The effects of shallow saline groundwater on evaporation, soil moisture, and temperature distribution in the presence of straw mulch

Ashkan Yusefi, Ahmad Farrokhian Firouzi and Milad Aminzadeh

ABSTRACT

Mitigating evaporative water loss from terrestrial surfaces is of central importance to water resources management in arid and semi-arid regions. This study was intended to experimentally address the effect of straw mulch layer on soil evaporation and temperature distribution in the presence of shallow saline groundwater. A factorial-based experiment with a completely randomized design was carried out in mini-lysimeters (MLs) with different concentrations of saline groundwater and soil types, with and without straw mulch. The lysimeters were placed on the soil surface in the field. Water table in MLs was kept at the depth of 60 cm, and evaporation rate, soil moisture content, soil salinity, and temperature were continuously monitored. The analysis of variance (ANOVA) indicated significant differences in the soil evaporation rates due to the effects of soil types (i.e., loam and sand) and straw mulch ($p < 0.01$). The results showed that soil temperature fluctuations at the 5 cm depth in loamy soil with and without mulch were 11.5 and 17.5 °C, while in sandy soil the fluctuations rates were 15 and 18.5 °C, respectively. The application of a mulch layer was found to significantly reduce the evaporative loss by 27 and 8% in loamy and sandy soils, respectively.

Key words | bare soil, evaporation, soil temperature, straw mulch, water content

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HIGHLIGHTS

- The effect of straw mulch cover on soil evaporation in the presence of shallow water table was investigated experimentally in a hot and humid environment with different soil types.
- In addition to significant reduction in soil evaporation, mulch cover dramatically changed soil moisture and temperature distribution in soil profile.
- Depending on the soil type and thus associated effect of capillary rise, the suppression of evaporative loss by mulch cover alleviated salt accumulation in soil layers.
- Mulch cover influenced the surface energy balance and thus reduced soil temperature fluctuations thereby improving the condition for seed germination and root growth.

INTRODUCTION

Soil evaporation as one of the key processes in the hydrological cycle and water balance of arid and semi-arid regions (Shaw *et al.* 2010; Harwell 2012; Assouline *et al.* 2014) can be divided into three stages. During the first stage, a rather constant evaporation rate controlled by atmospheric forcing is kept for a significant time (Shokri *et al.* 2008). The surface of the soil, then, begins to dry and a sharp drop is observed in the evaporation rate during the so-called falling stage

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(van Brakel 1980; Prat 2002; Shokri & Salvucci 2011). Eventually, at the onset of the third stage, the vaporization plane recedes into the soil profile and the diffusion processes govern vapor transfer to the soil surface (Aminzadeh & Or 2013).

Soil evaporation is primarily affected by the intrinsic soil properties (e.g., soil texture, hydraulic properties), the initial water content and the depth of water table, as well as the atmospheric forcing (e.g., solar energy, air temperature, humidity, and wind speed) (Rasheed *et al.* 1989; Alkhaier *et al.* 2012; Aminzadeh & Or 2014; Mengistu *et al.* 2018). Soil texture is, indeed, one of the important parameters in water retention and evaporation from the soil, and fine-textured soils tend to retain more water as compared with the coarse-textured ones. As such, the evaporation rate in fine-textured soils is higher than that of the coarse-textured ones. On the other hand, in fine-textured soil when groundwater is shallow, a significant amount of water evaporates through the capillary rise (Trenberth *et al.* 2009; Assouline *et al.* 2013).

Moreover, evaporation from soil surface not only causes water loss, but also induces soil salinity where salts are left in the vaporization plane (Salvucci & Entekhabi 1995; Hayashi 2013). For instance, in arid regions with high potential evaporation, about 50–70% of the rainfall (needed for plants' growth) is lost via evaporation (Jalota & Prihar 1990). Considering the complexity of plant transpiration, various methods such as plowing or mulching have been invoked to control the evaporative soil water loss (Freitas *et al.* 2014). Mulching indeed covers soil surface by adding organic and inorganic materials to it so as to increase the productivity of water, and provide a more favorable environment for plant growth (Parmanik *et al.* 2015). Vial *et al.* (2015) reported that the addition of straw mulch reduced evapotranspiration about 114–161 mm, which, in turn, increased water productivity on corn farms. Similarly, Chen *et al.* (2019) concluded that the application of mulch could effectively keep soil moisture and reduce evapotranspiration. Investigating the effect of wheat residues on soil surface evaporation, Bhatt & Sanjay (2015) showed that the presence of mulch suppressed the evaporative loss up to 80%. Likewise, Akhtar *et al.* (2019), in a study conducted in Northwest China, reported that straw mulch increased soil moisture by 4.7%, leading to a 3% temperature decrease in soybean farms. The results of Yan *et al.* (2018) also demonstrated that the presence of straw mulch enhanced water use efficiency of wheat farms enabling dry land farming. According to McMillen (2013), a layer of wheat straw mulch, grass, and fresh leaves with a thickness of 5–10 cm could increase moisture content up to 10% compared with bare soil. However, the results of Ashrafuzzaman *et al.* (2011) were in disagreement with the results of other studies as they did not find significant differences in retaining soil moisture content among different types of mulch covers.

In turn, soil temperature, as one of the most important factors affecting heat and mass exchanges in soil, plays a significant role in various processes ranging from seed germination, plant growth, root development, soil microorganism's activity, transport and dissolution of pollutants and herbicides, as well as soil salinity (Grifoll *et al.* 2005) to soil ventilation, infiltration, and evapotranspiration (Nassar & Horton 1999). In some studies, it has been acknowledged that the application of straw mulch increases soil temperature (Nath & Sarma 1992; Ramakrishna *et al.* 2006). By contrast, the results of other studies have shown that mulch reduces soil temperature (Wu *et al.* 2007).

Similarly, soil temperature distribution, water content in soil profile and salt precipitation induced by evaporation in arid and semi-arid regions have been extensively studied (Jalili *et al.* 2011; Ojo *et al.* 2011; Mengistu *et al.* 2018). However, some evidence shows that the existence of shallow saline water tables with high potential evaporation in these regions (Gholami *et al.* 2015) results in salt accumulation at soil surface (along with its associated problems in soil quality). This, thus, highlights the need for using efficient measures to mitigate the evaporative losses in soil moisture by considering the concurrent impacts on key thermal and transport processes of soil. Accordingly, this study was intended to systematically investigate the effect of straw mulch on soil evaporation, soil moisture, and temperature distribution, as well as salt precipitation in a set of lysimetric experiments in the southwest of Iran (Khuzestan province) with a shallow saline water table and high atmospheric evaporative demand. Farmers in Khuzestan province struggle with shallow and saline groundwater that results in considerable evaporative water loss and salt precipitation on soil surface. Indeed, the main objective of this study was to simultaneously evaluate the effect of using mulch as a protective layer on the evaporation rate, water content, salinity, and temperature distribution in soil profile with different textures, and also provide a scientific basis for the application of such a simple and cost-effective technique to control the problems associated with evaporative soil water loss.

MATERIALS AND METHODS

Experimental site

The experiment was conducted during the summer period with the maximum air temperature and potential evaporation from June 22 to September 22, 2018 on the agriculture farm of Shahid Chamran University of Ahvaz, Iran, with the coordinates of 48°39′ E and 31°18′ N and a height of 17 meters above sea level. The mean annual air temperature and rainfall in the region are 29 °C and 243 mm, respectively. According to Ambereje method, the climate of this region is semi-desert with hot and long summers and mild and short winters. Table 1 shows the meteorological parameters including the minimum and maximum air temperature, wind speed, sun hours as well as the minimum and maximum relative humidity in the study period.

Preparation and management of mini-lysimeters (MLs)

In the experiment, cylindrical PVC tubes with an inner diameter of 25 cm and length of 75 cm were used as MLs to investigate the effect of mulch cover on soil evaporation in a controlled domain. To that end, the lysimeters were placed on soil surface in the field and insulated with 4 cm-thick glass wool sheets to minimize the lateral heat fluxes. Using a Mariotte bottle system (Rose *et al.* 2005), during the experiment, the same as the site where the lysimeters were placed, the water table in mini-lysimeters (MLs) was kept at a depth of 60 cm (Karimi & Naseri 2012) to simulate the effect of the actual water table on evaporation, soil moisture, and temperature distribution (Figure 1). Indeed, each lysimeter was initially saturated, and after the gravitational drainage in which soil water content was approximately equal to field capacity the experiment began. The salinity of irrigation water in the study region varies in the range of 1.5–2.5 dS m^{-1} during the year. To prepare the saline water with electrical conductivity (EC) of 5, 10, and 15 dS m^{-1}, we used 1.5 g/L NaCl + 2 g/L $CaCl_2$, 3.5 g/L Nacl + 4 g/L $CaCl_2$, and 7 g/L NaCl + 10.5 g/L $CaCl_2$, respectively (Rose *et al.* 2005). Then, two types of soil with different physical characteristics (as shown in Table 2) along with two soil cover conditions (i.e., M: mulch and nM: no mulch) were used. Furthermore, wheat straw (0.35 kg m^{-2}) was applied as mulch treatment in this study.

Measurement of soil moisture, salinity, and temperature distribution

The volumetric water content, soil salinity, and soil temperature in MLs were measured at five depths, namely, 5, 10, 20, 30, and 50 cm. Then, the digital temperature sensors (DS18b20, China) connected to a data logger were used to record soil temperature hourly, while soil moisture and EC were monitored on a daily basis using time domain reflectometry (TDR) probes with 0.01% accuracy (HD2, IMKO, Germany).

Sensor calibration

Considering different soil textures in the experiments, soil moisture and temperature sensors were calibrated. The

Table 1 | Meteorological parameters during the experiment

	Temperature (°C)			Relative humidity (%)			Wind speed ($m.s^{-1}$)	Sun (hr)
	Max	Min	Mean	Max	Min	Mean	Mean	Mean
July	52.4	26.9	40.65	68	3	19	8	11.8
August	50.2	27.6	39	37	6	15	9.2	11.6
September	48.2	25	37.25	92	8	36	6.4	10.9

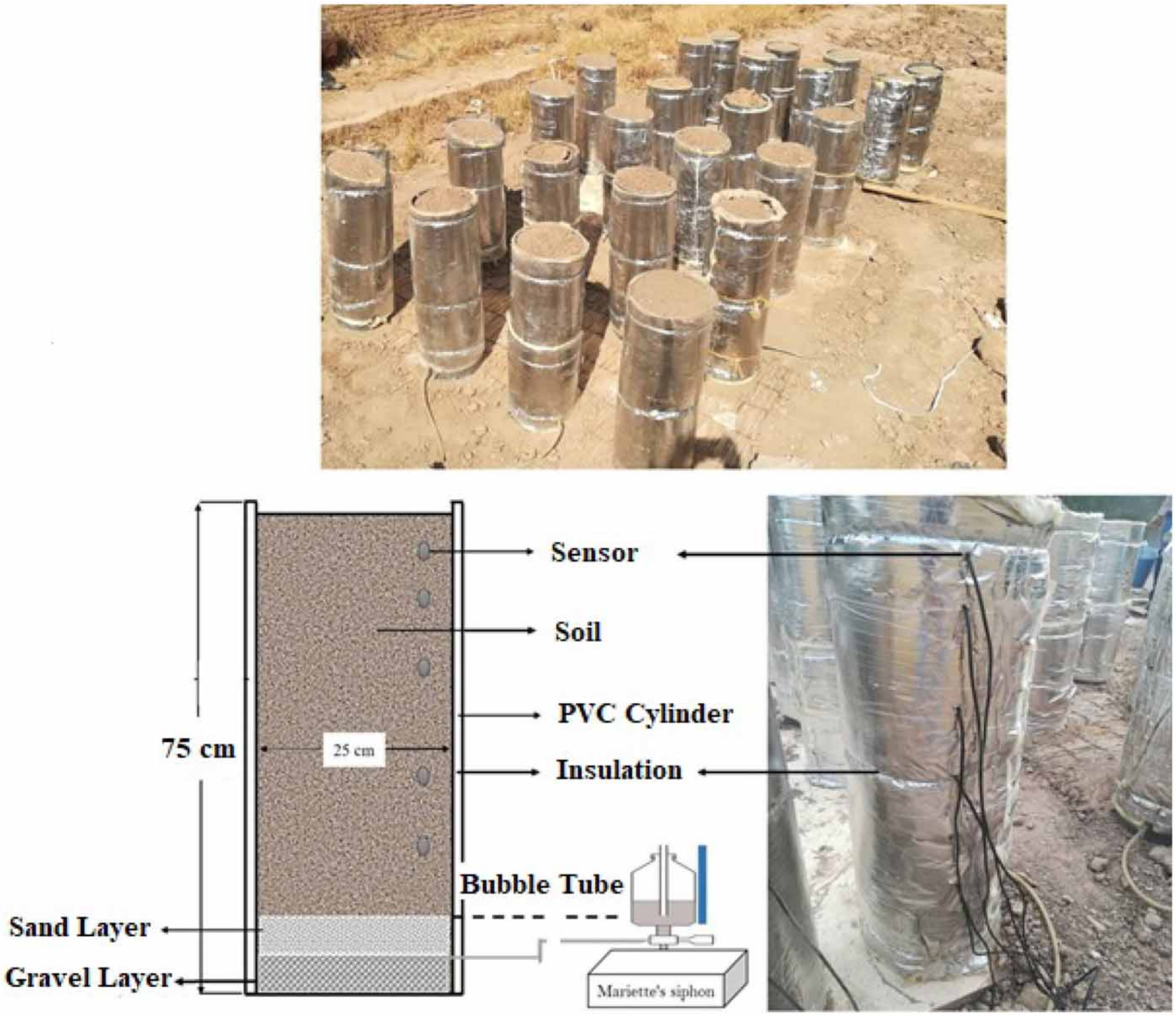

Figure 1 | Experimental setup for studying evaporation, soil temperature distribution and water content from different soil types in the presence of shallow water table.

HD2 moisture probes were then placed inside separate soil pots to measure daily soil moisture concurrently by weighing the pots. Finally, the best fitting curve (not shown here) was obtained using the data recorded by HD2 probe and the volumetric soil moisture content measurements.

Soil water retention curves (SWRC)

A sandbox and pressure plate apparatus were used to obtain water retention curves of the two soil types. The van Genuchten (1980) model was then fitted on the measured data to determine the corresponding parameters (Equation (1), Figure 2):

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

where θ_r and θ_s are the residual and saturated moisture content, respectively, α is related to the inverse of the air entry suction (cm^{-1}), n and m are the shape parameters in which $m = 1 - 1/n$, and h is the matric potential (cm). The maximum height of capillary rise (h_{max}) within the soil columns can be calculated using the shape parameters of soil moisture curve (α and n) based on Equation (2)

Table 2 | Summary of the physical characteristics of different soil types

Physical properties	Loam	Sand
Sand (%)	46	88
Silt (%)	32	8
Clay (%)	22	4
ρ_b (gr.cm^{-3})	1.45	1.59
ρ_s (gr.cm^{-3})	2.57	2.65
Ks (cm.d^{-1})	16	120
θ_s (%)	51	36
θ_r (%)	11	1
α (1/cm)	0.009	0.012
n	1.214	1.716
m	0.17	0.417
β	0.035	0.076

(Lehmann et al. 2008):

$$h_{\max} = \frac{1}{\alpha}\left(\frac{n-1}{n}\right)^{\frac{1-2n}{n}} \tag{2}$$

Soil water evaporation

The simplest form of soil water balance indicates that in a given volume of soil, the difference between the amount of input and output water shows soil moisture variation (Hillel 2004):

$$E_s = P + I + G_O - R_O - T_r - \Delta W \tag{3}$$

where P is the precipitation, I is the irrigation, G_o stands for the contribution of groundwater in evaporation (here, water consumption from the Mariotte bottle), R_o is the runoff, E_s and T_r are the water loss via evaporation and transpiration, respectively, and finally, ΔW shows the variation of soil water content. Considering that our measurements were conducted in the lysimeters under controlled conditions with no irrigation, therefore $I = 0$. During the experiment, there was no rain ($P = 0$), and thus no run-off ($R_o = 0$). In addition, there was no plant in this experiment, therefore $T_r = 0$. By simplifying Equation (2), the evaporation rate from the soil surface is obtained as:

$$E_s = G_o - \Delta W \tag{4}$$

On the other hand, the maximum soil evaporation in the presence of shallow groundwater (e_{max}) depends on the water table depth and soil characteristics (β and Ks)

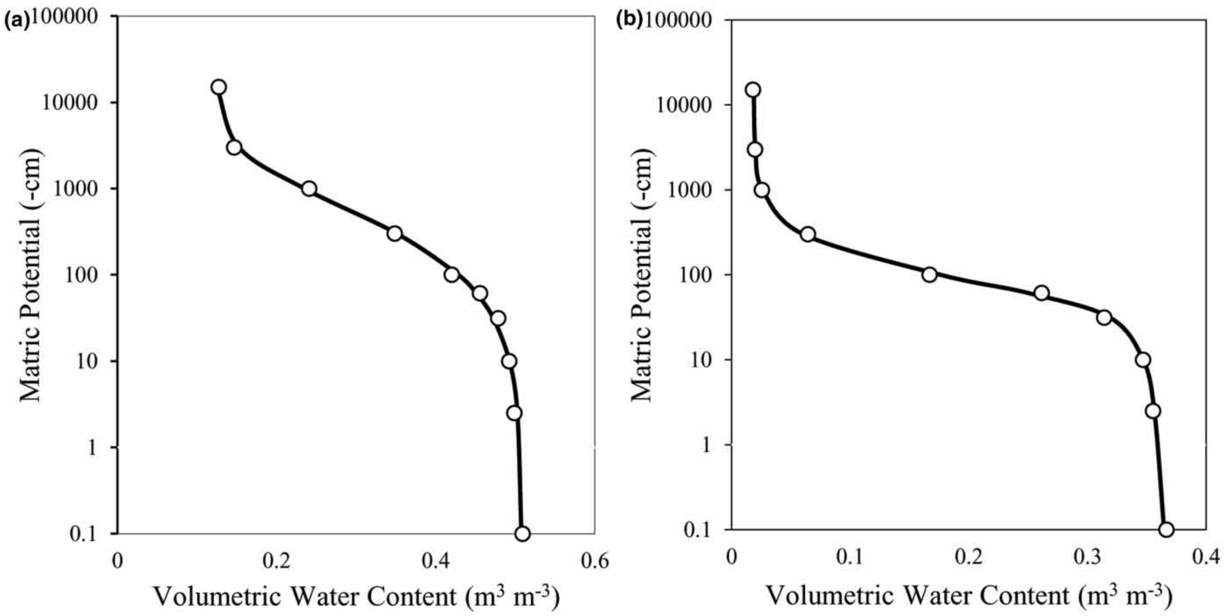

Figure 2 | Soil water retention curve (SWRC) of loam (a) and sand (b).

(Lehmann & Or 2009) as:

$$e_{\max} = K_s \frac{-\exp^{-\beta L}}{\exp^{-\beta L} - 1} = \frac{K_s}{\exp^{\beta L} - 1} \quad (5)$$

where Ks is the saturated soil hydraulic conductivity, L is the water table depth, and β is an empirical factor (Gardner 1959).

Daily potential evaporation data were obtained from a Class-A evaporation pan in a meteorological station located 5 km away from the experimental site.

Statistical analysis

The study was conducted as a factorial-based experiment using a completely randomized design with three replications. The experiment consisted of three treatment factors: groundwater salinity (5, 10, and 15 dS m^{-1}), wheat straw mulch (0 and 0.35 kg m^{-2}), and soil texture type (i.e., sand and loam). Furthermore, evaporation, soil moisture content, salinity, and temperature were measured for three months (from 22.06 to 22.09, 2018). To remove the effect of time in this research, the mean value of daily evaporation from the 90-day data was used.

RESULTS

Variation of soil water content

Daily variations of moisture content in two soil textures (i.e., loamy and sandy soils) with and without straw mulch in a three-month period are depicted in Figure 3. As seen, in all treatments the soil moisture content in the surface layers was lower than that in the deeper layers. Figure 3(a) shows that the volumetric moisture content at the 5 cm depth of loamy soil with mulch cover changed from 0.26 to 0.19 m^3 m^{-3} (26% decrease) after 10 days from the onset of the experiment. However, at the same depth and in the absence of mulch (Figure 3(b)), the moisture content decreased to 0.16 m^3 m^{-3} indicating 44% reduction relative to the onset of the experiment. These findings clearly highlight the effect of mulch covering on the suppression of surface evaporation yielding maintenance of the moisture content in the soil profile. After 30 days, the moisture content of bare relative to the mulch-covered loamy soil decreased by 32, 19, and 3% in 10 cm, 20 cm, and 30 cm depth, respectively. In the absence of straw mulch, however, the moisture content at the depth of 5 cm of sandy soil during the first 5 days of the experiment rapidly changed with 29% reduction. On the 30th day, it reached 0.01 m^3 m^{-3} and remained stable until the end of the experiment. The results showed that the mulch cover effectively retained a moisture content of about 20% in the surface layer of sandy soil. Similarly, in the second layer after the 5th day, the moisture content decreased by 32 and 50%, in the presence and absence of mulch, respectively (Figure 3(d)). In the lower layers (depths more than 20 cm), soil moisture content was almost constant in both sandy and loamy soil treatments and the effect of mulch covering on the moisture content of deeper layers was almost ineffective.

Soil temperature distribution

Temperature distribution in the soil profile is reported to be affected by such soil properties as texture, moisture content, surface covering, meteorological parameters, etc. (Holmes *et al.* 2008). The measurements showed that the maximum temperatures on July 3 recorded in the 5 cm-depth layer of loamy soil were 53.25 and 54.75 °C, while in sandy soil they were 52.25 and 54.5 °C with and without cover, respectively. The minimum temperatures observed on September 21 were 27.25 and 26.5 °C in loamy soil with and without mulch cover, respectively. However, they were 24.5 and 22.75 °C in sandy soil for the same surface treatment. In order to demonstrate the details of soil temperature dynamics, the hourly temperature variations in the second 11 days of the experiment day of year (DOY) 184–194 with the maximum air temperature in both soils with and without mulch treatment are shown in Figure 4.

Figure 5 shows the vertical soil temperature profiles at different depths of 5, 10, 20, 30, and 50 cm in one day (second day of the experiment) for different treatments (M and nM) of sandy and loamy soils. For all soil types and surface treatments, temperature fluctuations decreased with increasing depth. As expected, the maximum temperature fluctuation was seen in the 5 cm depth that was recorded in bare loamy soil as 17.5 °C (Figure 5(a)), while in the

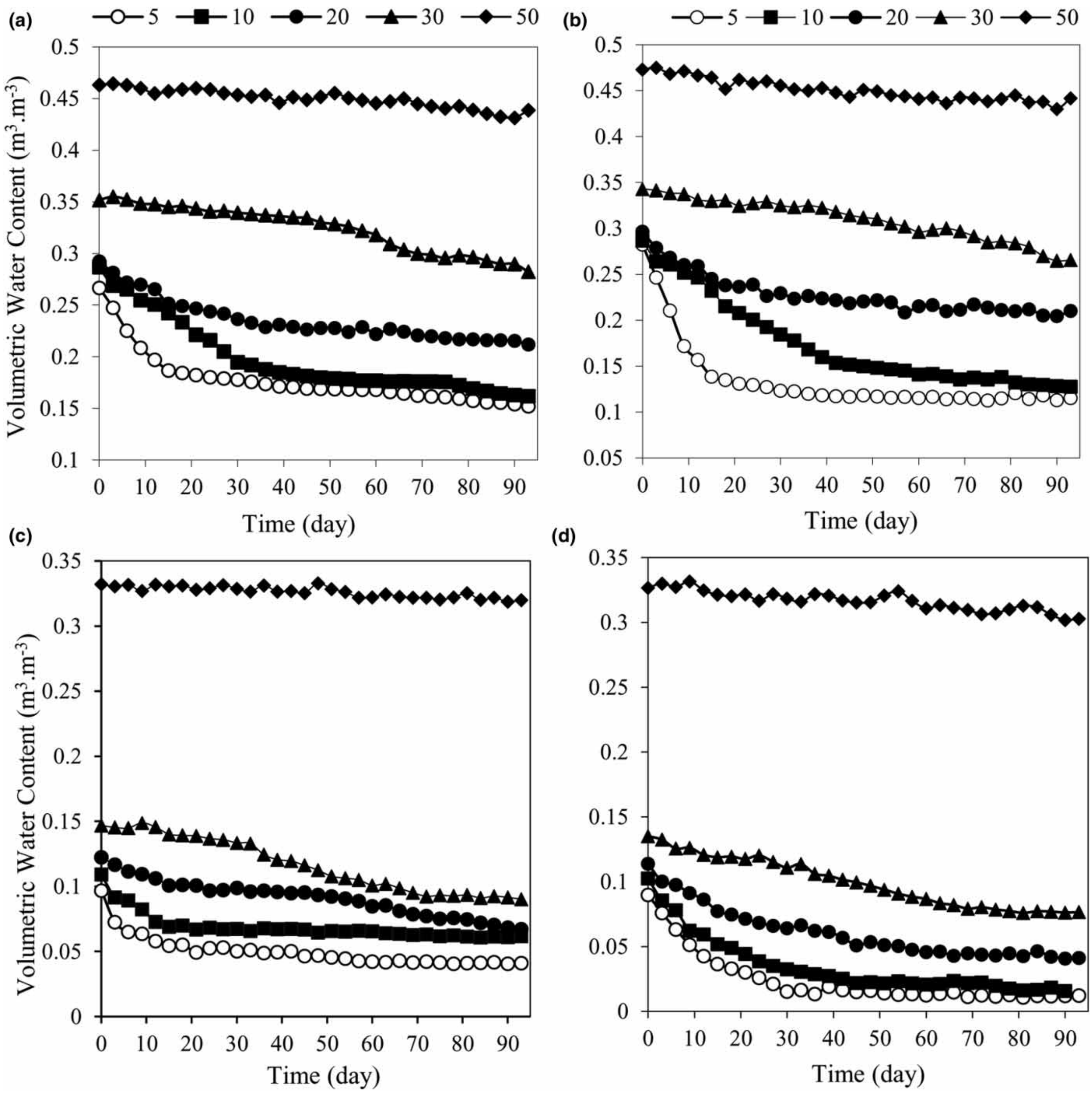

Figure 3 | Variation of water content at different depths of mulch-covered loamy soil (a), bare loamy soil (b), mulch-covered sandy soil (c), and bare sandy soil (d) in S1.

loamy soil with mulch cover it was found to be 11.5 °C (Figure 5(b)). Also daily variations of temperature in the surface layer of sandy soil in the presence and absence of mulch were 15 and 18.5 °C, respectively. These measurements clearly indicate that mulch cover dampens the near-surface temperature fluctuations, where the highest diurnal variations are often expected. Similarly, in the underlying layers, daily fluctuations of temperature decreased slowly from the surface to the depth of soil, and were almost identical in both soils with and without straw mulch. In both loamy and sandy soils, the temperature in the wetter soil profiles induced by mulch cover was less than that of dry soil.

Soil salinity

The vertical variations of salt content in the soil profiles for all treatments on the 5th, 45th, and 90th day of the

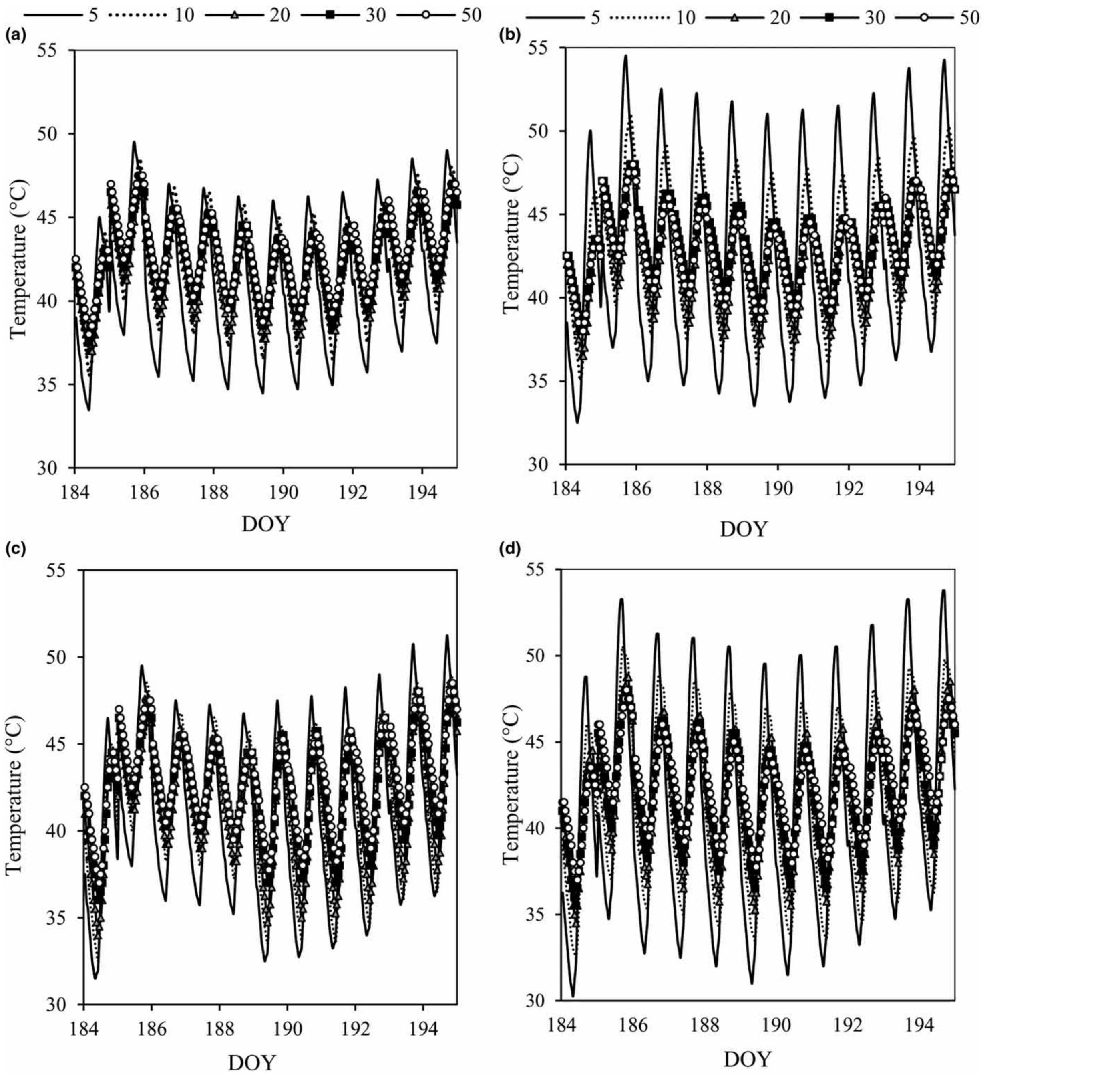

Figure 4 | Hourly changes in soil temperature of mulch-covered (a) and bare (b) loamy soil, mulch-covered (c) and bare (d) sandy soil at five depths (i.e., 5, 10, 20, 30, and 50 cm) from DOY 184 to 194.

experiment are depicted in Figure 6. As expected, salt accumulation (reflected in EC measurements) mainly occurred in the upper layers of the soil near the surface. In the loamy soil, the salt accumulation was very high in the surface layers and then decreased monotonically to the bottom. In both treatments of loamy soil (with and without mulch), the highest salt accumulation was found in the top layer for all the groundwater salinity treatments (5, 10, and 15 $dS\,m^{-1}$), with generally higher salt content in bare loamy soil (especially in $EC = 15\ dS\,m^{-1}$ of groundwater)

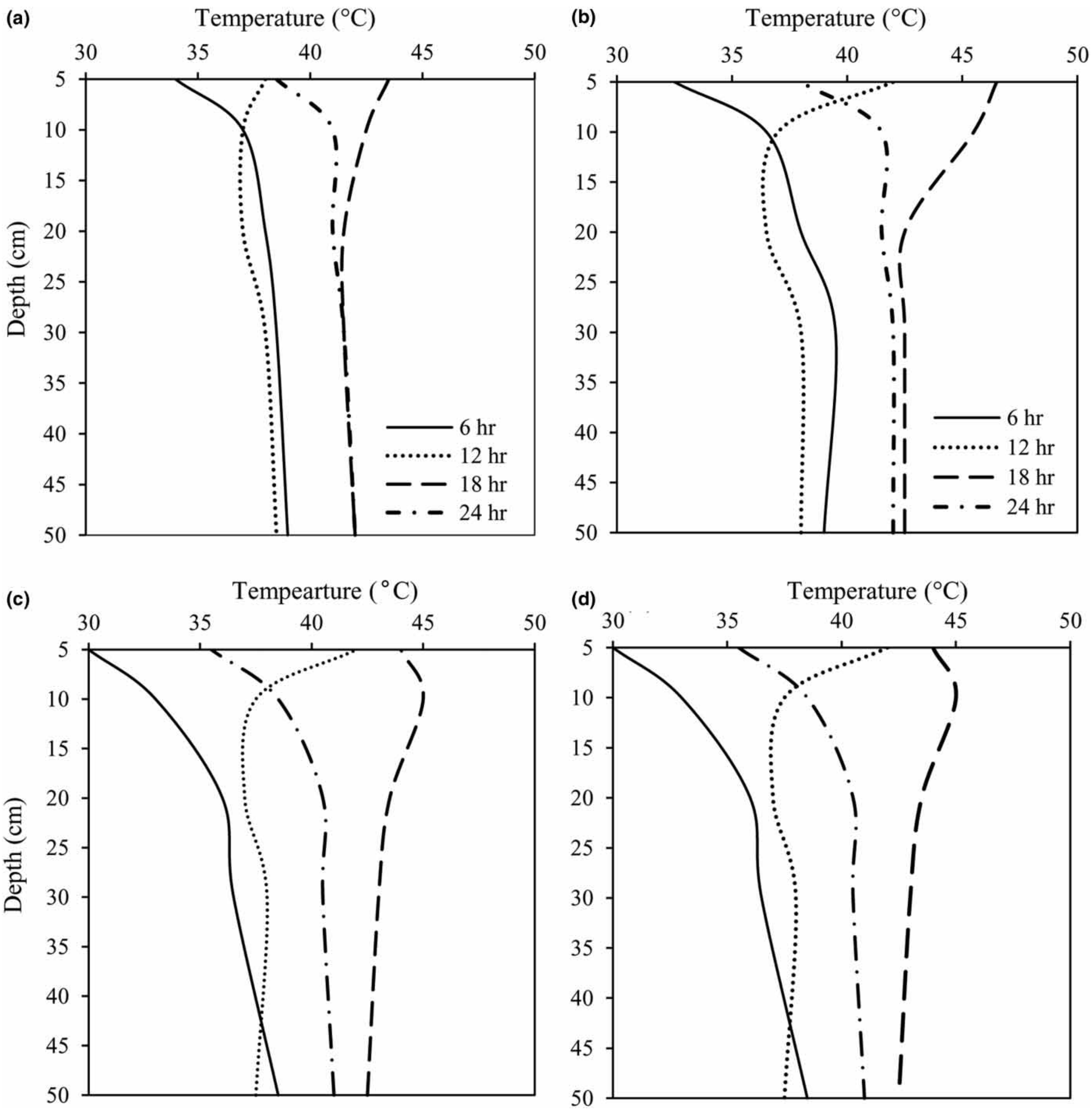

Figure 5 | Hourly changes in vertical soil temperature profile (DOY 175) of mulch-covered (a) and bare (b) loamy soil, and mulch-covered (c) and bare (d) sand.

relative to the mulch-covered treatment. In bare loamy soil, the salinity concentrations in the 5 cm depth at the end of the experiment for three different groundwater salt concentrations of S1, S2, and S3 (5, 10, and 15 $dS\,m^{-1}$) were measured as 16.87, 33.84, and 48.65 $dS\,m^{-1}$, respectively. With mulch cover, these values were decreased by 31, 46, and 23% compared to those in the bare soil (Figure 6(a) and 6(b)). At the depth of 10 cm, mulch covering caused salt reduction by 26, 14, and 17%, respectively, compared to those in the bare soil in three groundwater salinity treatments. Moreover, a sharper salinity gradient was observed towards the surface that was due to the presence of the vaporization plane at the surface of the sample. Below the depth of 10 cm, there was no significant change and salt concentration remained constant (close to the salt concentration in the groundwater). However, in sandy soil

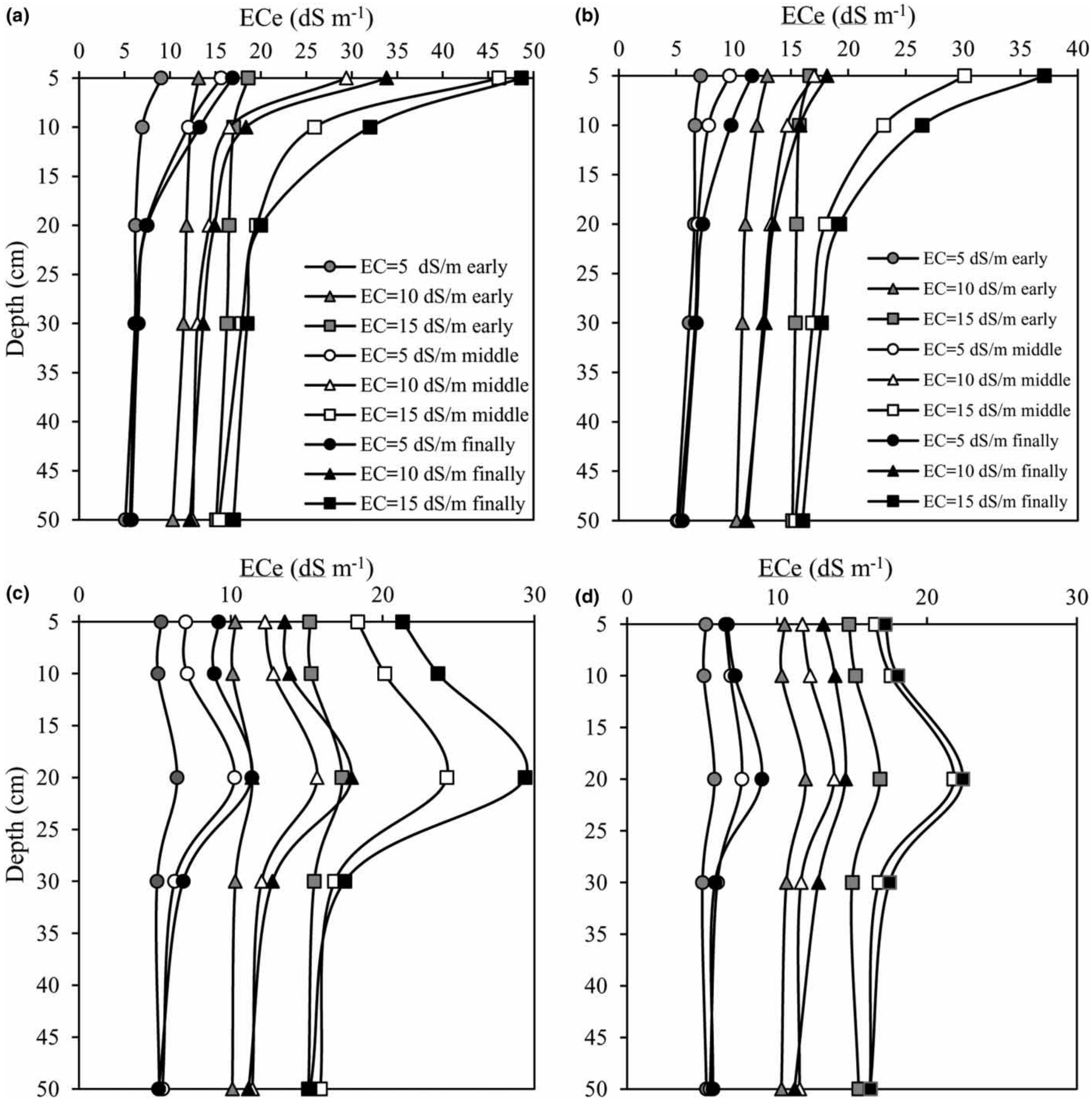

Figure 6 | Variation of salt content profile above the saline water table at different times from the onset of the experiment (early: 5 days, middle: 45 days, and end: 90 days) in bare (a) and mulch-covered (b) loamy soil, bare (c) and mulch-covered (d) sand.

(Figure 6(c) and 6(d)), salt accumulation in the soil profile was less than that of the loamy soil in all treatments. In contrast, the shapes of the measured salt content profiles of the sandy soil looked different. The findings also showed that in both bare and mulch-covered sandy soil profiles, salt content increased with depth (from the surface) and reached a maximum at approximately 20 cm depth. Then, salt accumulation rapidly dropped and remained almost similar to the groundwater salinity below the 30 cm depth. Likewise, in the 5 cm depth for S1, S2, and S3, salt concentrations were measured as 9.2, 13.56, and 21.32 dS m^{-1}, respectively (Figure 6(c)). As the results revealed, the maximum salinity in the soil profile occurred at the depth of 20 cm, indicating the position of vaporization plane within the soil column.

Daily and cumulative evaporation in the presence of shallow groundwater

The daily evaporation rates from June 22 to September 22, 2018 in the three salinity levels of shallow groundwater (i.e., S1, S2, and S3) for loamy and sandy soils, with and without straw mulch, are shown in Figure 7. As seen, the pattern of daily evaporation rates in both soils was almost the same in all treatments (primarily induced by the atmospheric forcing). The results of the analysis of variance (ANOVA) of the effect of groundwater salinity, soil texture, and mulch treatments on the average daily evaporation are illustrated in Table 3. The finding revealed that the single effect of groundwater salinity, soil type, and mulch on evaporation was statistically significant ($p < 1\%$). However, the interactions between soil texture and groundwater salinity, and mulch cover and groundwater salinity on evaporation were not significant. Interestingly, the interaction between soil texture and mulch on evaporation was notable ($p < 1\%$). In addition, the results of mean comparison indicated that the evaporation rate in loamy soil was 17% higher than that of sandy soil (Figure 8(a)), and straw mulch cover reduced the evaporation rate by 26% compared to that in the bare soil (Figure 8(b)). Among different salinity levels of groundwater, S1 treatment had more soil evaporation than S2 and S3 (Figure 8(c)). Besides, the highest amount of evaporation was from bare soil with the groundwater salinity of $5\,\mathrm{dS\,m^{-1}}$ while the lowest rate of evaporation was from the mulch-covered soil with salinity of $15\,\mathrm{dS\,m^{-1}}$. Also, in S1 treatment, the mulch cover during the experiment period caused a 20% reduction in the evaporation rate as compared to that in the bare soil (Figure 8(d)).

By measuring the water level in Mariotte bottles and calculating the water balance in the soil column, the cumulative evaporation for loamy soil in the three salinities of S1, S2, and S3 with and without mulch cover was obtained as 246, 161, 106 and 338, 217, 150 mm, respectively. These results indicate that with increasing salinity of groundwater and its potential effect on water vapor pressure, the cumulative evaporation decreases (Bittelli et al. 2008). Also, in accordance with Equation (5), the maximum amount of evaporation in sandy soil was found to be $12.8\,\mathrm{mm\,day^{-1}}$ while it was $22.4\,\mathrm{mm\,day^{-1}}$ in loamy soil.

Figure 9 shows the relation between the cumulative evaporation (ΣEs) and the total potential evaporation (ΣPE). As seen, there was a linear relationship between the cumulative evaporation and the potential evaporation in all treatments. In bare soils, the ratio of the cumulative evaporation to the total potential evaporation ($\Sigma Es/\Sigma PE$) was much higher than that of the mulch-covered soil. For salinity of S1, the ratio for loamy and sandy soils without coverage was about 0.78 and 0.48, respectively, while in the presence of mulch it was found to be 0.54 and 0.43. The values of water losses for different treatments in both soils relative to the potential evaporation are shown in Table 4 to highlight the relative contribution of each treatment in the soil evaporation. As expected, the results revealed that in all the groundwater salinity treatments and both soil textures, the cumulative evaporations in bare soil were more than those of the mulch-covered soils. Moreover, loamy and sandy bare soils in the S1 treatment had the highest ratio of cumulative evaporation to the total potential evaporation with 55.9 and 43%, respectively. However, both loamy and sandy mulch-covered soils in the S3 treatment had the lowest ratio with 24 and 16%, respectively. The results of Table 4 indicated that the cumulative evaporation decreased with increasing groundwater salinity, which, in turn, can be attributed to the effect of salts on soil hydraulic properties and vapor pressure. Some other studies also revealed that salt crystallization on the soil surface (efflorescence) enhances with increasing groundwater salinity. The salt crystals create complex, branching structures which can significantly increase the surface area available for evaporation. In addition, the heat released during the salt crystallization process provides some of the heat required for evaporation (Shokri-Kuehni et al. 2017). Furthermore, the vertical variations of salt content in the soils' profiles for all treatments on the 5th, 45th, and 90th day of the experiment show salt accumulation in soil profile with increasing groundwater salinity, especially in the upper layers of soil near the surface (Figure 6). The accumulation of salt between soil particles changes soil pore size distribution, soil water retention capacity, hydraulic conductivity, and dispersivity (Lebron et al. 2002; Gonçalves et al. 2010; Zhang et al. 2014). Consequently, by changing the soil properties, the amount of evaporation from the soil surface will change over time. Overall, the results highlighted that soil

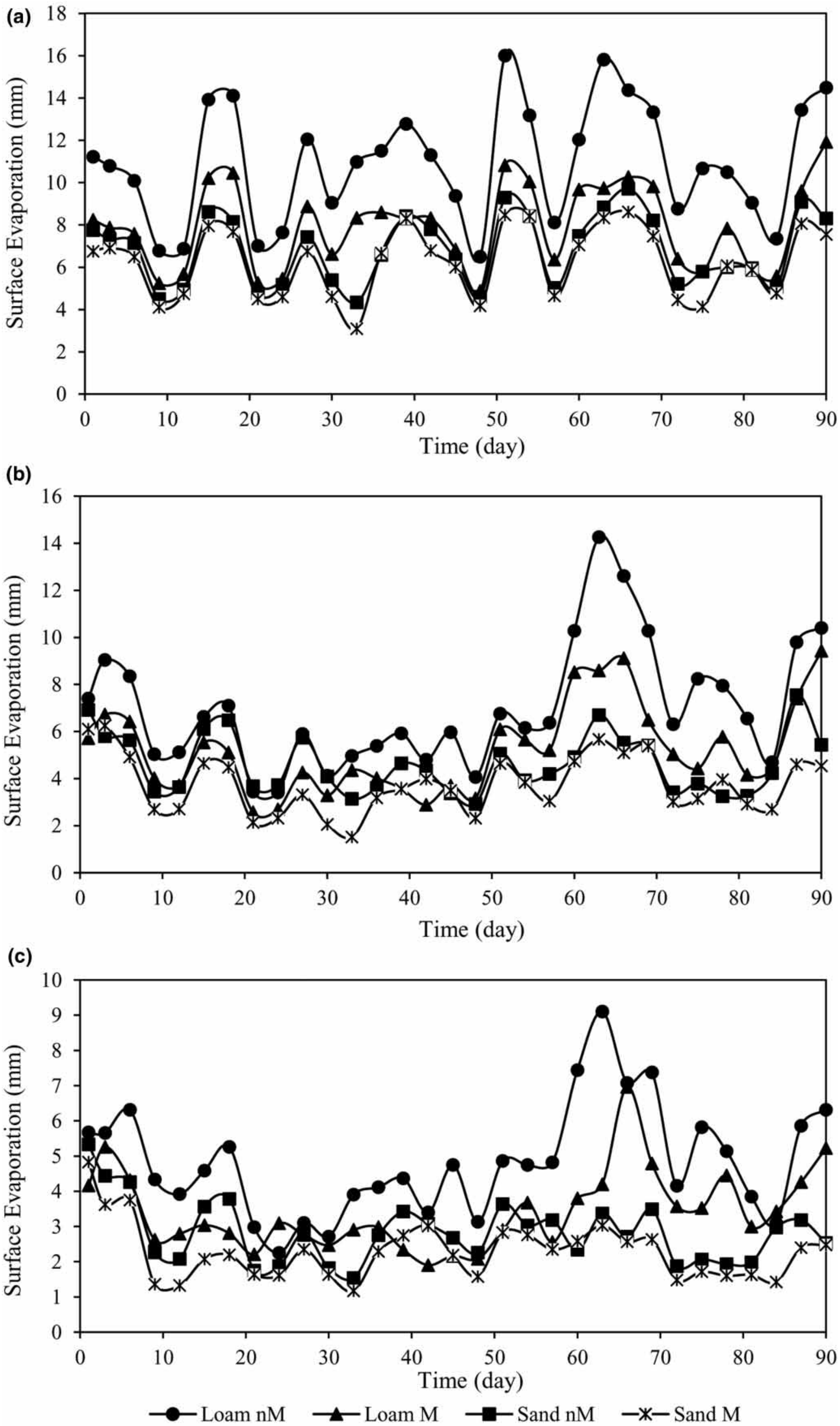

Figure 7 | The daily rate of soil evaporation in two soil types with different saline groundwater, S1 (a), S2 (b), and S3 (c).

Table 3 | ANOVA test for the interaction effect of soil type, saline water, and mulch on soil evaporation

Source	SSE	df	MSE	F value	Sig.
Saline water	56.310	2	28.15	43.13	0.0001
Mulch	11.745	1	11.74	17.98	0.0002
Soil	31.42	1	31.42	48.11	0.001
Soil*Mulch	7.03	1	7.03	10.77	0.0001
Soil*Salinity	3.947	2	1.97	3.02	0.068
Salinity*Mulch	2.64	2	1.32	2.03	0.153
Error	15.67	24	0.65		
C.V%	4.23				

texture and groundwater salinity had great impacts on the evaporative losses observed.

DISCUSSION

The effect of mulch on soil moisture in the presence of shallow water table

Effective soil treatment practices are deemed to improve soil heat and moisture conditions (Mohler & Callaway 1995;

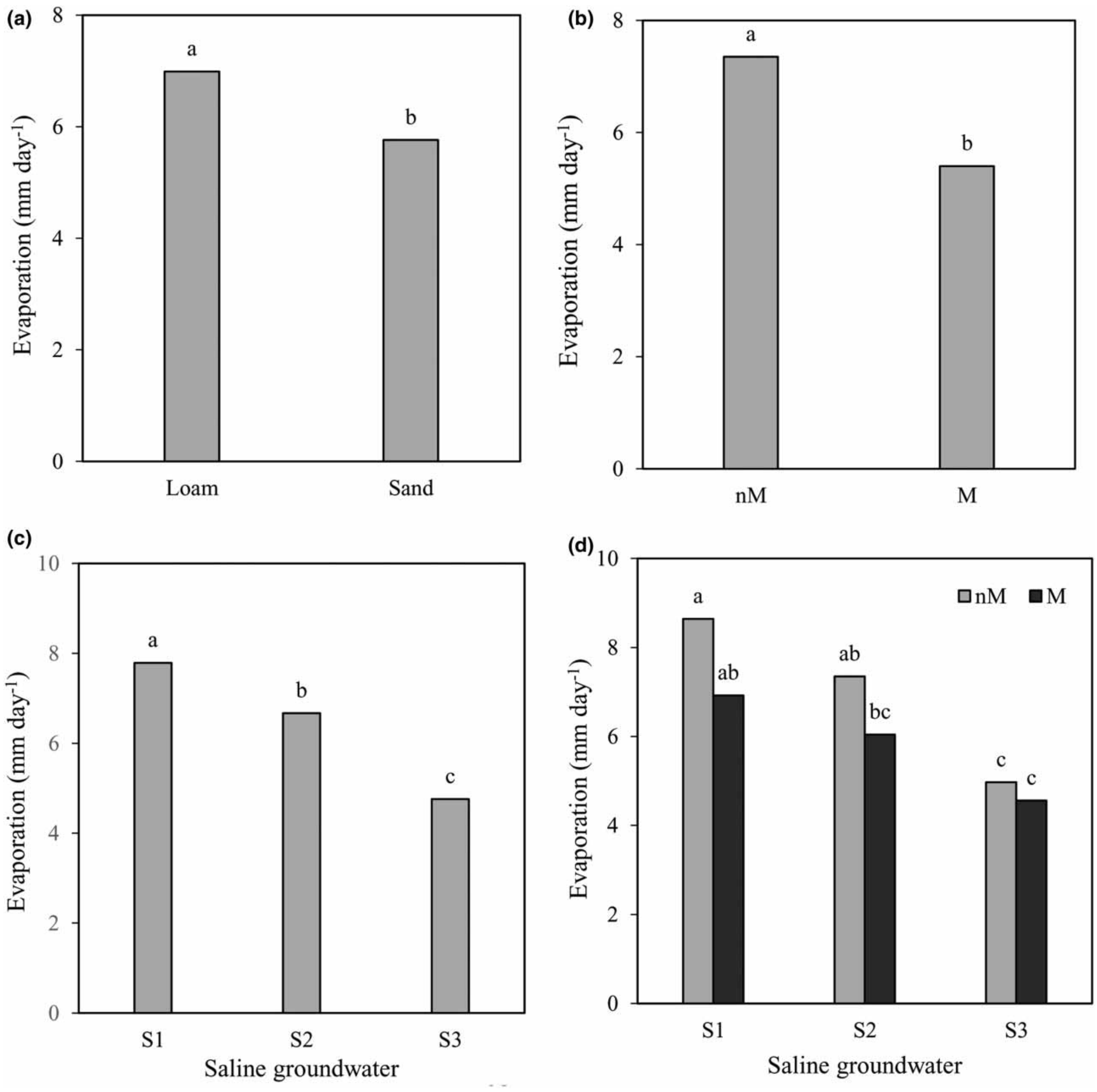

Figure 8 | Comparison of mean soil type (a), mulch (b), saline groundwater (c), and the interaction of saline groundwater and mulch cover (d) on soil evaporation.

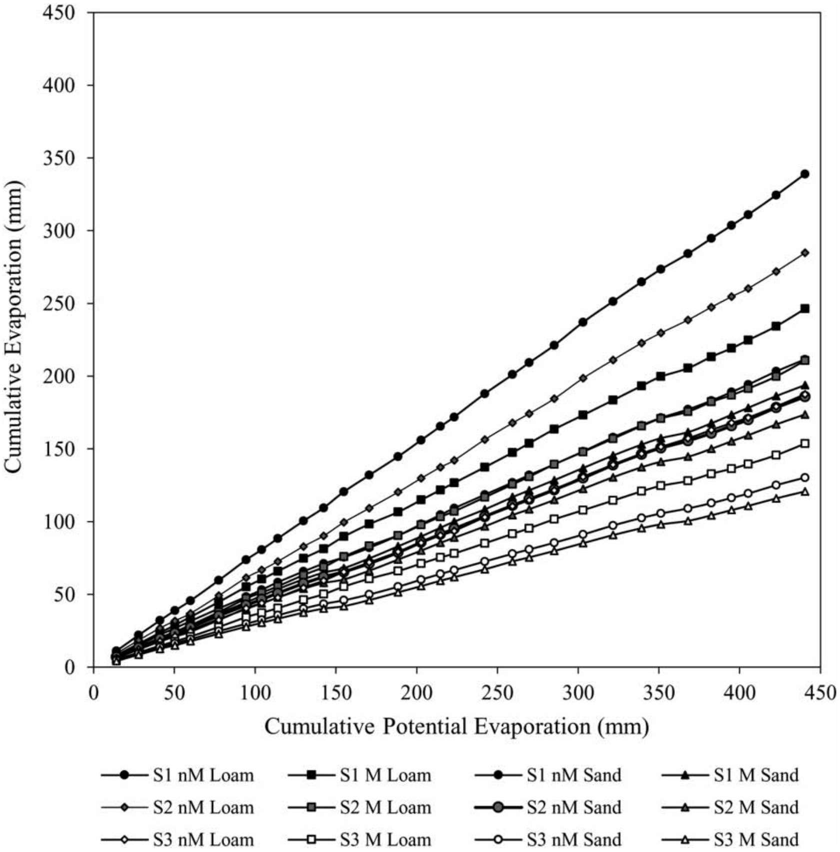

Figure 9 | Comparison between the cumulative potential evaporation and the cumulative actual evaporation for different treatments: M and nM stand for mulch and no-mulch; S1, S2, and S3 are salinity levels of groundwater with ECs of 5, 10, and 15 dS m^{-1}.

Table 4 | Comparison of relative profile water loss through soil evaporation from loamy and sandy soil under different mulch and water salinity treatments

		Loamy		Sandy	
	Mulch	**Σ Es (mm)**	**% loss**	**Σ Es (mm)**	**% loss**
S1	With	246.31	55.9	193.89	43
	Without	338.98	77	211.60	48
S2	With	161.91	36.7	116.73	26.5
	Without	217.14	49	143.82	32.6
S3	With	106.14	24	70.71	16
	Without	150.01	35	87.91	19.9

Kouwenhoven *et al.* 2002) as effective parameters playing important roles in the product development and water management (Zhao *et al.* 2014a, 2014b). The effect of mulch cover on the moisture content of soil mainly depends on rainfall, climatic conditions, and shallow groundwater, as it was in the present study. Indeed, by controlling the evaporation rate, mulch has desirable effects on the moisture regime of the soil. As expected, the moisture content in soil treatments with mulch for both sandy and loamy soils was found to be higher than that in the bare (uncovered) soil during the experiment (Figure 3). The moisture retention in loamy soil was, in turn, much higher than that of the sandy soil. This could be attributed to the higher clay content in loamy soils than that of the sandy soils. Loamy soil with smaller particles (more silt and clay content) has a larger surface area and much smaller pore size distribution which allows it to hold more moisture. Due to proximity to the water table, moisture variations in the lower layers (i.e., 20 cm depth and lower) were slight in both treatments until the end of the experiment period. In addition, there was no significant change in soil moisture content as it approximately remained at the same extent as it was at the beginning of the experiment. Similar to our findings, Kader *et al.* (2017) observed that the use of straw mulch resulted in significant retention of moisture near the surface of soil, where water availability played a vital role in crop productivity. Ji & Unger (2001) also showed that straw mulching could increase water storage in the vadose zone, leading to improvement in water productivity by limiting moisture exchanges with the atmosphere.

The effect of mulch on soil thermal regimes

Thermal and radiative properties of mulch cover are deemed to affect soil temperature regimes significantly (Lamont 2005). The results of this study showed that in loamy and sandy soils the mulch layer reduced the temperature in the surface layers of the soil as compared with that in the bare soil. In addition, the temperature fluctuations at the 5 cm depth of the covered soil surface in loamy and sandy soils decreased by 37 and 24%, respectively, relative to those in the similar uncovered samples.

Also, it was found that by increasing the depth, the effect of mulch on the soil temperature became negligible. In the lower layers (20 cm depth), slight differences were, however, observed between mulch and no-mulch treatments in both soils. This, in turn, highlights the thermal damping with the depth and the effect of water table that ultimately reduced the temperature fluctuations, influencing soil-water regulation and energy balance in the soil profile. In effect, effectively limiting the interception of radiative energy on the soil surface, mulch cover affected the exchange of latent and sensible heat fluxes between the surface and the air flow. It also reduced the heat dissipation from the soil at night, which, in turn, decreased the temperature fluctuations in the soil profiles and provided a desirable environment for seed germination (Chen *et al.* 2007; Mahdavi *et al.* 2017).

Salt accumulation in soil profile

In arid lands with saline groundwater, salinity control in the root zone is considered as one of the most important factors in seed emergence and stand (Meiri & Plaut 1985; Dong *et al.* 2010). The results of this study clearly showed that soil evaporation in the presence of shallow saline water table caused salt accumulation near the soil surface. In sandy soil, however, salt accumulation occurred in the lower layers of the soil (almost 20 cm depth). In accordance with Equation (2), the maximum height of capillary rise (h_{max}) in sandy soil was obtained at 24.4 cm, indicating the position of vaporization plane, where moisture phase change causes high salinity levels relative to the other layers. Below this depth, the salt content was almost constant, close to the groundwater salinity. On the other hand, the maximum height of capillary rise in loamy soil was 63 cm, which was greater than the length of MLs in the experiment; hence, the highest salt accumulation occurred in the soil surface. Many studies have already shown that salt distribution patterns and accumulation in soil profile depend significantly on the salinity of groundwater (Rose *et al.* 2005; Gowing *et al.* 2006; Liu *et al.* 2019). By comparing sandy soil and loamy soil, it was shown that salinity in the vadose zone had a direct relation with the capillary rise in this study. As such, salt accumulation depends on the salinity level and evaporation rate. When the groundwater depth is less than the capillary rise, salt accumulation appears on the surface of the soil (as in the loamy soil), while in sandy soil, h_{max} is less than the groundwater depth yielding salt accumulation below the soil surface. Li *et al.* (2013) maintained that when the water table depth is greater than h_{max}, water vaporization and thus salt accumulation occur beneath the soil surface. Similarly, Rose *et al.* (2005) and Hassan & Ghaibeh (1977) reported that during the evaporation process, the maximum salt accumulation occurs in the upper layers of the vadose zone. Our results showed that salt content in the upper layers in the soil with mulch cover was significantly lower than that of the bare soil. Previous studies have similarly acknowledged that straw mulch is an effective technique for controlling salinity in agricultural fields (Deng *et al.* 2006; Bezborodov *et al.* 2010; Pang *et al.* 2010; Zhao *et al.* 2014a, 2014b).

Evaporation from shallow groundwater

In the early days of the experiment, due to the high moisture content of the samples, the evaporation rate was high and the role of water table on the evaporation from the soil surface was negligible. As such, there was sufficient moisture for evaporation in the soil profile. With the reduction of soil moisture, the suction gradient and thus the capillary rise from the water table to the soil surface was enhanced. Therefore, climatic conditions such as air temperature, relative humidity, and radiation determined the evaporation rate. As shown in Figure 7, the evaporation pattern in the three salinity treatments of S1, S2, and S3 was almost the same following the atmospheric forcing. Also, with increasing the salinity of groundwater, the evaporation rate reduced in all treatments. Nachshon *et al.* (2011) indicated that one of the main mechanisms affecting evaporation under saline conditions is the accumulation of salt crystals in the soil matrix reducing the permeability of the soil profile. By comparing the evaporation rates in sandy and loamy soils without mulch (Figure 7), it can be seen that sandy soils are more rapidly dried, and thus the amount of evaporation is less relative to loamy soils. It was also observed that the evaporation from the coarse-textured soil (sand) was more sensitive to the water content and water table level changes in comparison with that in the fine-textured soil (loam). Moreover, several other studies have reported that the upward flow due to the capillary rise in the fine-textured soils continues for longer periods before evaporating pores completely dry (Nassar & Horton 1999). In effect, as surface pores dry out, water loss occurs with diffusion processes within the soil medium, as the vapor diffusion requires more energy than the capillary rise (Noy-Meir 1973; Van de Grend & Owe 1994). Moreover, by increasing the distance from the water table, the amount of water content then decreases gradually and the upper limit in capillary rise becomes insignificant (especially in sandy soil where groundwater does not reach the soil surface). As such, soil is divided into two wet and dry regions below and above the vaporization plane, respectively. The distance of water table to the boundary between dry and wet regions shows the maximum height of capillary rise obtained as 24.4 cm for the sandy soil and 63 cm for the loamy soil.

In the final days of the experiment, the amount of evaporation in the bare sandy soil was reduced in all saline groundwater treatments. Indeed, an effective factor in the reduction of evaporation in the sandy soil (in addition to the decrease in air temperature and the increase in relative humidity in September) was the increase in dry region thickness near the surface of the soil column that imposed higher resistance to vapor flow from the vaporization plane to the soil surface (Yamanaka & Yonetani 1999; Zhang *et al.* 2015; Lehmann *et al.* 2018).

CONCLUSIONS

This study investigated the effect of shallow groundwater with different salinity levels on the surface evaporation, soil salinity, water content, and temperature distribution in the soil profile. It also addressed the impact of mulch cover on these parameters. Regardless of the soil type, it was found that mulching practice can effectively reduce soil temperature fluctuations and increase the water content in the surface layer (0–5 cm). The results also showed that with increasing the salinity of groundwater, due to the increase in salt concentration, the evaporation rate in all the investigated treatments decreased. Moreover, straw mulch cover was found to reduce the evaporation rate by 26% compared to that in the bare soil. Also, the findings highlight the importance of groundwater salinity in changing the soil quality as well as the positive impacts of mulch cover on evaporation suppression and also the improvement of water storage in arid and semi-arid regions. It is recommended that other researchers conduct further studies, especially on the contribution of shallow groundwater with different salinity levels to the water requirement of plants in the presence of mulch coverage. Furthermore, it is suggested that mulch covering with different thicknesses be used in other studies to couple the transfer of water and heat in the soil profile.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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