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The differences of water balance components of *Caragana korshinkii* grown in homogeneous and layered soils in the desert–Loess Plateau transition zone

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ABSTRACT

Soil texture greatly influences soil water movement, thus may affect the water balance and vegetation growth in the desert–Loess Plateau transition zone. This study is to determine if the water balance differs in homogeneous and layered soils with *Caragana korshinkii* stands in semiarid region. Soil water measurements up to 500-cm depth were taken in 2006 and 2007 on homogeneous sandy soil, homogeneous silt loam soil, and layered soil with sand overlying silt loam. HYDRUS-1D was used to simulate the soil water balance. The results indicated the annual water balance components were greatly affected by soil layering. The ratio of average actual evapotranspiration (ET_a) to precipitation (P) during the two years in the layered soil was slightly lower than that in homogeneous soils. The ratios of annual actual transpiration (T_r) to evapotranspiration were 50.9%, 41.2% and 30.6% in layered soil, homogeneous sandy soil, and homogeneous silt loam soil, respectively. *C. korshinkii* grown in layered soil had deeper soil water recharge and higher T_r/ET_a ratio, thus had more available water for transpiration than that in homogeneous soils. This study suggested the layered soil with sand overlying silt loam is more favorable to *C. korshinkii* growth in terms of water use than homogeneous soils in the desert–Loess Plateau transition zone.

1. Introduction

Water is a key limiting factor for plant growth in arid and semiarid regions (Duniway et al., 2010; Kemp et al., 1997; Sala and Lauenroth, 1982; Smith et al., 1997). Thus, any control on soil water could affect plant community composition and its function (Loik et al., 2004). Soil water movement was affected by soil physical characteristics, such as particle size distribution, bulk density and hydraulic conductivity (Jury and Horton, 2004; Zhao et al., 2011). These properties influence not only the amount of rainfall entering soil through infiltration, but also the available water storage of the soil after infiltration. Vertical heterogeneity such as layers in soil also affects water flow in soil. A number of laboratory and simulation studies on evaporation and water redistribution in layered soils have been conducted over the years (Huang et al., 2011; Willis, 1960; Wilson, 1990; Wilson et al., 1997). However, little is known on the interaction between the layered soil and vegetation and consequently on water balance in the layer soils in arid and semiarid regions. The poor understanding led to insufficient understanding of regional water balance.

In the Loess Plateau of China, water erosion is very serious, and the soils in the region are among the most erodible in the world. The average annual soil loss resulting from both wind and water erosion is as much as 15 000 t km^{-2} (Yang et al., 2010). Approximately 18.8% of this area has been desertified (Chang et al., 2005). For example, the desert has advanced 3–10 km from the northwest to the southeast during the past 20 years (Tang et al., 1993). As a result, soil textures are modified by the serious desertification. Silt loam soil (one of the main soil types on the Loess Plateau), sandy soil and layered soil (sand overlying silt loam soil) are distributed in a fragmented mosaic pattern, in the transition zone from the fertile loess hills to the desert on the Northern Loess Plateau.

In order to reduce soil erosion, control land desertification, and improve environmental quality on the Loess Plateau, a series of soil conservation practices are being implemented to increase vegetative recovery. *Caragana korshinkii* Kom, a drought-tolerant mesquite

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that can grow with precipitation from 100 mm to 550 mm, is widely planted in the Loess Plateau. *C. korshinkii* is known to conserve water and soil, and to control land desertification (Yang, 2001; Yang et al., 2006). However, little is known about the difference in water consumption by *C. korshinkii* grown in homogeneous soil (silt loam or sandy soil) and layered soils (sand overlying silt loam) in this region. Therefore, it is important to understand the water balance of *C. korshinkii* growing in different soil profile in order to better manage and expand the planted areas and thus to improve vegetation restoration in the transition zone.

The objectives of this study were: (1) to simulate soil water dynamics in homogeneous and layered soils under *C. korshinkii* stands using HYDRUS-1D; (2) to determine the actual transpiration characteristics in different soils; and (3) to compare the water balance components in homogeneous and layered soils in the transition zone on the Loess Plateau. HYDRUS-1D model (Simunek et al., 2008) was used to simulate water flow of the unsaturated zone in layered soils. This model has been used for a number of hydrological studies under different climatic and vegetation conditions (Gutierrez-Jurado et al., 2006; Hernandez, 2001; Meiwirth and Mermoud, 2004; Sommer et al., 2003).

2. Materials and methods

2.1. Site description

This study was conducted during 2006–2007 at the Liudaogou watershed in Shenmu County (110°22′ E, 38°48′ N; mean altitude 1163 m), Shaanxi province, China. The area of Liudaogou watershed is around 6.89 km^2, located in the transition zone from desert to the fertile loess hills, in the semiarid region of the Northern Loess Plateau. The mean annual temperature is 8.4 °C, and the frost-free period is 135 days. The long-term average annual precipitation is 430 mm, 77% of which falls from June to September. The growing season precipitation (April–October) was 367.8 mm in 2006 (which was 16% lower than the long-term average) and 435.7 mm in 2007 (close to average) (Fig. 1). Drainage is negligible in the study area, and the observed maximum infiltration depth of rainfall in sand is about 3 m (Li, 2001). The groundwater level is about 30–100 m below the soil surface, therefore, groundwater has negligible influence on the soil water balance (Li, 2001).

2.2. Experimental plots

Because the Liudaogou watershed is located in the transition zone from desert to the fertile loess hills, the soil texture profile is different from location to location in the watershed. According to

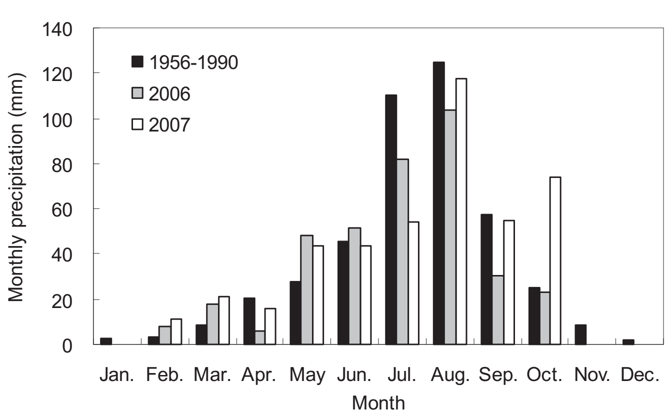

Fig. 1. Monthly precipitation of the study area in 2006 and 2007 and the long-term normal (1956–2007).

soil survey done by Tang et al. (1993), the main soil texture profiles include homogeneous sand, homogeneous silt loam, and partly sand overlying silt loam. Experimental plots were selected based on soil profile information and vegetative information. When the experimental plots were primarily selected, soil profile (to a depth of 500 cm) was dug in each soil type. Soil samples were collected at 0.1 m increments between 0 and 1 m soil depth, and at 0.2 m increments below 1 m depth, to determine soil physical properties. Soil mechanical composition was measured using a laser particle-size analyzer (Master Sizer 2000, Malvern, UK). Bulk density with soil volume measured on oven-dried natural clods. Selected soil physical properties of these soils are shown in Table 1. Two plots of 4×15 m^2 were established on slopes for *C. korshinkii* grown in each of the three soil profiles. The slopes of plot were 14%, 13% and 7% for the homogeneous sand plots, homogeneous silt loam plots, and layered soil plots, respectively. All plots had a southeastern aspect and their distance apart was within 1.5 km. Each plot was bordered with iron sheeting that was 15 m in length, 4 m in width, and 0.2 m in height. At the lower end of the plot, the sheeting funneled runoff water into two barrels (Fig. 2).

2.3. Plant characteristics measurements

The *C. korshinkii* is a deciduous mesquite shrub, with growing season from the beginning of April until late October. The *C. korshinkii* grown in these plots had been planted in 1984. Shrub height in each plot was measured with a tape measure, 6–8 samples (selected according to average height, limb and crown width) outside the plot were harvested to estimate aboveground biomass (kg ha^{-1}). Plant density was estimated by the number of shrub in the plot. Plant cover was calculated by shrub crown width divided plot area. LAI was measured by LAI-2000 plant canopy analyzer (LI-COR Inc, Lincoln, Nebraska, USA). Characteristics of the plants on the three soils are shown in Table 2. There were a few grasses, mainly *Stipa breviflora* Griseb, growing under the shrubs; otherwise the ground surface was bare. Generally, C. *korshinkii* grown in homogeneous sand and layered soil profiles had larger biomass than homogeneous silt loam profile (Table 2).

2.4. Soil water measurements

In each plot, three 530 cm long neutron access tubes were installed to measure soil water, at 10 cm increments between 20 and 100 cm soil depth, and at 20 cm increments below 100 cm depth using a CNC-503B(DR) neutron probe (Beijing ST Ltd., China). Neutron probe measurements were calibrated by the gravimetric method and the neutron count ratio was subsequently converted to volumetric water content. Soil water content of 0–10 cm and 10–20 cm soil layers were measured by the gravimetric method. Measurements of volumetric water content were made at approximately two week intervals during the period of May–October, 2006, and April–September, 2007.

2.5. Fine roots measurements

The vertical fine root distributions of *C. korshinkii* in the three soil profiles were investigated using the trench-profile method (Böhm, 1979). One soil pit ($1 \times 2.5 \times 3$ m) was dug to expose the vertical section in each plot under the *C. korshinkii* canopy. Roots were selected from a 40×40 cm^2 grid at 10 cm increments in the soil pit, and were stored in polythene plastic bags for later surface area measurement. A total of 64 fine root samples were collected from the homogeneous sand profile, 108 samples from the silt loam profile, and 80 samples from sand overlying silt loam profile. Root surface area and diameter were measured using a WinRHIZO that

Table 1
Soil properties of sample plots.

Soil profile	Soil type	Soil depth (cm)	Soil texture			Soil bulk density (g cm^{-3})
			Sand (0.02–2 mm) (%)	Silt (0.002–0.02 mm) (%)	Clay (<0.002 mm) (%)	
Homogeneous sand	Sand	0–500	80.8	18.2	1.0	1.51
Homogeneous silt loam	Silt loam	0–500	44.7	53.2	2.1	1.38
Sand overlying silt loam	Sand Silt loam	0–192	88.5	9.8	1.7	1.53
		192–500	47.2	50.3	2.5	1.35

Fig. 2. The method of runoff measurements.

included a high quality scanner and root image analysis software (Regent Instruments Inc. 2001, Canada). Fine root area density (surface area of roots per unit soil volume, FRAD) was determined for every soil grid sample. Vertical distributions of fine roots for the three soils are shown in Fig. 3.

2.6. Meteorological data

Meteorological data were collected from a meteorological station about 500 m away from the experimental site. Air temperature and relative humidity were measured with a psychrometer (Vaisala HMP45A), and the net short and long wave radiations were measured with a Kipp & Zonen CNR-1 radiometer. The wind speed and direction at 2.0 m above the ground surface were measured with an anemometer and anemoscope (Yang, 2001). The amount of precipitation was measured at 1 m height above the ground surface with a rain-gauge. All meteorological measurements were recorded automatically with data logger system (Campbell CR200).

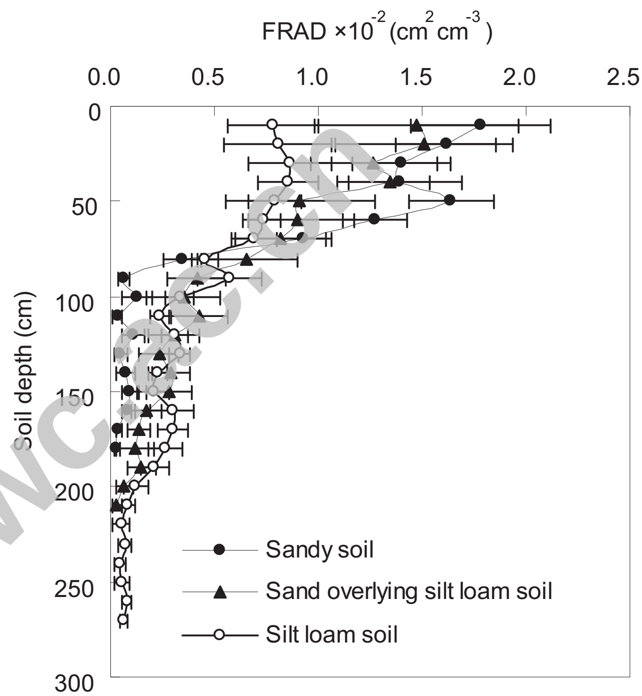

Fig. 3. Mean distribution of fine root area density (FRAD) with depth in the sandy soil, sand overlying silt loam and silt loam soils. Error bars represent the standard error.

2.7. Simulation model

The computer program HYDRUS-1D version 4.0 was used to simulate the movement of water in the shrubland. The program is based on the Richards equation for variably saturated water flow. The Richards equation for one-dimensional flow can be written as:

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

where θ is volumetric soil water content [cm^3 cm^{-3}]; t is time [d]; h is soil water pressure head [cm]; z is gravitational head as well as vertical coordinate [cm] taken positive upward; β is the angle between the flow direction and the vertical axis; K is the unsaturated hydraulic conductivity [cm d^{-1}]; and S is actual roots uptake [cm^3 cm^{-3} d^{-1}].

Table 2
Plant characteristics in three soils.

Soil profile	Tree height (cm)	Aboveground biomass (kg ha^{-1})	Maximum LAI	Plant cover (%)	Plant density (tree ha^{-1})
Homogeneous sand	131	2208.7	1.4	40	3500
Homogeneous silt loam	146	2022.2	1.3	35	3275
Sand overlying silt loam	135	2588.3	1.6	43	3750

van Genuchten equation (van Genuchten, 1980) was used to describe the water retention curve and conductivity curve:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{\left[1+|\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{2}$$

$$K(h) = \begin{cases} K_s S_e^{1/2}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 & h < 0 \\ K_s & h \geq 0 \end{cases} \tag{3}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4}$$

where θ_s is saturated volumetric soil water [cm^3 cm^{-3}]; θ_r is residual volumetric soil water [cm^3 cm^{-3}]; S_e is the relative water content [unitless]; α, n and m are the van Genuchten equation parameters, and $m = 1 - 1/n$; K_s is the saturated hydraulic conductivity [cm d^{-1}].

The actual root uptake rate is limited by the potential transpiration rate (T_p), root distribution function, $b(x)$, and by the rate at which soil can supply water to roots. The HYDRUS-1D incorporates these mechanisms into a single relationship as described by Feddes et al. (1974):

$$S(h) = a(h)b(x)T_p \tag{5}$$

where $a(h)$ is the root water uptake stress response function.

Xia and Shao (2008) found that the discrete function based on two pressure heads was effective for *C. korshinkii* as follows:

$$a(h) = \begin{cases} 1, & h \geq h_1 \\ \frac{h_2 - h}{h_2 - h_1}, & h_2 < h < h_1 \\ 0, & h \leq h_2 \end{cases} \tag{6}$$

where the two pressure heads (h_1 and h_2) were determined based on previous studies reported in the literature. For *C. korshinkii*, the reported value was 200 and 2000 kPa for h_1 and h_2, respectively (Xia, 2008).

In HYDRUS-1D, the $b(x)$ is defined as:

$$b(x) = \frac{b\prime(x)}{\int_0^{LR} b\prime(x)\mathrm{d}z} T_p \tag{7}$$

where *LR* is the maximum root depth, $b'(x)$ is measured root distribution (FRAD) in each soil layer. In this study, the maximum root depth was assumed to be constant and equal to 180 cm in homogeneous sandy soil, 275 cm in homogeneous silt loam soil, and 220 cm in layered soil for *C. korshinkii* (Fig. 3).

2.8. Input parameters in HYDRUS-1D

The lower boundary condition was set to free drainage. At the upper boundary (soil surface), input meteorological variables included the daily potential transpiration (T_p), the potential evaporation (E_p) and the effective precipitation (P_e). Potential evapotranspiration (ET_0) were calculated using the Penman–Monteith equation (Monteith, 1965), and ET_0 were divided into T_p and E_p by the measured leaf area index (LAI) using the following equations:

$$T_p = ET_0\left(1 - e^{-\mu LAI}\right) \tag{8}$$

$$E_p = ET_0 e^{-\mu LAI} \tag{9}$$

where μ is an empirical parameter varying from 0.41 to 0.72 for shrub (White et al., 2000). In this study, an average value of 0.55 was used for estimating T_p and E_p from LAI for *C. korshinkii* vegetation (White et al., 2000).

In HYDRUS-1D, canopy interception loss was computed using the following equation:

$$I = a \cdot LAI\left(1 - \frac{1}{1 + \frac{bP}{a \cdot LAI}}\right) \tag{10}$$

$$b = 1 - e^{-\mu LAI} \tag{11}$$

where I is interception; P is precipitation; and a is an empirical parameter equal to 2.1, which was determined by fitting the measured canopy interception losses in three soils.

Canopy interception of *C. korshinkii* was measured on the three soils during the growing season in 2006 and 2007. Ten iron sheeting gauges, with a diameter of 20 cm, height of 25 cm, were placed randomly in each *C. korshinkii* stand. Throughfall was measured immediately after every rain event using a rainfall measuring cylinder. The net precipitation was confirmed from canopy interception loss, and stemflow was neglected for *C. korshinkii*.

The soil profile of 0–500 cm is discretized into 29 nodal points for water balance simulation, at 10 cm increments between 0 and 100 cm soil depth, and at 20 cm increments from 100 cm to 500 cm depth.

Soil water characteristic curve (SWCC) for each soil type was measured. Two intact soil cores were collected from each soil type, whereby the water content of each soil sample was measured at increasing soil suctions of 0.01, 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.4, 0.6, 0.8 and 1 MPa using the centrifuge method (Townend et al., 2001). The RETC software (van Genuchten et al., 1991) was used to fit the SWCCs.

The observed soil water content data in 2006 was employed to calibrate K_s values for the three soils. During the model calibration, the K_s values were optimized to reduce the deviations between the simulated and measured soil water contents using the procedure of inverse solution (Table 3). The calibrated K_s values for all soils were then used to simulate water balance in 2007. The measured soil water content profiles on May 15, 2006 and April 8, 2007 were used as initial values for calibration and validation, respectively.

2.9. Data analysis

The simulated soil water contents in the three soils were compared with the measured values. The goodness of the fit between measured and simulated soil water content was statistically

Table 3
Soil hydraulic parameters used for water balance simulation.

Parameters	Homogeneous sand	Homogeneous silt loam	Sand overlying silt loam	
	0–500 cm	0–500 cm	0–192 cm	192–500 cm
Measured				
θ_r (cm^3 cm^{-3})	0.026	0.045	0.018	0.041
θ_s (cm^3 cm^{-3})	0.403	0.421	0.385	0.426
α (cm^{-1})	0.046	0.036	0.038	0.013
n	1.906	1.560	2.582	1.489
Calibrated				
K_s (cm d^{-1})	265	48	406	72

estimated by model efficiency (ME) and the root mean square error (RMSE):

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{N} (M_i - E_i)^2}{\sum_{i=1}^{N} (M_i - \overline{M})^2} \tag{12}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N} (E_i - M_i)^2\right]^{1/2} \tag{13}$$

where M_i is measured soil water values, E_i is simulated soil water values; $\overline{M}$is mean of observed soil water values; N is the number of observations.

A one-way ANOVA was performed to test the difference of water balance components for the three soils ($P = 0.05$). All these data were analyzed using SPSS 16.0 for Windows (Chicago, SPSS Inc.).

3. Results

3.1. Soil water dynamics

Soil water contents in the 0–500 cm of the soil profile, during the *C. korshinkii* growing seasons of 2006 and 2007, in the homogeneous and layered soils are shown in Figs. 4 and 5, respectively. Great change in the water content in the soil profile during the two growing seasons mainly occurred at the depth of 0–80 cm for the homogeneous sandy soil, 0–100 cm and 180–260 cm for the layered soil, and 0–60 cm for the homogeneous silt loam soil. Rainfall recharge to soil profile was the deepest (about 240 cm) in layered soils, and followed by that in homogeneous sandy soil (about 120 cm) (Fig. 4). The depth of rainfall recharge was within 100 cm for homogeneous silt loam soil. Soil moisture content was close to the wilting point within 0–280 cm in sandy soil and 0–260 cm for layered soil during the intraseasonal drought period, and both soils at greater depth were relatively wetter. On the contrary available water in 360–500 cm in the silt loam soil was almost zero throughout the growing season, and soil water in upper soil layer was relatively wet.

3.2. Soil water simulation

The measured and simulated soil water contents in the three profiles of homogeneous and layered soils are shown in Figs. 6 and 7 for 2006 and 2007, respectively. The simulated soil water contents agreed well with the measured values for the homogeneous soils. The soil water content in the layered soil were slightly underestimated at the 20 cm depth in 2007, and were slightly overestimated at 60 cm and 100 cm depth in 2006. The seasonal change of soil water was obvious at the shallow depths (20 cm and 60 cm), and soil water content was almost constant below the 200 cm depth during the study period.

The differences between measured and simulated results were confirmed by the ME and RMSE. The ME was the greatest in the homogeneous silt loam during the simulation period, followed by ME in the homogeneous sand soil, and ME in the layered soil were the least. RMSE varied from 0.010 $cm^3\ cm^{-3}$ to 0.021 $cm^3\ cm^{-3}$ (Table 4). Not surprisingly, the simulation accuracy in layered soil decreased relative to homogeneous soil, because of the numerical difficulty in dealing with abrupt interface boundary. Compared with the calibration of 2006, the simulated errors increased in 2007 for all three soils (Table 4).

3.3. Actual transpiration

Actual transpiration (T_r) was calculated using the HYDRUS-1D model (Fig. 8). The trend of daily T_r change with time for *C. korshinkii* stands was similar between the homogenous and the layered soils during the 2006 and 2007 simulation period. The daily T_r, which obviously responded to rainfall, was higher in layered soil than that in homogenous soils during the two growing seasons, while the value of T_r was slightly higher in homogenous sandy soil than that in homogenous silt loam soil. Higher T_r values lagged 1–2 d following significant rainfall events. Total T_r was the highest in the layered soil in 2006 and 2007, followed by T_r in homogeneous sandy soil, and the T_r value was the lowest in the homogeneous silt loam soil.

3.4. Soil water balance

The results of the water balance are presented in Table 5. Total actual evapotranspiration (ET_a) from the homogeneous and layered soils slightly exceeded the precipitation in 2006, and total ET_a was higher for layered soil than that for homogeneous soil. The ratio of evaporation (E_s) to ET_a was higher in the homogeneous soils than the layered soils: the ratio was 62.8% for the homogeneous silt loam soil and 49.5% for the homogeneous sandy soil, and 42.9% for the

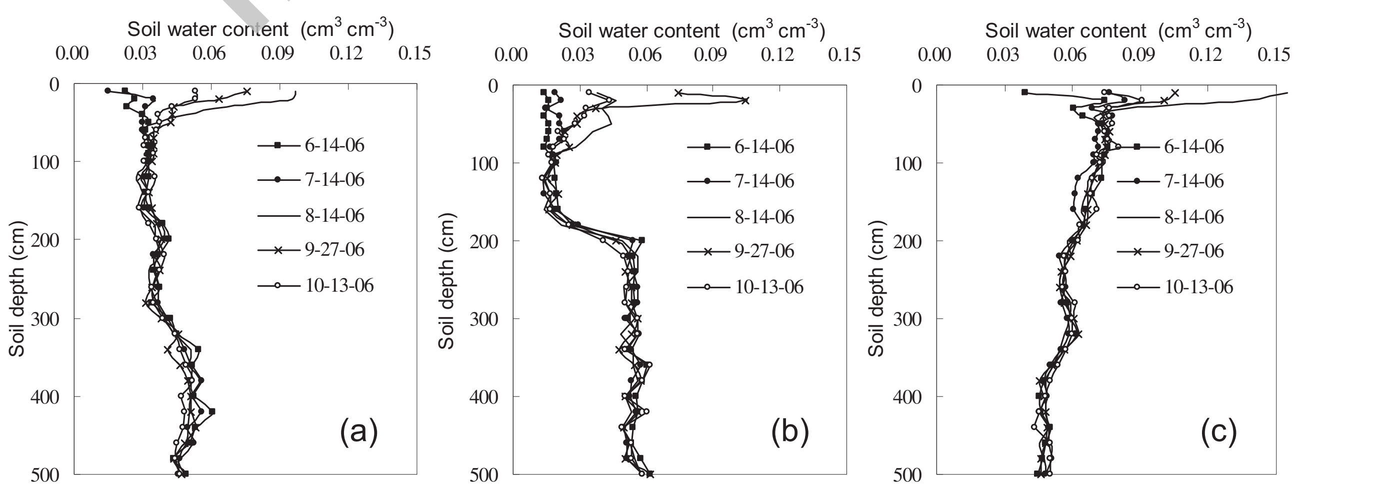

Fig. 4. Soil moisture dynamics in the soil profile from 0 to 500 cm for the sandy soil (a), sand overlying silt loam soil (b), and silt loam soil (c) during the period of May–October, 2006.

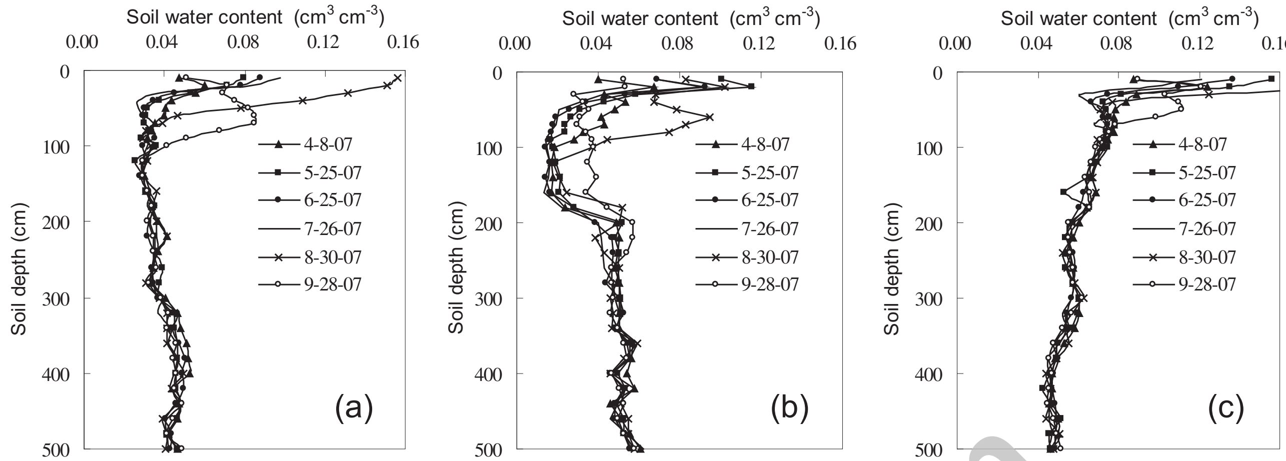

Fig. 5. Soil moisture dynamics in the soil profile from 0 to 500 cm for the sandy soil (a), sand overlying silt loam soil (b), and silt loam soil (c) during the period of April–September, 2007.

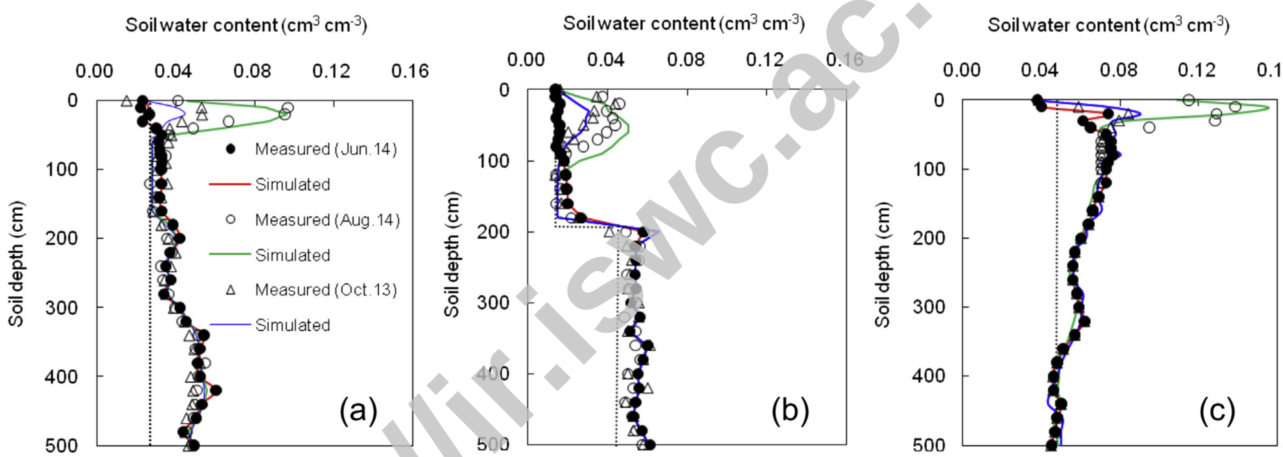

Fig. 6. Comparison of measured and simulated soil water contents in 0–500 cm profile in sandy soil (a), sand overlying silt loam soil (b), and silt loam soil (c) on Jun. 14, Aug. 14, and Oct. 13, 2006.

layered soil. The water consumption through plant transpiration (T_r) was the greatest in layered soil, accounting for 50.8% of ET_a, while T_r accounted for 44.5% and 31.5% of ET_a in homogeneous sandy soil and homogeneous silt loam soil, respectively. Canopy interception (I) loss was smaller relative to ET_a, which varied from 5.8% to 6.7% of the precipitation. Soil water storage decreased in all three soils at the end of 2006, and the water loss was up to 22.3 mm in the layered soil, 17.5 mm for the homogeneous sandy soil and

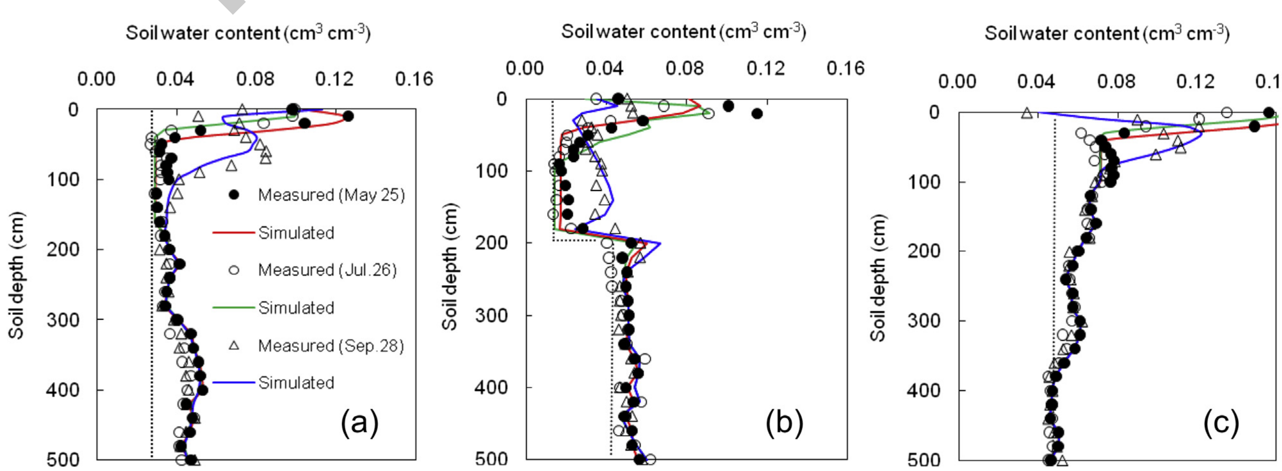

Fig. 7. Comparison of measured and simulated soil water content in 0–500 cm profile in sandy soil (a), sand overlying silt loam soil (b), and silt loam soil (c) on May 25, Jul. 26, and Sep. 28, 2007.

Table 4
Statistical analyses of the measured and simulated soil water contents in 2006 and 2007.

	No.	Homogeneous sand	Homogeneous silt loam	Sand overlying silt loam
2006 (Calibration)				
ME	310	0.778	0.834	0.769
RMSE ($cm^3\ cm^{-3}$)	310	0.012	0.010	0.016
2007 (Validation)				
ME	341	0.720	0.821	0.618
RMSE ($cm^3\ cm^{-3}$)	341	0.014	0.011	0.021

Table 5
Precipitation (P) and simulated total evapotransipiration (ET_a), canopy interception (I), transpiration (T_r), evaporation (E_s), runoff (R) and soil water storage change (S) for homogenous sandy soil, silt loam soil and layered soil in 2006 and 2007.

Year	Soil type	P	ET_a	I	T_r	E_s	R	S
		mm	mm	mm	mm	mm	mm	mm
2006	Homogeneous sand	367.8	385.3	22.9	171.5	190.9	0	−17.5
	Homogeneous silt loam	367.8	378.6	21.5	119.4	237.7	0	−10.8
	Sand overlying silt loam	367.8	390.1	24.5	198.2	167.4	0	−22.3
2007	Homogeneous sand	435.7	368.2	32.7	139.6	195.9	0	67.5
	Homogeneous silt loam	435.7	380.7	29.1	110.9	240.7	0	55.0
	Sand overlying silt loam	435.7	360.5	34.3	183.5	142.7	0	75.2

10.8 mm for the homogeneous silt loam soil. There was no observable runoff in all three soils. There were no significant difference in ET_a, I and R among the three soils ($P > 0.05$). T_r from the layered soil was significantly higher than the homogeneous soils ($P < 0.05$), while evaporation (E_s) from the layered soil was reversed. The water loss (S) in the layered soil was significantly higher than the homogeneous silt loam soil ($P < 0.05$), and no significant difference was detected between the layered soil and homogeneous sand soil ($P > 0.05$).

In 2007, total ET_a value was the highest in the homogeneous silt loam soil, followed by that in the homogeneous sandy soil. ET_a in the layered soil was the least. The ET_a accounted for 87.4%, 84.5% and 82.7% of the precipitation for the homogeneous silt loam soil, the homogeneous sandy soil and the layered soil, respectively. T_r was still the main water loss term in ET_a in layered soil, while the total E_s was higher than T_r for the homogeneous soil profiles (Table 5). Canopy interception loss in 2007 was higher than in 2006, about 6.7%–7.9% of precipitation. Contrary to the observations in 2006, soil water storage increased in all three soils at the end of 2007; soil water storage (S) increased by 75.2 mm in the layered soil, 67.5 mm for the homogeneous sandy soil and 55 mm for the homogeneous silt loam soil. Similar to 2006, no runoff was produced in all three soils. There were no significant differences in I and R among the three soils ($P > 0.05$). The T_r value from the layered soil was significantly higher than the homogeneous soils ($P < 0.05$), while evaporation (E_s) from the layered soil was reversed. S in the layered soil was significantly higher than the homogeneous silt loam soil ($P < 0.05$). However, there was no significant difference in S between the layered soil and homogeneous sand soil ($P > 0.05$).

4. Discussion

Soil texture and layering in soils greatly affected soil water distribution and movement. In the current study, rainfall infiltration depth was deeper in layered soil (sand overlying silt loam) (about 260 cm) than that in homogeneous silt loam soil (about 140 cm) and sandy soil (about 100 cm) during the simulation period of 2007. The simulated results were agreed well with the observed values (Figs. 6 and 7). Water infiltration depth was shallower in homogeneous silt loam soil than in homogeneous sandy soil. This difference might be related to soil hydraulic conductivity; generally hydraulic conductivity increases with coarsening soil texture. Hydraulic conductivity of the top sand soil in the layered soil was higher than that of the homogeneous sandy soil (Table 3), thus the depth of water infiltration was deeper in the layered soil than in homogeneous sand. Most studies found soil layering increased soil water content in the upper soil layer because of the different hydraulic conductivity between topsoil and subsoil (Baker and Hillel, 1990; Hill and Parlange, 1972; Wang et al., 2005). We also observed water content was higher at the interface of the layered soil (Figs. 4b and 5b). This flow behavior is known as the capillary barrier effect where there is elevated soil water content right above the interface (Warrick et al., 1997). The pattern of water consumption in the 0–500 cm profile was also different in the homogeneous soil and layered soil. Soil water consumption was mainly from the 0–300 cm soil layer in homogeneous sandy soil, while soil water below 300 cm was also utilized by plants in homogeneous silt loam soil. For the layered soil, soil water consumption was almost from topsoil layer in wet and normal years,

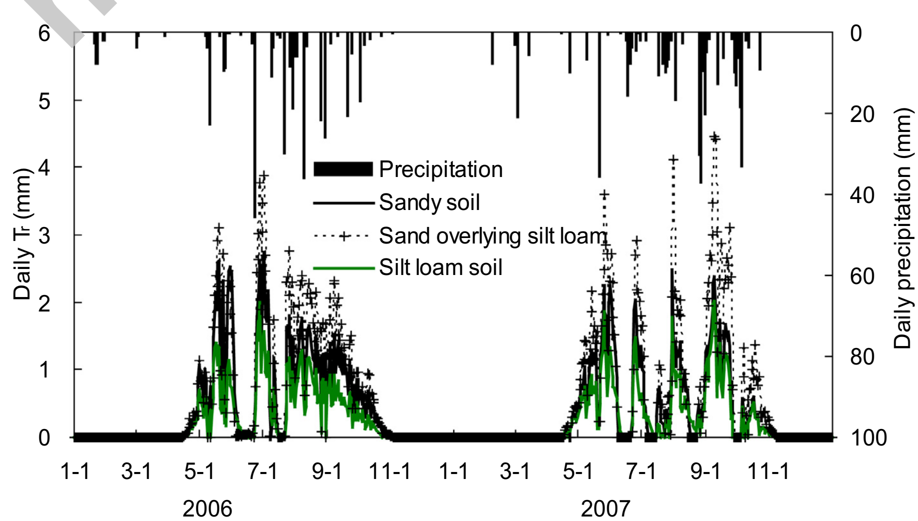

Fig. 8. Simulated T_r in sandy soil, sand overlying silt loam soil and silt loam soil and daily precipitation in 2006 and 2007.

and water in subsoil was only used by plant during the extreme drought period.

In this study, we found *C. korshinkii* grown in the homogeneous soil and layered soil has similar seasonal patterns of root water uptake, while T_r was slightly higher from layered soil than homogeneous soil during the two growing seasons. This may be related to the fact that subsoil provided more water in layered soil than the homogeneous soils during intraseasonal drought period. Because the depth of water recharge was up to 260 cm in layered soil, and most of growing season water consumption came from 0 to 200 cm soil layer. The available water was very limited in homogeneous sandy soil and homogeneous silt loam soil profile, compared to that of layered soil. Previous studies have shown that T_r was higher in plant communities with deep roots because the plants can access more water (Donohue et al., 2007; Porporato et al., 2001). However, the total T_r was lower in homogeneous soil profiles than the layered soil, although root distribution was the deepest in silt loam soil. This is because water consumption from the layer below 260 cm by *C. korshinkii* and very little subsequent recharge to that layer during the rainy season left very little water in the layer. Therefore, deeper soil layer (>260 cm) did not supply a detectable amount of water during the relatively dry period.

T_r was clearly affected by precipitation in the study area. High T_r values in the three soils followed relatively large rainfall events, and usually the peak transpiration rate was lagged 1–2 d compared to rainfall. This is in agreement with other research from shrubland under semiarid conditions (Cuomo et al., 1992; Moran et al., 2009; Reynolds et al., 2000; Scott et al., 2006; Vivoni, 2012). Furthermore, physiological investigations also demonstrated that the transpiration rates for mesquite depended mostly on soil water recharge by rainfall in semiarid regions (Ansley et al., 1994).

Actual evapotranspiration (ET_a) accounted for more than 90% of all precipitation that infiltrated soil in semiarid environments (e.g. Carlson et al., 1990; Huxman et al., 2005; Wilcox et al., 2003). The proportion of components (plant transpiration, T_r, soil evaporation, E_s, and canopy interception, I) of ET_a varied in different ecosystems, which were affected by vegetation cover, rainfall regime and soil properties. Reynolds et al. (2000) summarized that T_r/ET_a in semiarid shrublands ranged from 7% to 80%. Annual components of ET_a was simulated in several different Chihuahuan desert communities and found that annual T_r/ET_a was about 40% for a creosote community with about 30% plant cover, but T_r/ET_a increased to 60% in a mixed community with 60% plant cover (Kemp et al., 1997). Moran et al. (2009) estimated T_r/ET_a was 64% for the shrub-dominated site with a coarse-loamy soil (annual precipitation is about 350 mm) in Tucson, USA. Vivoni (2012) indicated that T_r/ET_a was 20% over the season in subtropical scrublands with a shallow soils (<2 m) range in texture from sandy to sandy clay loam. The ratio T_r/ET_a was 45% in a semi-arid pine forest with clay-loam soil (Yaseef et al., 2009). In our study, the average T_r/ET_a during the two years was 50.9% for layered soil, 41.2% for homogeneous sandy soil, and 30.6% for homogeneous silt loam soil. The difference, on the one hand, was related to plant characteristics, there were positive relationship between T_r/ET_a and shrub cover, LAI and biomass in three soils. On the other hand, soil texture and layering could be another important reason. *C. korshinkii* grown in coarse textured soil (sandy soil) had more easily accessible water than in medium textured soil (silt loam soil). Particularly, layered soil (sand overlying silt loam) is more favorable in the study area. The coarse textured soil had higher infiltration and drainage rates than medium textured soil, meaning more water storage in soil for plant transpiration in rainy season. Furthermore, after the surface dries, the soil texture is one of the dominant controlling factors influencing the evaporation rate. Surface sandy soils dry more rapidly than silt loam soil due to the decreasing upward capillary movement of water. The dry surface layer of sand can restrict evaporation because of reduced vapor diffusion (Mutziger et al., 2005; Scott et al., 2006; Yamanaka and Yonetanib, 1999).

Our result found that the pattern of soil water balance in three soils varied in different years. In 2006, a relatively dry year, ET_a exceeded precipitation in homogeneous and layered soils. The ET_a/P in three soils varied from 82.7% to 87.4% in 2007 (a normal year). The total ET_a in layered soil and sandy soil in 2007 was lower than that in 2006, but the total ET_a in 2007 was slightly higher than that in 2006 for the silt loam soil. This difference was related to the annual variation and seasonal distribution of precipitation. In 2007, rainfall was sparse in July, and more rainfall occurred at later stages of shrub growth (from Aug. to Oct.), so water consumption was relatively smaller than that in 2006. As a result, soil water storage significantly increased at the end of study period in the three soils. The result was consistent with Yaseef et al. (2009) who investigated in a semi-arid forest. This suggests that spatial and temporal variability of precipitation (P) greatly influenced water balance characteristics in semiarid ecosystems (Farmer et al., 2003).

Compared to our observed values, the overestimation in interception loss was less than 1 mm by Eqs. (10) and (11), while the underestimation for I was larger than 1 mm (Fig. 9). But the total estimated I was similar between observed and simulated values in 2006 and 2007 (P > 0.05). According to simulation results, the canopy interception loss (I) was low during the two year period, which varied from 6.8% to 8.3% of total precipitation. The

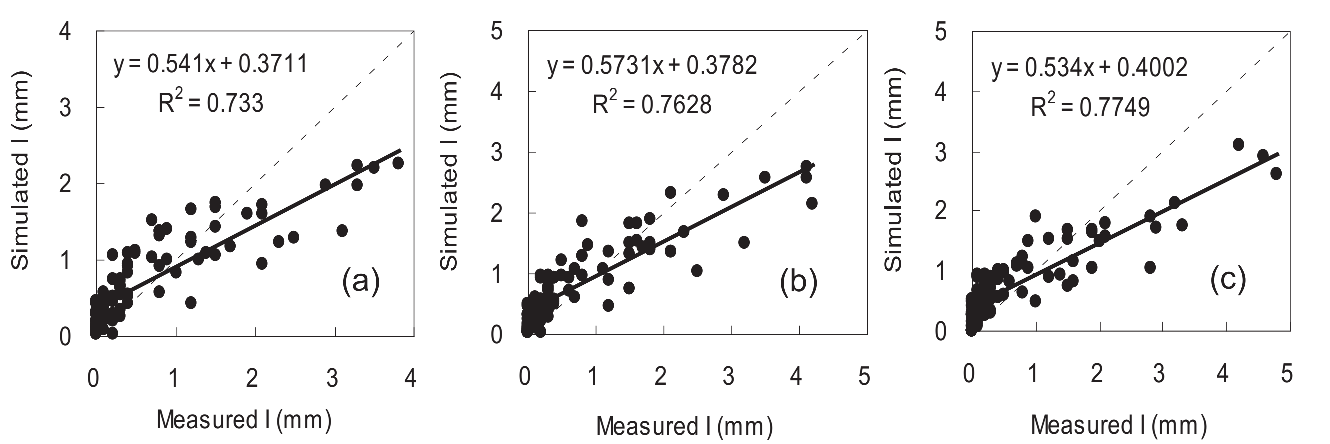

Fig. 9. Comparison of measured and simulated canopy interception (I) from the sandy soil site (a), silt loam soil site (c), and sand overlying silt loam soil site (c) in 2006 and 2007.

differences among soil types were explained by measured plant LAI from the three soils.

The soil water storage (S) was underestimated in 2006, and overestimated in 2007. The ratio of simulated water loss (S) to precipitation (P) varied from 2.9% to 6.1%, while the observed S/P values were from 0.6% to 3.3% in 2006. In 2007, the simulated and observed S/P values were from 12.6% to 17.3% and from 10.7% to 15.1%, respectively. Overall, the simulated soil water storage changes agreed well with the observed values. Average S during the two growing seasons was not significantly different between the three soils ($P > 0.05$).

According to our observations, no runoff was produced from the homogeneous sandy soil and layered soil plots, and less than 4 mm was generated from the homogeneous silt loam plots in 2006 and 2007. The simulated runoff values were lower than the measured one in homogeneous silt loam plots, but the difference was negligible compared to annual precipitation, therefore there were no significant difference between simulated and measured runoff. Furthermore, the layered soil had smaller slopes (7%) than the other two soils (13 and 14%). Because there was almost no runoff, the effect of slope on the water balance was negligible in soils. This is further corroborated by the fact that there were approximately the same amounts of water recharge due to precipitation in the three soils as shown in Figs. 4 and 5, indicating that rainfall water infiltration was not affected by the different slopes. Hanna et al. (1983) showed that surface runoff appeared to increase with increasing slope, and internal drainage beyond the 137-cm depth decreased at approximately the same rate for the slopes of 8%, 4%, and 2%. Therefore, the overall water depletion was not significantly affected by slope.

5. Conclusion

In this study, the water balance of *C. korshinkii* stands in homogeneous (sandy soil and silt loam soil) and layered soils (sand overlying silt loam soil) were simulated using HYDRUS-1D model. Model simulation described the observed soil moisture well in homogeneous and layered soils.

According to the HYDRUS model, annual water balance in homogeneous and layered soils were greatly affected by precipitation regime. In a relatively dry year (2006), the estimated total ET_a in homogeneous soil and layered soil slightly exceeded precipitation, and soil water storage decreased by 10.8 mm–22.3 mm for the three soils. The ET_a/P in three soils varied from 82.7% to 87.4% in 2007 (a normal year), soil water increased by 75.2 mm, 67.5 mm and 52 mm in layered soil, homogeneous sandy soil and silt loam soil, respectively. Interception loss accounted for 6.8%–8.3% of precipitation in the three soils. The average T_r/ET_a during two years was 50.9%, 41.2% and 30.6% for layered soil, homogeneous sandy soil and silt loam soil, respectively.

This study suggested that layered soil (sand overlying silt loam soil) is more favorable to *C. korshinkii* growth in terms of water use than homogeneous sandy soil and silt loam soil in the transition zone of the Loess Plateau. This is because the coarser topsoil of the layered soils enhanced water infiltration, reduced soil evaporation, and resulted in more soil water for plant transpiration, compared to homogeneous sand and silt loam soil.

The research finding is significant because sand deposition on existing soil (silt loam soil) could enhance *C. korshinkii* establishment, thus reducing desertification. Established vegetated shrub can be useful in reducing or preventing erosion by wind or water, and in restoring vegetation cover in this region. Given the fact that rain recharge to soil mostly occurred within 260 cm depth, and *C. korshinkii* growth entirely depends on precipitation. This research could improve understanding of the effect of soil type and heterogeneity in profile on the water cycle in the semiarid region of the Loess Plateau.

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References

Ansley, R.J., Dugas, W.A., Heuer, M.L., Trevino, B.A., 1994. Stem flow and porometer measurements of transpiration from honey mesquite (*Prosopis glandulosa* Torr.) trees. Journal of Experimental Botany 45, 847–856.

Baker, R.S., Hillel, D., 1990. Laboratory tests of theory of fingering during infiltration in to layered soils. Soil Science Society of America Journal 54, 20–30.

Böhm, W., 1979. Methods of Studying Root Systems. Springer, Berlin, p. 188.

Carlson, D.H., Thurow, T.L., Knight, R.W., Heitschmidt, R.K., 1990. Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland. Journal of Range Management 43, 491–496.

Chang, X., Cheng, X., Liu, G.B., Qiu, H.J., 2005. Discussion on sustainable agricultural development on Loess Plateau. Science & Technology Review 3, 52–56 (in Chinese with English Abstract).

Cuomo, C.J., Ansley, R.J., Jacoby, P.W., Sosebee, R.E., 1992. Honey mesquite transpiration along a vertical site gradient. Journal of Range Management 45 (4), 334–338.

Donohue, R.J., Roderick, M.L., McVicar, T.R., 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. Hydrology and Earth System Sciences 11, 983–995.

Duniway, M.C., Snyder, K.A., Herrick, J.E., 2010. Spatial and temporal patterns of water availability in a grass–shrub ecotone and implications for grassland recovery in arid environments. Ecohydrology 3, 55–67.

Farmer, D., Sivapalan, M., Jothityangkoon, C., 2003. Climate, soil and vegetation controls upon the variability of water balance in temperate and semi-arid landscapes: downward approach to hydrological prediction. Water Resources Research 39 (2), 1035–1055.

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1974. Simulation of Field Water Use and Crop Yield. In: Simulation Monographs, pp. 1–189. Wageningen.

Gutierrez-Jurado, H.A., Vivoni, E.R., Harrison, J.B.J., Guan, H., 2006. Ecohydrology of root zone water fluxes and soil development in complex semiarid rangelands. Hydrological Processes 20, 3289–3316.

Hernandez, T.X., 2001. Rainfall-runoff Modeling in Humid Shallow Water Table Environments (M.Sc. thesis). University of South Florida, South Florida.

Hill, D.E., Parlange, J.Y., 1972. Wetting front instability in layered soil. Soil Science Society of America Proceedings 36, 697–702.

Huang, M.B., Barbour, S.L., Si, B.C., Elshorbagy, A., Zettl, J., 2011. Infiltration and drainage processes in multi-layered coarse soils. Canadian Journal of Soil Science 91, 169–183.

Huxman, T.E., Wilcox, B.P., Breshears, D.D., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K., Pockman, W.T., Jackson, R.B., 2005. Ecohydrological implications of woody plant encroachment. Ecology 86, 308–319.

Jury, W.A., Horton, R., 2004. Soil Physics, sixth ed. John Wiley and Sons, Inc., Hoboken, New Jersey, pp. 74–85.

Kemp, P.R., Reynolds, J.F., Pachepsky, Y., Chen, J.L., 1997. A comparative modeling study of soil water dynamics in a desert ecosystem. Water Resources Research 33, 73–90.

Li, Y.S., 2001. Effects of forest on water circle on the Loess Plateau. Journal of Natural Resources 16 (5), 427–432 (in Chinese with English Abstract).

Loik, M.E., Breshears, D.D., Lauenroth, W.K., Belnap, J., 2004. A multi-scale perspective of water pulses in dryland ecosystems: climatology and ecohydrology of the western USA. Oecologia 141, 269–281.

Meiwirth, K., Mermoud, A., 2004. Simulation of herbicide transport in an alluvial plain. In: Pahl-Wostl, C., et al. (Eds.), iEMSs 2004 International Congress: Complexity and Integrated Resources Management. iEMSS, Switzerland, pp. 951–955.

Monteith, J.L., 1965. Evaporation and environment. In: Fogg, G.E. (Ed.), Symposium of the Society for Experimental Biology, The State and Movement of Water in Living Organisms, vol. 19. Academic Press, Inc., NY, pp. 205–234.

Moran, M.S., Scott, R.L., Keefer, T.O., Emmerich, W.E., Hernandez, M., Nearing, G.S., Paige, G.B., Cosh, M.H., O'Neill, P.E., 2009. Partitioning evapotranspiration in semiarid grassland and shrubland ecosystems using time series of soil surface temperature. Agricultural and Forest Meteorology 149, 59–72.

Mutziger, A.J., Burt, C.M., Howes, D.J., Allen, R.G., 2005. Comparison of measured and FAO-56 modeled evaporation from bare soil. Journal of Irrigation and Drainage Engineering-ASCE 131, 59–72.

Porporato, A., Laio, F., Ridolfi, L., Rodrı'guez-Iturbe, I., 2001. Plants in water-controlled ecosystems: active role in hydrological processes and response to water stress. III: vegetation water stress. Advances in Water Resources 24, 725–744.

Reynolds, J.F., Kemp, P.R., Tenhunen, J.D., 2000. Effects of longterm rainfall variability on evapotranspiration and soil water distribution in the Chihuahuan desert: a modeling analysis. Plant Ecology 150, 145–159.

Sala, O.E., Lauenroth, W.K., 1982. Small rainfall events: an ecological role in semiarid regions. Oecologia 53, 301–304.

Scott, R.L., Huxman, T.E., Cable, W.L., Emmerich, W.E., 2006. Partitioning of evapotranspiration and its relation to carbon dioxide exchange in a Chihuahuan Desert shrubland. Hydrological Processes 20, 3227–3243.
Simunek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M, Th., 2008. The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media. Version 4.0. In: HYDRUS Software Series 3. Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, p. 315.
Smith, S.D., Monson, R.K., Anderson, J.E., 1997. Physiological Ecology of North American Desert Plants. Springer-Verlag, Berlin, pp. 286–287.
Sommer, R., Folster, H., Vielhauer, K., Carvalho, E.J.M., Vlek, P.L.G., 2003. Deep soil water dynamics and depletion by secondary vegetation in the Eastern Amazon. Soil Science Society of America Journal 67, 1672–1686.
Tang, K.L., Hou, Q.C., Wang, B.K., Zhang, P.C., 1993. The environment and administration way of wind-water erosion crisscross region and Shenmu experimental area on the Loess Plateau. In: Memoir of Northwestern Institute of Soil and Water Conservation, Academia Sinica and Ministry of Water Conservancy. Shaanxi Scientific and Technology Press 18, pp. 2–15 (in Chinese with English Abstract).
Townend, J., Reeve, M.J., Carter, A., 2001. Water release characteristic. In: Smith, K.A., Mullins, C.E. (Eds.), Soil and Environmental Analysis. Physical Methods, second ed. Marcel Dekker, New York, NY, pp. 95–140.
van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.
van Genuchten, M.Th., Leij, F.J., Yates, S.R., 1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils. Version1.0. EPA Report 600/2-91/065. US Salinity Laboratory, USDA, ARS, Riverside, CA.
Vivoni, E.R., 2012. Diagnosing seasonal vegetation impacts on evapotranspiration and its partitioning at the catchment scale during SMEX04-NAME. Journal of Hydrometeorology 13, 1631–1638.
Wang, W.Y., Zhang, J.F., Wang, Z.R., Wang, Q.J., 2005. Infiltration reduction effect of sand layer in loess. Journal of Hydraulic Engineering 36, 650–655 (in Chinese with English Abstract).
Warrick, A.W., Wierenga, P.J., Pan, L., 1997. Downward water flow through sloping layers in the vadose zone: analytical solutions for diversions. Journal of Hydrology 192, 321–337.
White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and Sensitivity Analysis of the BIOME-BGC Terrestrial Ecosystem Model: Net Primary Production Controls. In: Earth Interactions, 4, pp. 1–85. Paper No. 3.
Wilcox, B.P., Seyfried, M.S., Breshears, D.D., 2003. The water balance on rangelands. In: Stewart, B.A., Howell, T.A. (Eds.), Encyclopedia of Water Science. Marcel Dekker, New York, New York, USA, pp. 791–794.
Willis, W.O., 1960. Evaporation from layered soil in the presence of a water table. Soil Science Society of America Proceedings 24, 239–242.
Wilson, G.W., 1990. Soil Evaporative Fluxes for Geotechnical Engineering. Problems (PhD thesis). University of Saskatchewan, Saskatoon, Canada.
Wilson, G.W., Fredlund, D.G., Barbour, S.L., 1997. The effect of soil suction on evaporative fluxes from soil surfaces. Canadian Geotechnical Journal 34, 145–155.
Xia, Y.Q., 2008. The Process Modeling of Soil Water Carrying Capacity for Vegetation in Small Watershed Within the Wind-water Crisscrossed Erosion Zone on the Loess Plateau (PhD thesis). Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences.
Xia, Y.Q., Shao, M.A., 2008. Soil water carrying capacity for vegetation: a hydrologic and biogeochemical process model solution. Ecological Modelling 214, 112–124.
Yamanaka, T., Yonetanib, T., 1999. Dynamics of the evaporation zone in dry sandy soils. Journal of Hydrology 217, 35–48.
Yang, W.B., Ding, G.D., Wang, J.Y., Yao, J.C., Dong, Z., Yang, H.Y., 2006. Windbreak effects of belt scheme *Caragana korshinskili* kom plantation for sand fixation. Acta Ecologica Sinica 26, 4106–4112 (in Chinese with English Abstract).
Yang, X.M., 2001. Study on the characteristics of water environment in shrubbery land of Loess Plateau. Arid Zone Research 18, 7–13 (in Chinese with English Abstract).
Yang, X.P., Liu, T., Yuan, B.Y., 2010. The Loess Plateau of China: aeolian sedimentation and fluvial erosion, both with superlative rates. In: Geomorphological Landscapes of the World, pp. 275–282.
Yaseef, N.R., Yakir, D.E., Rotenberg, S.G., Cohen, S., 2009. Ecohydrology of a semi-arid forest: partitioning among water balance components and its implications for predicted precipitation changes. Ecohydrology 3, 143–154.
Zhao, Y., Peth, S., Hallett, P., Wang, X.Y., Giese, M., Gao, Y.Z., Horn, R., 2011. Factors controlling the spatial patterns of soil moisture in a grazed semi-arid steppe investigated by multivariate geostatistics. Ecohydrology 4, 36–48.