and properties of each layer. The soil systems consisting of a thick coarse (C) layer overlying a fine (F) layer, or a very thin F layer overlying a C layer exhibit near-surface moisture, temperature and fluxes nearly identical to that of a homogeneous C system; in these cases, a homogeneous C soil could be used to represent the above two layered systems. However, some soil profiles cannot be described by a single set of soil properties, nevertheless, they show distinct characteristics that can serve as indicators for soil layering conditions, e.g., “first slowly then rapidly” decreasing dynamics of near-surface soil moisture. As some characteristics are not unique to layered soil, the combined information including the near-surface soil moisture defined at different depths and evaporation behavior of an entire drying cycle can be used to better characterize the layering conditions.

1 | INTRODUCTION

Soil layering is important to many agricultural and engineering applications. For example, in agriculture, the loose surface layer caused by soil tillage or application of soil mulches suppresses soil water evaporation, and hence irrigation demands in a similar way to a coarse-textured surface layer (e.g., gravel, sand or soil aggregations) (Fuchs & Hadas, 2011; Harris, Chesters, & Allen, 1966; Yamanaka, Inoue, & Kaihotsu, 2004). In engineering, the dynamics of water transport through layered soil are considered in the design of capillary barriers for soil landfill covers to manage rainfall infiltration and gas emissions (Aubertin et al., 2010).
2009; Ng, Liu, Chen, & Xu, 2015). However, what is not well understood is how the near-surface soil moisture and evaporation, which play important roles in the overall hydrological and energy cycles, are dependent on the soil layering characteristics (i.e., layering sequence, thickness, and properties of each layer).

Generally, for an initially saturated homogeneous soil, evaporation initiates with the air invasion into the saturated region after overcoming the capillary head defined as the air-entry value ($h_b$), forming a drying front that is the interface between saturated and partially air-filled regions. As long as there is a continuous hydraulically connected liquid network between the drying front and the soil surface, the evaporation rate remains high and nearly constant (Stage I). The Stage I evaporation lasts until the surface dries to a point that the liquid network is disrupted and then the evaporation steps into Stage II. At the end of Stage I, the maximum depth that the drying front can reach is defined as the evaporative characteristic length ($L$), and the surface capillary pressure head is defined as the critical capillary pressure head ($h_{\text{min}}$) (Lehmann, Assouline, & Or, 2008). During the drying process, the near-surface soil moisture keeps decreasing. Subsequently, an air-dried soil layer at the surface (dry surface layer, DSL) is induced that only allows for gas flow with vapor diffusion. As the thickness of DSL increases, Stage II evaporation rate decreases because of the increase in the associated diffusive length. However, compared with a homogeneous soil, a layered soil shows special characteristics of soil moisture and evaporation dynamics because the liquid–gas phase displacement during evaporation is largely affected by the soil property profile.

The special soil moisture and evaporation dynamic characteristics for layered soil were previously studied using laboratory-scale visualization, sampling, and recording techniques (e.g., neutron-based imaging [Shokri, Lehmann, & Or, 2010], dye imaging [Assouline & Narkis, 2019; Kumar & Arakeri, 2018], port sampling [Huang, Bruch, & Barbour, 2013], weight recording, etc.). Shokri et al. (2010) showed that a top fine layer had a higher saturation than the underlying coarse layer during evaporation, which was caused by the preferential invasion of air into the underlying coarse layer through the large pores of the top fine layer. Huang et al. (2013) showed very different liquid phase displacement characteristics and evaporation behavior among different soil property profiles, with the silt–sand (fine–course) column evaporating more water than homogeneous soil column of either sand (coarse) or silt (fine). However, many previous experiments only allowed for the measurement or visualization of one state variable or system property, rather than the collective view of moisture, temperature, and evaporation over time, masking their interconnected nature.

**Core Ideas**

- Soil moisture and evaporation dynamics are studied over the entire drying cycle.
- The top soil layer affects the evolution of dry surface layer and Stage II evaporation.
- Near-surface soil moisture varies with layering characteristics and depth.
- Fine over coarse layered soil shows distinct moisture dynamics over time.
- Homogeneous course properties can be used as effective properties of a thick C/F and a thin F/C.

Representative elementary volume (REV) scale numerical modeling has the advantage of describing all coupled processes and related state variables such as soil moisture, temperature, and evaporation. Nevertheless, current studies about layered soil systems using REV scale models mainly focus on the analysis of cumulative evaporation or water distribution behavior instead of the near-surface information to include near-surface soil moisture and evaporation over time (Assouline, Narkis, Gherabli, Lefort, & Prat, 2014; Huang et al., 2013). In addition, for soil profiles with a thin coarse-textured surface layer, the top coarse layer tends to dry quickly, accompanied by the development of an extremely nonlinear hydraulic conductivity, which brings challenges for numerical simulations to correctly represent the near-surface process (Assouline & Narkis, 2019; Dijkema et al., 2018).

Not only are near-surface soil moisture and evaporation important components of the hydrological cycle, they also are useful for estimating soil properties, which are critical for the proper description of the systematic subsurface process and surface fluxes. Although inverse modeling to estimate soil properties based on ground- and remote-sensed soil surface states and fluxes has been demonstrated in various studies for vertically homogeneous soil (Camillo, Neill, & Gurney, 1986; Dimitrov et al., 2015; Mohanty, 2013; Santanello et al., 2007), there are difficulties in estimating effective soil parameters for layered soil across scales (Durner, Jansen, & Iden, 2008; Groh et al., 2017; Nasta & Romano, 2016; Shin, Mohanty, & Ines, 2012; Steenpass, Vanderbooght, Herbst, Simunek, & Vereecken, 2010; Vereecken et al., 2016; Yang, Koike, Ye, & Bastidas, 2005). Specifically, difficulties include (a) whether a single effective hydraulic parameter set is representative of the key processes due to the high nonlinearity of the soil parameters (Vereecken et al., 2016), and if it is not, (b) what information would then be needed to properly characterize...
TABLE 1  Experimental soil profiles and select free-flow conditions

| Experiment | Soil profile | Averaged wind speed, $u_a$ (m s$^{-1}$) | Averaged air temperature, $T_a$ (°C) | Averaged air humidity, RH$_a$ | Net radiation, $R_n$ (W m$^{-2}$) |
|------------|-------------|---------------------------------------|--------------------------------------|-----------------------------|----------------------------------|
| Exp. 1     | C/F         | 0.64                                  | 20.4                                 | 0.31                        | 1.31–21.62                        |
| Exp. 2     | F/C         | 1.12                                  | 22.1–36.5                            | 0.01–0.23                   | 0.18–76                           |

*C/F, coarse soil overlying a fine soil; F/C, fine soil overlying a coarse soil.

the soil property profile to properly represent the key processes. For example, Yang et al. (2005) used measured soil moisture and temperature at several depths to inversely estimate the soil layering configuration and soil properties (i.e., hydraulic and thermal properties) in a land surface model, showing that the soil subsurface process and the surface soil states cannot be effectively approximated by vertically homogeneous soil. Rather, it is important to account for the vertical heterogeneity in land surface models for accurate hydrological estimates.

To identify how we can use knowledge of the near-surface information to characterize the soil properties, it is first necessary to comprehensively study how the soil layering characteristics affect the near-surface soil moisture and evaporation fluxes over the entire drying cycle. Here, we provide detailed experimental observations and numerical simulations in a two-layered soil profile (a) to investigate how the near-surface soil moisture and evaporation flux are influenced by the top soil layer, and (b) to identify the amount and type of information (i.e., characteristics of moisture and evaporation dynamics) needed for the interpretation of the soil properties. Experimental data and the associated analysis framework can be used to help develop appropriate data analysis and model calibration strategies when interpreting the soil properties based on near-surface soil states and fluxes.

2 | MATERIALS AND METHODS

2.1 | Experimental setup and procedures

Water flow and evaporation from layered soil profiles were investigated in a soil tank and boundary layer wind tunnel experiment apparatus, which was equipped with a sensor network to continuously monitor moisture–pressure–temperature variables in both the free flow and porous media domain. Two laboratory experiments were conducted with two-layered soil profiles consisting of a coarse soil overlying fine soil (C/F) and fine soil overlying coarse soil (F/C) with a top layer of 5-cm thickness, under various ambient conditions. The experimental soil profiles and the selected free-flow conditions are summarized in Table 1. Steady free-flow condition was used in the C/F experiment, whereas F/C experiment was conducted using diurnal air temperature, air humidity, and radiation (transient). The different free-flow conditions that were used for the two soil profiles do not allow comparing the experimental results from the two experiments directly with each other. However, the experiments serve as a dataset for the validation of the model under different free-flow conditions. The impact of the top soil layer on moisture and evaporation dynamics is then evaluated by comparing simulations of different soil profiles with the validated model.

Two uniform specialty silica sands with particle sizes of 0.85–1.70 mm (#12/20, coarse) and 0.21–0.30 mm (#50/70, fine) were used in the experiment. The key properties of the sands are summarized in Supplemental Table S1.

Experiments were conducted in a rectangular tank constructed of plexiglass (45 cm long, 30 cm tall, and 9 cm wide) connected to an open-channel low-speed wind tunnel, as shown in Figure 1. The soil tank was wet packed using deionized water and sand. The porosity of each sand was consistent in the two experiments so the sand properties remained unchanged. The soil tank was maintained fully saturated until the experiments started and the soil surface was exposed to the air for evaporation. Soil moisture, temperature, and water pressure in the soil tank, as well as the weight of the tank, were continuously monitored every 1 h. Four relative humidity and temperature sensors were placed in contact with the soil surface. The wind tunnel was constructed out of galvanized steel ductwork with a duct fan, along with a speed controller, installed. To better understand the diurnal dynamics of evaporation under natural conditions, a diurnal air temperature and radiation environment was generated in Exp. 2 (F/C) by ceramic infrared heaters (Salamander Model FTE 500-240, Mor Electric Heating Associates) installed in the tunnel connected to a temperature control system (Chromalox 2104 model, Chromalox) and the fluorescent lighting system (FLP24 model, EnviroGro, Hydrofarm), which was then connected to an ASTRO digital heavy-duty timer (Model 457864) on a 12-h shift. The wind speed, free-flow relative humidity, temperature, and pressure were continuously monitored every 1 h. The net radiation was measured using a net radiometer (Model NR01, Hukseflux Thermal Sensors, accuracy for daily sums of net radiation: ±0.4 x 10$^6$ J m$^{-2}$). Additional information (e.g.,
sensor installation, sensor type, and accuracy) can be found in Li, Vanderborght, and Smits (2019). Each experiment ran for 20 d.

### 2.2 Numerical model description

The model described by Li et al. (2019) that accounts for nonequilibrium phase change and simulates the coupled heat, water vapor, and liquid water flow through the soil is used. The model is modified so that the energy balance boundary condition is used at the soil surface to better account for the practical free-flow conditions. The model is then tested with the precision data obtained from laboratory experiments with well-controlled boundary conditions in an attempt to test its ability to account for soil layering under various free-flow conditions. The reader is directed to Li et al. (2019) for the full model description; however, an overview of the model is presented here.

In this model, it is assumed that (a) the soil is a rigid porous medium containing two phases (liquid and gas), (b) the dissolved gas in the liquid phase is ignored, (c) the gas phase is assumed to be composed of dry air and water vapor, and (d) the temperature of the solid, liquid, and gas phases are identical.

The liquid water flow, gas flow, heat, and vapor transport are simulated. The state of the soil is described by the liquid phase pressure ($p_l$, Pa), gas phase pressure ($p_g$, Pa), and the temperature ($T$, K). Two separate partial differential equations for the liquid phase and gas phase are used to describe the water and gas flow, respectively, which are coupled through capillary pressure ($p_c = p_g - p_l$). The phase change between liquid water and water vapor is assumed to be at nonequilibrium and described by an explicit phase change rate term (Gao, Davarzani, Helmig, & Smits, 2018). In the gas phase, the vapor transport is simulated independently by considering the vapor advection along with gas phase and diffusion due to the vapor pressure gradient.

The initial and boundary conditions for this study are defined based on the experimental setup shown in Figure 2. Initially, the soil is fully saturated at a temperature of 20 °C. The measured free-flow variables (air temperature, air humidity, wind speed, and net radiation) above the soil surface are used to define the top boundary condition (Neumann-type) for water flow and heat transfer. Specifically, the top boundary condition for water flow is based on the vapor gradient between the soil surface and the free flow ($J_C$, kg m⁻² s⁻¹). The top boundary condition for heat transfer is based on the energy balance equation at the soil surface ($J_T$, W m⁻²). There is no representation of latent heat flux in the surface energy balance equations because it is assumed that the soil water vaporizes in the soil instead of only at the soil surface in this model. Thus, the latent heat due to phase change has been included in the energy balance equation in the soil domain (van de Griend & Owe, 1994; Yamanaka, Takeda, & Sugita, 1997). The top boundary condition for the gas flow is a
Dirichlet boundary condition \( p_b = p_{atm} \), where \( p_{atm} \) is the atmospheric air pressure. The remaining boundaries (bottom and two sides) for liquid water, gas, vapor, and heat are assumed to be no-flow.

The two-dimensional simulation domain has the same length and height as the soil tank used in the experiment. The model is implicitly solved using the COMSOL Multiphysics software based on the finite element methods. The model domain is discretized by unstructured triangle elements, and the average element size is \( \sim 6.5 \text{ mm} \) with a total of 7,448 elements for most scenarios. Mesh refinement is used at the soil surface and the interface between two soil layers with an average element size of 3.75 mm.

The model inputs include measured ambient temperature \( (T_a) \), ambient relative humidity \( (R_{H_a}) \), wind speed \( (u_a) \), and net radiation \( (R_n) \) for the parameterization of top boundary conditions for water flow and heat transfer. Additionally, the measured soil property profile is also known as model input.

### 2.3 Numerical simulation setup

With the validated model, a series of numerical simulation scenarios are conducted for various layered soil profiles (Table 2) with the uniform free-flow conditions measured in Exp. 2. The layered soil systems are composed of sand materials with different layering sequences, textural contrast, and top soil layer thicknesses. The pore-size distributions of the #12/20 and #50/70 sand do not overlap (Deepagoda, Smits, Ramirez, & Moldrup, 2016); thus, the textural contrast between these two types of sand is defined as high. In contrast, a different coarse soil (#30/40, coarse) of which the pore size distribution partially overlaps with #50/70 sand is included in the simulation study. The properties of #30/40 sand are presented in Supplemental Table S1. To better define the simulation scenarios for generic results, the properties of each material that closely relate to evaporation processes are further represented by the evaporative characteristic length, air entry value, and critical capillary pressure (Lehmann et al., 2008). They are obtained by conducting numerical simulations of homogeneous profiles in this study, and results are shown in Supplemental Table S1. The top soil layered thicknesses \( (Z) \) are selected to represent different cases. For example, the top coarse layer thicknesses \( (Z_C) \) in a C/F system are selected to represent cases with layers both smaller and larger than the characteristic length of the coarse layer \( (L_C) \).

### 3 RESULTS AND DISCUSSION

This section addresses how near-surface soil moisture and evaporation fluxes are influenced by top soil layer properties and thicknesses. The numerical model is first verified against observed evaporation, water content, and soil temperature data from the layered experiments. Then, a series of numerical scenarios varying in soil property profiles are conducted to investigate the effect of the top soil layer on near-surface soil moisture and evaporation dynamics. Additionally, the analysis of these
near-surface processes is connected with the evolution of soil moisture profiles that are affected by the top soil layer. In the last part, the special characteristics of near-surface moisture and evaporation dynamics shown by layered soil systems are identified and summarized for the interpretation of soil properties.

3.1 Numerical simulation and comparison with experimental results

As mentioned in the modeling section, the numerical model was previously tested for homogeneous soil profiles in steady free-flow conditions (Li et al., 2019; Smits, Cihan, Sakaki, & Illangasekare, 2011) and was amended to account for the transient free-flow conditions closer to nature. To validate the model, numerical simulation results for evaporation, moisture, and temperature are compared with experimental results. Some key experimental results for C/F and F/C experiments are shown in Supplemental Figures S1 and S2, respectively.

The numerical simulations generally provide reasonable estimates of cumulative evaporation, water saturation, and soil temperature for the C/F and F/C experiments (Figure 3). Small differences, especially in the soil temperature and saturation with depth, could be due to the uncertainty of soil hydraulic property characterization, or the interference of laboratory temperature during the F/C experiment. Despite the small differences, the model generally captures both the system- and local-level state and flux behavior, indicating that it is appropriate to be used for further investigation of the behavior of various soil profiles during evaporation.

3.2 Effect of the top soil layer on moisture and evaporation dynamics

3.2.1 Coarse soil overlying fine soil (C/F)

Effect of soil layer thickness on evaporation behavior

Figure 4 demonstrates the effect of the overlying coarse soil layer thickness on evaporation for a range of thickness ($Z_C$) from 1 to 15 cm. As noted in Supplemental Table S1, the characteristic length of the coarse layer ($L_C$) is 10 cm. The cumulative evaporation curve for the C/F gradually converges with the cumulative evaporation for the homogeneous coarse soil profile as the top coarse layer thickness approaches the characteristic lengths of the coarse soil. The characteristic length of the C/F layered system is the top coarse layer thickness ($L_{C/F} = Z_C$) (Shokri et al., 2010). When $Z_C$ is larger than $L_C$, as in the case when $Z_C = 12$ or 15 cm, the cumulative evaporation shows little difference compared with the homogeneous coarse soil profile ($L_{C/F} = L_C$). This is in agreement with the finding in Shokri et al. (2010) and Assouline et al. (2014) that the C/F can behave much like a homogeneous coarse system regarding to evaporation behavior when $Z_C > L_C$. The characteristic lengths of layered soil systems are summarized in

### FIGURE 3

Observed and simulated cumulative evaporation (CE), water saturation ($S_w$) at three depths of 2.5, 7.5, and 12.5 cm, and soil temperature ($T$) at the 2.5-cm depth with ambient temperature ($T_a$) as a reference for the (a–c) coarse soil overlying a fine soil (C/F) and (d–f) fine soil overlying a coarse soil (F/C) experiments. For the soil temperature, only 10 d are plotted for a clear view. $t$ is time.
Supplemental Table S2. However, what is not well understood from previous studies is the evaporation rate behavior of C/F soil with smaller coarse layer thickness or low textural contrast.

Figure 5a shows the evaporation rate for a C/F soil for two cases, also shown in Figure 4 for cumulative evaporation. These two cases were selected because they demonstrate two behavior extremes, where the thin C/F shows an initial rapid decline but maintains a high and daily constant Stage II evaporation rate, whereas a thick C/F soil profile shows identical Stage I evaporation but a slightly smaller Stage II evaporation rate compared with homogeneous coarse configuration. Figure 5b summarizes the effect of the top coarse layer thickness specifically on the Stage II evaporation rate, which is averaged from the onset of Stage II until 20 d (denoted as $E_2$ here). The ratio between $E_2$ for a C/F system and the corresponding value for the homogeneous coarse system ($E_{2,\text{homo}}$) changes nonmonotonically with the ratio between $Z_C$ and $L_C$. For small coarse layer thicknesses, the ratio is larger than 1 and decreases with increasing $Z_C/L_C$ until it reaches a minimum smaller than 1, after which it increases again with $Z_C/L_C$. This indicates the important and complex role of the top coarse layer thickness in affecting the transient Stage II evaporation rate. On the other hand, the transient evaporation rate dynamics contains valuable information about layering characteristics.

Specifically, the evolution of the effective water saturation ($S_{\text{ew}}$) profiles shown in Figure 6 could better explain how the soil layer thickness affects DSL evolution and subsequently the Stage II evaporation rate in C/F layered soil. The very thick C/F (Figure 6b) shows nearly identical behavior to the homogeneous coarse soil where the drying front gradually recedes and DSL develops without being affected by the underlying fine layer. However, the development of the DSL in the top layer of 8-cm C/F is accelerated as the desaturation of the underlying fine soil is much reduced. In the case of a thin coarse layer on the top
Figure 6 illustrates the times when the Stage I evaporation ends for the C/F profiles with high textural contrast. As expected, this happens before the desaturation of the underlying soil because the critical capillary pressure of the top coarse soil is smaller than the air entry value of the underlying fine soil, as noted in Supplemental Table S1. A different situation is shown later for C/F layered systems with low textural contrast.

The soil moisture profile evolution not only relates closely to the Stage II evaporation rate shown above but also can reflect the availability of water in the sublayer, which can be used for plant transpiration. Considering the important role of the top soil layer thickness in affecting soil moisture profile evolution, the layered soil property profile to include the top soil layer thickness should be characterized precisely.

Effect of soil layer thickness on near-surface soil moisture
Simulated near-surface soil moisture for layered soil with different top soil layer thicknesses is shown in Figure 7. The upper 5-cm thickness is first defined as the near surface because it is often used in the soil moisture remote sensing by L-band radiometers and radar (Mohanty, Cosh, Lakshmi, & Montzka, 2017). As can be seen, the near-surface soil moisture for a C/F soil profile with a thin coarse layer (1, 3-cm C/F) deviates significantly from the homogeneous system for most drying periods, whereas the C/F system with a thicker coarse layer (same or larger than 5 cm) is nearly identical to the homogeneous coarse system.

The averaged soil moisture of the upper 2 cm for selected soil profiles is shown in Figure 7b as a comparison. Results show that the near-surface soil moisture for the homogeneous coarse and fine soils is not affected much, but the soil moisture for 3-cm C/F is significantly changed because soil moisture profiles for 3-cm C/F are highly nonlinear and the upper 2 cm does not contain the underlying fine layer. The variations of near-surface soil moisture dynamics caused by the difference of top soil layer thickness and definition of near-surface depth could be used to inform the interpretation of the sensed soil moisture data.

Effect of top coarse layer properties
Figure 8a shows the effective water saturation at the end of Stage I ($t = 0.4 \text{ and } 0.8 \text{ d}$) and 20 d for layered soil systems with low textural contrast when using #30/40 coarse soil as a surface layer, compared with the high-textural-contrast system when using #12/20 as a surface layer. As can be inferred from Figure 8a, air enters the underlying fine soil prior to the end of Stage I evaporation for the low-textural-contrast soil system, which is different from the case discussed above (high textural contrast), extending the characteristic length of the layered system larger (Figure 6d), the DSL develops rapidly and water vaporizes at the C/F interface. The pressure head at the C/F interface keeps high and the vapor pressure remains saturated, so the vapor transports through the DSL at a constant rate. A similar evaporation pattern (i.e., the early transition of Stage I to a high and constant Stage II evaporation rate) has also been reported in experimental results with a thin hydrophobic soil layer on the surface (Shokri, Lehmann, & Or, 2008).

Figure 6 also illustrates the times when the Stage I evaporation ends for the C/F profiles with high textural contrast. As expected, this happens before the desaturation of the underlying soil because the critical capillary pressure of the top coarse soil is smaller than the air entry value of the underlying fine soil, as noted in Supplemental Table S1. A different situation is shown later for C/F layered systems with low textural contrast.

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FIGURE 7 Simulated near-surface soil moisture ($\theta_{SW}$, averaged over the upper 5-cm thickness) vs. time ($t$) for coarse soil overlying a fine soil (C/F) soil profiles, with different top coarse (C) layer thicknesses ($Z_C = 1, 3, 5, 8, 10,$ and 12 cm) with homogeneous C and fine (F) profiles results as references, and (b) simulated $\theta_{SW}$ averaged over the upper 2- and 5-cm thicknesses for a 3-cm C/F layered soil profile and homogeneous profiles.

FIGURE 8 Simulation results for a coarse soil overlying a fine soil (C/F) system with two coarse (C) materials as the top C layer (i.e., a high- and low-textural-contrast C soil compared with an underlying fine [F] soil). The simulation results are (a) effective water saturation ($S_{sw}$) profile at different times ($t$) for a 1-cm C/F layered soil at the end of Stage I and 20 d, (b) the ratio between cumulative evaporation of Stage I for a C/F soil with different top soil thicknesses ($E_{SI}$) and the corresponding value for the homogeneous C system ($E_{SI,homo}$) vs. $Z_C/L_C$, where $L_C$ is the characteristic length of the coarse layer, and (c) the ratio between cumulative evaporation at 20 d for a C/F soil with different top soil thicknesses ($E_{CE}$) and the corresponding value for the homogeneous C system ($E_{CE,homo}$) vs. $Z_C/L_C$

than the top coarse soil thickness. Figure 8b shows the ratio between cumulative evaporation of Stage I ($E_{SI}$) for a C/F soil with different top soil thicknesses and the corresponding value for the homogeneous coarse system ($E_{SI,homo}$) along with $Z_C/L_C$ for the two different coarse soils. The ratio for both soil profiles is less than 1 when $Z_C/L_C$ is less than 1, and a smaller slope is shown when a low-contrast soil is used as the top coarse soil. Together with the results shown in Figure 8a, we conclude that the presence of the fine layer reduces the duration and cumulative
evaporation of Stage I compared with the homogeneous coarse soil, and the reduction is less evident when the coarse layer has less textural contrast with the underlying fine layer. Figure 8c shows the ratio between cumulative evaporation at 20 d for a C/F soil (CE) and the corresponding value for the homogeneous coarse system \((CE_{\text{homo}})\) along with \(Z_C/L_C\). Similarly, the \(CE/CE_{\text{homo}}\) for the C/F system with low textural contrast is closer to 1 compared with high contrast at all depths. If we only put \(E_{SI}\) or CE as the criteria of defining the effective soil properties, these results illustrate that the less the textural contrast between the coarse and fine, the smaller the discrepancies will be if the properties of the top soil are used as the effective soil properties for the C/F system. In other words, it is more important to characterize the C/F soil property profile, instead of using the properties of the top soil as the effective parameters, for a system with high textural contrast.

3.2.2 Fine soil overlying coarse soil (F/C)

**Effect of soil layer thickness on evaporation behavior**

Figure 9 shows the simulated cumulative evaporation and evaporation rate for F/C soil profiles with different top fine layer thicknesses from 1 to 8 cm and also plotted against the homogeneous fine case for reference. A sharp drop in evaporation rate at the onset of Stage II is clearly shown in a layered F/C soil, contrary to a smooth decline of evaporation rate in the homogeneous fine soil profile. This phenomenon is also supported by the F/C experimental results of cumulative evaporation (Figure 3d). When the top fine layer is very thin (1-cm F/C), the presence of the underlying coarse layer shortens the duration of Stage I by disrupting the hydraulic continuity of the homogeneous fine soil, leading to smaller cumulative evaporation compared with the homogeneous fine soil. The duration of Stage I evaporation increases with the increase of the overlying fine layer thickness \((Z_F)\) and even becomes larger than the duration of Stage I in a homogeneous fine soil profile. Meanwhile, Stage II evaporation rate decreases remarkably (e.g., the averaged evaporation rate for the 8-cm F/C case during Stage II is \(\sim 0.28 \text{ mm d}^{-1}\), which is much lower than the averaged Stage II evaporation for the homogeneous fine profile \(1.77 \text{ mm d}^{-1}\)). The behavior of a lower Stage II evaporation rate for a F/C soil compared with a homogeneous fine soil is consistent with experimental results in Assouline et al. (2014). Assouline et al. (2014) showed that the averaged Stage II evaporation for an 8-cm-thick F/C is \(\sim 0.47 \text{ mm d}^{-1}\), which is much lower than the corresponding value for a homogeneous fine soil \(2.2 \text{ mm d}^{-1}\). The lower Stage II evaporation rate in F/C compared with homogeneous fine soil can be better explained in the effective water saturation profiles as shown in Figure 10.

Figure 10 shows effective water saturation profiles for F/C when the top layer thickness is 8 cm compared with the homogeneous fine soil profile. For the homogeneous fine soil, a nearly linear decrease of water content from the soil surface to the drying front can be seen. The Stage I evaporation ends at about Day 4, as shown in Figure 10a. However, when fine soil overlies coarse soil, air invades the underlying coarse layer through the large pores of the overlying fine soil during Stage I, as can be seen in the observed soil moisture data in both layers (variations of measurements from different sensors are not shown here, but the averaged values are shown in Figure 3e) and neutron radiography measurements in Shokri et al. (2008). The evaporation losses lead to a reduction in water content in both layers. At about Day 5.3, DSL forms in the overlying fine layer, leading to a maximum hydraulic connection length, which is the summation of the overlying fine layer thickness and the characteristic length of the underlying coarse
layer. Then, the evaporation is limited by the water supply from the underlying coarse layer to the fine layer and vapor diffusion through the DSL (i.e., the thickness of the fine layer), giving rise to the low Stage II evaporation rate. The above special liquid–gas displacement patterns attributed to the soil layering can explain not only the evaporation behavior but also the near-surface soil moisture dynamics introduced below.

Effect of soil layer thickness on near-surface soil moisture
Near-surface soil moisture is averaged over the upper 5 and 2 cm for layered soil with different top fine layer thicknesses from 1 to 8 cm (Figure 11). Results show that F/C has very distinct relations between near-surface soil moisture and time. When the averaged region only contains fine soil, near-surface soil moisture decreases slowly at first and then rapidly afterward. When near-surface soil moisture contains both layers (e.g., 1-cm F/C when averaged over upper 5 cm), it follows the homogeneous coarse curve first, then stabilizes before decreasing again. This near-surface soil moisture behavior of F/C differentiates it from other soil profiles (homogeneous and C/F), which present a monotonically decreasing trend with the quickest rate at the beginning. This behavior occurs because the evaporated water from the top fine layer is quickly replenished by the underlying coarse layer via capillary-induced upward flow, which also can be seen from experimental results of soil moisture dynamics at different depths (Figure 3e).

The high water content in top fine layer in the F/C system has also been partially shown by visualization and sampling techniques (Assouline & Narkis, 2019; Huang et al., 2013; Kumar & Arakeri, 2018; Shokri et al., 2010), but this “first slowly then rapidly” decreasing dynamic of near-surface soil moisture has not shown in the literature. This special characteristic can be used as an indicator of thick F/C soil profile, or thin F/C soil profile if the sensing depth is even thinner (e.g., 3-cm F/C when averaging the upper 2 cm).

3.3 Interpretation of the soil properties based on near-surface information

In the section above, we investigated the effect of the top soil layer on near-surface soil moisture and evaporation fluxes, concluding that the top soil layer affects the
The comparison of the near-surface soil information over time (t; i.e., $E$, evaporation rate; $\theta_{sw}$, near-surface soil moisture which is averaged over the upper 5 cm; and $T_s$, surface temperature) for different soil profiles: (a) homogeneous coarse (C) and fine (F) soils, (b) homogeneous C soil, 10-cm coarse soil overlying a fine soil (C/F) and 1-cm fine soil overlying a coarse soil (F/C) layered soils, (c) 1-cm C/F layered soil, and (d) 8-cm F/C layered soil.

near-surface information differently. Here, we address how the available near-surface information can be used to understand the soil properties (i.e., defining effective soil parameters or soil property profile).

The holistic near-surface information for selected layered soil profiles is presented for comparison in Figures 12b–12d and also plotted against the homogeneous cases (Figure 12a) for reference. The averaged soil moisture over the upper 5 cm is selected to represent the near-surface soil moisture. Soil surface temperature is also included for comparison in this section.

As shown in Figure 12b, the near-surface moisture, surface temperature, and evaporation fluxes for a C/F system with $L_C < Z_C$ or a F/C system with very thin fine soil are nearly identical to the homogeneous coarse soil, which suggests that the homogeneous coarse layer properties can be used as effective parameters for these two-layered systems. Similarly, such evaporation comparison can be found in previous studies that support our conclusion. In addition to the experimental evidence comparing coarse and C/F layers from the literature, discussed in the section above, Assouline et al. (2014) showed experimental evidence that 2-cm F/C (sandy loam/coarse sand) presented similar evaporation behavior to homogeneous coarse soil. In the field, a well-structured surface soil layer may be represented as a coarse-textured soil layer, whereas a crusted soil or compacted soil layer has properties more similar to a fine-textured soil. Both soil profiles (C/F or F/C) are common in the field because the shallow soil surface properties change significantly with time. If the thickness of the top soil applies to the criteria above, these layered soil profiles can be represented by the corresponding homogeneous coarse-textured soil profile.

However, some layered soil profiles show special characteristics in the top soil layer, which indicates that the properties of a homogeneous profile are insufficient to describe the behavior of the layered system. For example, a C/F with thin top coarse layer (1-cm C/F) shows an early transition from Stage I to Stage II, along with a sharp decrease in evaporation rate and a sharp increase in surface temperature at the onset of Stage II, but a slow decrease in near-surface soil moisture (Figure 12c). Several very coarse soils were tested to see if they can be used to represent the C/F system with a thin coarse layer, but the results were not
TABLE 3  Characteristics of near-surface information of layered soil

| Soil profile | Example | Characteristics |
|--------------|---------|-----------------|
| Very thin C/F ($Z_C < L_C$) | 1-cm C/F | Short duration of Stage I evaporation |
| | | Sharp change of $E$ and $T_s$ at the onset of Stage II |
| | | High and stable Stage II $E$ |
| | | $\theta_{SW}$ decreases slowly with time |
| C/F ($Z_C < L_C$) | 6-cm C/F | Sharp change of $E$ and $T_s$ at the onset of Stage II |
| | | Low and stable Stage II $E$ |
| F/C (thick F) | 8-cm F/C | Sharp change of $E$ and $T_s$ at the onset of Stage II |
| | | Low Stage II $E$ |
| | | $\theta_{SW}$ first decreases slowly then rapidly |

$^*$C/F, coarse soil overlying a fine soil; F/C, fine soil overlying a coarse soil; $Z_C$, top coarse layer thickness; $L_C$, characteristic length of the coarse layer; F, fine soil.

$^b$E, evaporation rate; $T_s$, surface temperature; $\theta_{SW}$, near-surface soil moisture.

satisfactory. The main difference is that the DSL in a homogeneous soil keeps extending into the soil with limited water underneath the DSL, so a high and constant Stage II evaporation rate is hard to achieve in a homogeneous soil. In addition, a thick F/C (8-cm F/C, Figure 12d) also exhibits special characteristics incapable of being represented by a homogeneous layer: a “first slowly then rapidly” decreasing dynamic of near-surface soil moisture, a sharp change of evaporation rate and surface temperature at the onset of Stage II, and a remarkably low Stage II evaporation rate. These characteristics of near-surface soil information are summarized in Table 3.

The described characteristics could be used to inform the estimation of soil property profiles. Among these characteristics, we find that the characteristic of near-surface soil moisture is more distinct than evaporation. However, capturing the characteristic of either the near-surface soil moisture or evaporation is only possible if we consider the entire drying cycle from full saturation to dry conditions. The evaporation behavior, especially the sharp drop in evaporation rate at the onset of Stage II, is consistent with previous findings (Assouline & Narkis, 2019; Assouline et al., 2014; Shokri et al., 2010) but is not unique to a layered soil profile, as it can be seen in some homogeneous soil profiles as well (Shokri and Or, 2011). Another understanding is that even though the sharp change is not that special, with extra information of near-surface soil moisture, a layered soil profile might be confirmed (e.g., 1-cm C/F). This illustrates the necessity of using the combined information to include the soil moisture and evaporation for the entire drying cycle to interpret the soil layering condition and its properties. Additionally, considering that the near-surface soil moisture dynamics vary with both top soil thickness and the definition of near-surface depth, it is helpful to include soil moisture measurements collected by various sensing technologies with different spectral frequencies and penetrating depths.

4  | CONCLUSIONS

In this study, the effect of the top soil layer on the near-surface soil moisture and evaporation flux was experimentally and numerically investigated. This was then extended to identify how we can use this information to characterize the soil properties.

Results show that the evaporation rate and near-surface soil moisture can be significantly affected by the top soil layer. The extent of the effect depends on the layering sequence, thickness, and the properties of the two layers. However, when significant, the effect of the top soil layer should be evaluated and considered in hydrological modeling for more reliable predictions.

The specific findings are summarized as follows:

- The near-surface soil moisture and evaporation flux for a C/F system are similar to the homogeneous coarse system when the characteristic length of the top coarse layer is less than its thickness. Otherwise, the Stage II evaporation flux for the C/F system presents a non-monotonic relationship with top layer thickness, which can be explained by the soil moisture profile evolution (especially DSL evolution) being affected by the top soil layer. The near-surface soil moisture dynamics depend on the top soil layer thickness and the definition of near-surface depth.
- For an F/C system, both the evaporation and near-surface soil moisture show distinct behavior compared with the homogeneous fine system as follows: a sharp drop in evaporation rate at the onset of Stage II, followed by a remarkably low Stage II evaporation rate, a “first slowly then rapidly” decreasing dynamic of near-surface soil moisture.
- The properties of the coarse soil layer can be used as the effective parameters of two types of layered soil systems: a C/F layered system with the characteristic length of the
coarse layer less than the thickness of the coarse layer, and an F/C layered system with a thin top fine layer.

- Special characteristics of near-surface moisture, temperature, and fluxes shown from some layered soil systems (i.e., very thin C/F and thick F/C) cannot be described with a homogeneous profile with effective parameters. Nevertheless, the unique characteristics provide us clues to estimate the layering conditions (i.e., a sharp change of evaporation rate and surface temperature at the onset of Stage II, high and constant evaporation rate during stage II, near-surface soil moisture dynamics, etc.).

- The characteristic of near-surface soil moisture is more distinct than the evaporation behavior in distinguishing soil property profiles. However, capturing these characteristics is only possible if we consider the entire drying cycle from full saturation to dry conditions.

Findings indicate the importance of including the spatial and temporal evolution of both evaporation and near-surface soil moisture over the entire drying cycle to better characterize the soil property profile. This knowledge can be used to inform the hydrological model calibration, field data analysis, and sampling strategies. It is acknowledged that this study is limited to sandy soils of which the soil properties are based on the current experimental data. When considering field soils with finer texture, a preliminary numerical experiment demonstrates the validity of the conclusion. However, further studies including experimental and numerical efforts are needed to fully understand the effect of the top soil layer on the moisture and evaporation dynamics under field conditions for multiple drying–wetting cycles. In addition, the reverse modeling of the soil properties based on near-surface states and variables for field systems are subject to future work. Furthermore, under which conditions (e.g., tillage activities in agricultural land, area with frequent rainfall, etc.) the soil layers are formed and how these effects can be integrated into large scales models are worth investigating.

**CONFLICT OF INTEREST**
The authors declare no conflict of interest.

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