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Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau

Shengqi Jian[a,*], Chuanyan Zhao[b], Shumin Fang[a,c], Kai Yu[d]

[a] State Key Laboratory of Grassland and Agro-Ecosystems, School of Life Sciences, Lanzhou University, Huyang Building 301, Tianshui South Road 222, Lanzhou, China
[b] State Key Laboratory of Grassland and Agro-Ecosystems, School of Life Sciences, Lanzhou University, Huyang building 316, Tianshui South Road 222, Lanzhou, China
[c] College of Resource and Environmental Sciences, Gansu Agricultural University, China
[d] Ministry of Education Key Laboratory of Western China Environmental Systems, Lanzhou University, Huyang Building 301, Tianshui South Road 222, Lanzhou, China

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ABSTRACT

Large-scale vegetation restoration in the Chinese Loess Plateau has been initiated by the central government over the past decades to control soil and water loss. However, no guidelines are followed in plant species selection for vegetation restoration. We examined the effects of planting *Pinus tabuliformis*, *Robinia pseudoacacia*, *Caragana korshinskii*, and *Hippophae rhamnoides* on soil water dynamics and water stresses by measuring canopy interception, soil evaporation, plant transpiration, and surface runoff from May to September of 2009–2013 in the semi-arid loess hilly area. Results showed the following: (1) Water loss exceeded precipitation in most months during the growing seasons. The amount of soil water storage decreased within a 100 cm depth in all land cover types from 2009 to 2013. Land cover examination showed that the slope of the decline trend of soil water storage for *C. korshinskii* was much lower than that of the other land cover types. However, *P. tabuliformis* exhibited the biggest decline slope among the four land cover types. (2) The ratio of actual evapotranspiration (ET) and pan evaporation (E_p) was low for all land cover types during the study period. The ET/E_p ratios followed the order (from highest to lowest) *C. korshinskii* > *R. pseudoacacia* > *H. rhamnoides* > *P. tabuliformis*. When the monthly rainfall amount was lower than 50 mm, *H. rhamnoides* showed the lowest ET/E_p ratio among the four land cover types, but high ET/E_p ratio was observed in *H. rhamnoides* with large rainfall amount (>70 mm). The current study suggested that *P. tabuliformis* plantation should not be the first choice for vegetation restoration in such a semiarid loess hilly area. *H. rhamnoides* is suitable for afforestation in areas with high levels of rainfall. *C. korshinskii* and *R. pseudoacacia* are highly recommended for vegetation restoration.

1. Introduction

Land degradation is one of the most serious ecological problems worldwide (Liu et al., 2010; Moran et al., 2009). Desertification, most likely, occurs when population and land use pressures are not carefully considered (Duniway et al., 2010; Huang et al., 2011). Vegetation restoration using woody species is encouraged worldwide because of its several benefits (Malagnoux, 2007), such as soil erosion control (Huang et al., 2011), sediment reduction (Moran et al., 2009), hydrological regime regulation (Yaseef et al., 2009), and carbon sequestration (Zhao et al., 2011). However, woody species consume more water by evapotranspiration than other vegetation types, such as natural grassland (Cao et al., 2009), and cause runoff reduction (Yi and Wang, 2013). Farley et al. (2005) analyzed 26 catchment data sets by comparing forest and grassland plots. They found that the reduction of the mean annual runoff can reach up to 44% in humid regions. This runoff reduction is more notable in the semi-humid and semi-arid regions of China, where it can reach more than 50% after forestation (Sun et al., 2006). Several researchers also reported that soils become extremely dry in both deep and shallow layers when vegetation restoration strategy is used (Yaseef et al., 2009; Wang et al., 2010; Cao et al., 2011). The negative effects of the initially promoted afforestation occur because of soil desiccation, such as decreasing the restoration effort (Liu et al., 2010; Wang et al., 2011; Rodríguez-Caballero et al., 2012),

* Corresponding author at: Huyang Building 316, Tianshui South Road 222, Lanzhou, China. Tel.: +86 13919048861.
E-mail address: jiansq10@lzu.edu.cn (S. Jian).

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vegetation deterioration and difficulties in renewal and reforestation (Chen et al., 2008), fluctuating agricultural crop production (Wang et al., 2008), and decreasing ecosystem services (Chazdon, 2008).

In arid and semi-arid regions, vegetation restoration is largely controlled by soil water availability (Zheng et al., 2014). Plants have strong effects on ecosystem water balances through their contrasting capacity to access, transport, and transpire soil moisture (Wang et al., 2014). Precipitation is among the most important factors that determine the occurrence and diversity of species (Fu et al., 2011). In arid and semi-arid regions, species need to cope with dry years or seasons. Chen et al. (2008) found that the high water consumption rate of several forest tree varieties causes drying up of soils and ecological degradation in arid and semi-arid regions. A similar phenomenon can be avoided by applying efficient water and soil management because of the prevailing fragile ecological environment. Hence, a proper understanding of how water balance limits and controls afforestation is particularly important. Water balance is not only important in investigating the ecosystem function and catchment hydrology (Issa et al., 2011), but is also necessary for developing viable water-saving management strategies that support high water-use efficiency and economic benefits in regions subjected to water scarcity (Jia et al., 2012). To encourage proper reforestation practices, common species need to be investigated to elucidate their water balance and determine their suitability for developing stable ecosystems that can improve the provision of ecosystem services and reverse degradation processes (Derak and Cortina, 2014).

The Loess Plateau in China experiences severe soil erosion, vegetation degradation, and desertification (Jiao et al., 2011). Thus, the Chinese government has implemented extensive vegetation reestablishment practices to overcome these problems (Zhang et al., 2009). The history of vegetation restoration in the Loess Plateau can be dated back to the 1970s (Qin et al., 2014). In 1999, the project "Grain for Green" was initiated to reduce soil erosion on cultivated slope farmland (Fu et al., 2005). In this project, farmers were compensated with grain in exchange for converting steep croplands (>15°) to green land (Fu et al., 2005). Consequently, part of the farmland was converted to forest or shrub lands mainly by planting black locust (*Robinia pseudoacacia* Linn.), Chinese pine (*Pinus tabuliformis* Carr.), korshinsk peashrub (*Caragana korshinskill* Kom.), and sea buckthorn (*Hippophae rhamnoides* Linn.). The other part of the farmland was abandoned and gradually converted to grassland through natural succession. Land-use type changed with the implementation of the "Grain for Green" project in the Loess plateau. However, the imbalance between water supply and demand has become particularly acute because the initially simple, cultivated vegetation system has developed into a complex, cultivated, and natural ecosystem capable of reversing desertification (Wang et al., 2013). Given this situation, studying the water balance of *P. tabuliformis*, *R. pseudoacacia*, *C. korshinskii*, and *H. rhamnoides*, assessing the effects of their cultivation on local hydrological resources, and finally determining the most suitable species for soil and water conversation locally are necessary.

This study focused on a small catchment in the western Chinese Loess Plateau to test the hydrological effects of *P. tabuliformis*, *R. pseudoacacia*, *C. korshinski*i, and *H. rhamnoides*. The results are expected to provide insights into the feasibility of large-scale planning for ecological restoration. The specific aims of this study were to examine soil water storage changes in different land uses and to quantify the changes of each component (canopy interception, soil evaporation, plant transpiration, and runoff) of water balance over time in different land uses.

2. Materials and methods

2.1. Study area

The study was conducted from 2009 to 2013 in the Anjiapo catchment, Dingxi County (35°35′N, 104°39′E) of Gansu province in western Chinese Loess Plateau. The annual mean precipitation of the area is 420 mm with significant seasonal variations. More than 60% of the precipitation falls between July and September, and more than 50% occurs in the form of storm. The average monthly air temperature ranges from −7.4 °C to 27.5 °C, with a mean annual temperature of 6.3 °C. The average annual pan evaporation is 1510 mm. The soil belongs to *Calcic Cambisol* group based on the FAO–UNESCO soil classification system. It is developed on loess parent material and has a relatively thick profile (Wang et al., 2010).

Vegetation restoration has been widely implemented since the late 1970s in the area where *P. tabuliformis*, *R. pseudoacacia*, *C. korshinski*i, and *H. rhamnoides* were planted. The land uses in the study area include croplands, grasslands, artificial shrublands, and woodlands.

2.2. Experiment design

Twelve experimental plots were constructed on the hill slopes between 10° and 20° slopes where rainfed crops (i.e., winter wheat

Table 1
Average geographical parameters, biological parameters and soil parameters for the top 1 m in Anjiagou catchment.

	Parameter	Sample numbers	Mean ± SD			
			P. tabuliformis	*R. pseudoacacia*	*C. korshinskii*	*H. rhamnoides*
Geographical parameters	Slope aspect	–	NE	NE	SE	NE
	Slope position	–	Middle	Middle	Middle	Upper
Biological parameters	Plant height (m)	160	11.42 ± 3.63	10.67 ± 2.41	1.70 ± 11	2.58 ± 1.7
	DBH/BD (cm)	200/160	20.11 ± 4.72	18.26 ± 3.74	1.51 ± 0.21	1.67 ± 0.33
	Projected area (m^2)	160	17.66 ± 5.29	15.41 ± 3.10	3.02 ± 0.44	3.54 ± 0.21
	Coverage in first year (%)	50	75–90	60–75	60–70	75–85
	Coverage in last year (%)	50	80–95	70–80	65–80	80–90
Soil parameters	Clay (<0.002 mm; %)	12	9.45 ± 2.31	10.22 ± 1.46	9.17 ± 1.20	11.04 ± 2.3
	Silt (0.05–0.002 mm; %)	12	75.46 ± 10.03	77.36 ± 10.24	75.59 ± 9.21	76.69 ± 11.34
	Sand (0.05–2 mm; %)	12	15.09 ± 1.15	12.42 ± 2.06	15.24 ± 1.16	12.27 ± 2.81
	Organic matter (%)	12	0.87 ± 0.09	0.94 ± 0.07	0.68 ± 0.08	0.71 ± 0.04
	pH	12	8.2 ± 0.3	8.1 ± 0.5	8.1 ± 0.9	7.9 ± 0.7
	Soil bulk density ($g\,cm^{-3}$)	12	1.33 ± 0.11	1.28 ± 0.15	1.12 ± 0.22	1.25 ± 0.20

Note: Slope, slope aspect and slope position were determined by compass; each parameter was measured from 2009 to 2013. Soil organic matter was determined by potassium dichromate volumetric method; pH was determined by potentiometry; particle size distribution was determined by sedimentation. Soil properties are for the top 1 m. DBH is the diameter at breast height for trees, DB is the basic diameter for shrubs. Coverage was measured in each month from May to September in the period of 2009–2013.

and potatoes) were grown previously. The plots used for each species measured 10 m × 10 m. *P. tabuliformis* and *H. rhamnoides* were planted in 1978, and *R. pseudoacacia* and *C. korshinskii* were planted in 1986. Each plot was constructed with a cement ridge 20 cm above the ground around the borders, and an H-flume was used to measure surface runoff. For each land cover type, three replications were used. A detailed information about the plots is shown in Table 1.

Leaf area index (LAI) was collected monthly (in the middle of each month during the growing seasons) from May to September of 2009–2013. The surface area of individual leaves was determined from photographs by using ImageJ 1.36b software (National Institutes of Health, USA). The LAI was obtained by averaging the surface area of 100 leaves, multiplying the total number of leaves in each plot, and dividing by the plot area. The total number of leaves was estimated by counting the average number of leaves of five plants and the total number of plants in each plot. Hemispherical photographing technique was used to obtain LAI (Jonckheere et al., 2004). A Sigma 8 mm fisheye lens (Sigma F3.5 EX DG Circular Fisheye-Sigma Corporation) mounted on a Canon EOS 5D digital SLR camera (Canon EOS 5D Mark II-Canon Corporation) was used to take the hemispherical photographs of each plot at 10 points for each measurement. The mean values were used to plot LAI.

Soil water content was measured from 2009 to 2013 using probes (Decagon Devices, Pullman, WA, USA) installed at five depths below the soil surface (20, 40, 60, 80, and 100 cm) in each plot. The soil water content was also measured every 30 days by oven drying to validate the soil water content data provided by the probes during the study period. The soil was backfilled, and the surface was flattened each time.

The surface runoff of each land cover plot was collected from May to September of 2009–2013. The collectors were cleaned up after each measurement, and the surface runoff modulus was calculated. A meteorological tower approximately 100 m from the study site was installed. The meteorological variables were wind speed, air temperature, relative humidity, net and photosynthetically active radiation, rainfall, and atmospheric pressure. These parameters were measured using an AG1000 automatic weather station (Onset Computer Corporation, Pocasset, MA, USA) from 2009 to 2013. Manual measurements on rainfall were also performed to check the automatically recorded data. Pan evaporation was measured by a water surface evaporator (E601B; WEISER, Xuzhou, China). Potential evapotranspiration was calculated by summing up the daily pan evaporation.

2.3. Water balance

2.3.1. Canopy interception

Throughfall was measured using 40 homemade rain gauges (with 20 cm inner diameter and 20 cm height), which were evenly distributed beneath the canopy in each plot. Stemflow was collected in a plastic tube (1 cm in diameter), which was wrapped around and attached to the tree trunk. Four trees were selected to represent different tree diameters at breast height in each plot for *P. tabuliformis* and *R. pseudoacacia*. For *C. korshinskii* and *H. rhamnoides*, stemflow was collected using collars constructed from flexible aluminum foil plates that were fitted around the entire circumference of the stems; 20 stems were selected to represent different basal diameters in each shrub plot. Throughfall and stemflow were measured from May to September of 2009–2013. The values for interception were derived by subtracting the mean throughfall and estimated stemflow from gross rainfall. The collected rain water was assumed to have no effect on soil evaporation, plant transpiration, and runoff.

2.3.2. Soil evaporation

Soil evaporation was measured with micro-lysimeters (Boast and Robertson, 1982). Four micro-lysimeters were installed in each plot. They had an internal diameter of 25 cm and a depth of 30 cm. The bottom of each micro-lysimeter was capped with a steel plane that did not permit free drainage of water. Soil evaporation was measured at 08:00 daily from May to September of 2009–2013.

2.3.3. Plant transpiration

Plant transpiration can be estimated from the sap flow (Yue et al., 2008; Wang et al., 2010). Stem flow gauges (Flow32, Model SGB16) were used with the stem-heat balance method to measure the sap flow of *C. korshinskii* and *H. rhamnoides*. Six stems were selected based on a statistical analysis within the plots to determine the "mean stem" before the gauges were set up. The theoretical method and methodology for the sap flow gauge have been described by Smith and Allen (1996), and in this study, the gauges were carefully installed following the manufacturer's instruction. A modified heat-pulse velocity technique (SF-L; Ecomatik, Germany) was used to measure the xylem sap flow on four trees from each plot of *P. tabuliformis* and *R. pseudoacacia*. The theoretical method and methodology for the sap flow sensor have been described by Lin et al. (2012). The sap flow was measured from May to September of 2009–2013. The measurements of water use by individual plants were extrapolated to determine the area-averaged transpiration of the shrublands and woodlands based on Yue et al. (2008) and Khanzada et al. (1998).

2.3.4. Water balance model

Precipitation (P) is considered the only source of water (i.e., input) in the Anjiapo catchment. The input (P) is balanced out either through runoff (R) or through net change in soil water content (ΔSW). The change in soil water content (ΔSW) is controlled by five processes, namely, (1) canopy interception (I), (2) soil evaporation (E), (3) plant transpiration (T), (4) runoff, and (5) drainage at the bottom layer of the soil profile (D). D is nil in the study area according to in situ observations. The soil water balance in the root zone (1 m) is given as follows:

$$\Delta \mathrm{SW} = P - I - E - T - R \quad (1)$$

where $\Delta \mathrm{SW} = \mathrm{SW}_1 - \mathrm{SW}_2$ with SW_2 as the antecedent soil water content measured at the beginning of the growing period on May 1st in each year and SW_1 as the soil water content in a certain time. Daily precipitation, canopy interception, plant transpiration, soil evaporation, and runoff were measured and simulated. The daily soil water content can thus be estimated by Eq. (1).

2.4. Data analysis

One-way ANOVA was performed to test the difference of the water balance components for the soil water content. All statistical analyses were conducted with SPSS software package (version 18.0 for windows; SPSS Inc., USA). The regression equations were performed in SigmaPlot version 11.0 (2008, Systat Software Inc., Chicago, IL, USA). $P < 0.05$ was considered statistically significant.

3. Results

3.1. Rainfall, environmental variables, and LAI

The variable rainfall during the study period provided an ideal opportunity to contrast the water balance of wet, dry, and average hydrological years. The rainfall in the study area from May to September of 2009–2013 ranged from 213 mm to 458 mm per year, 69–88% of the annual rainfall (Fig. 1). The largest rainfall

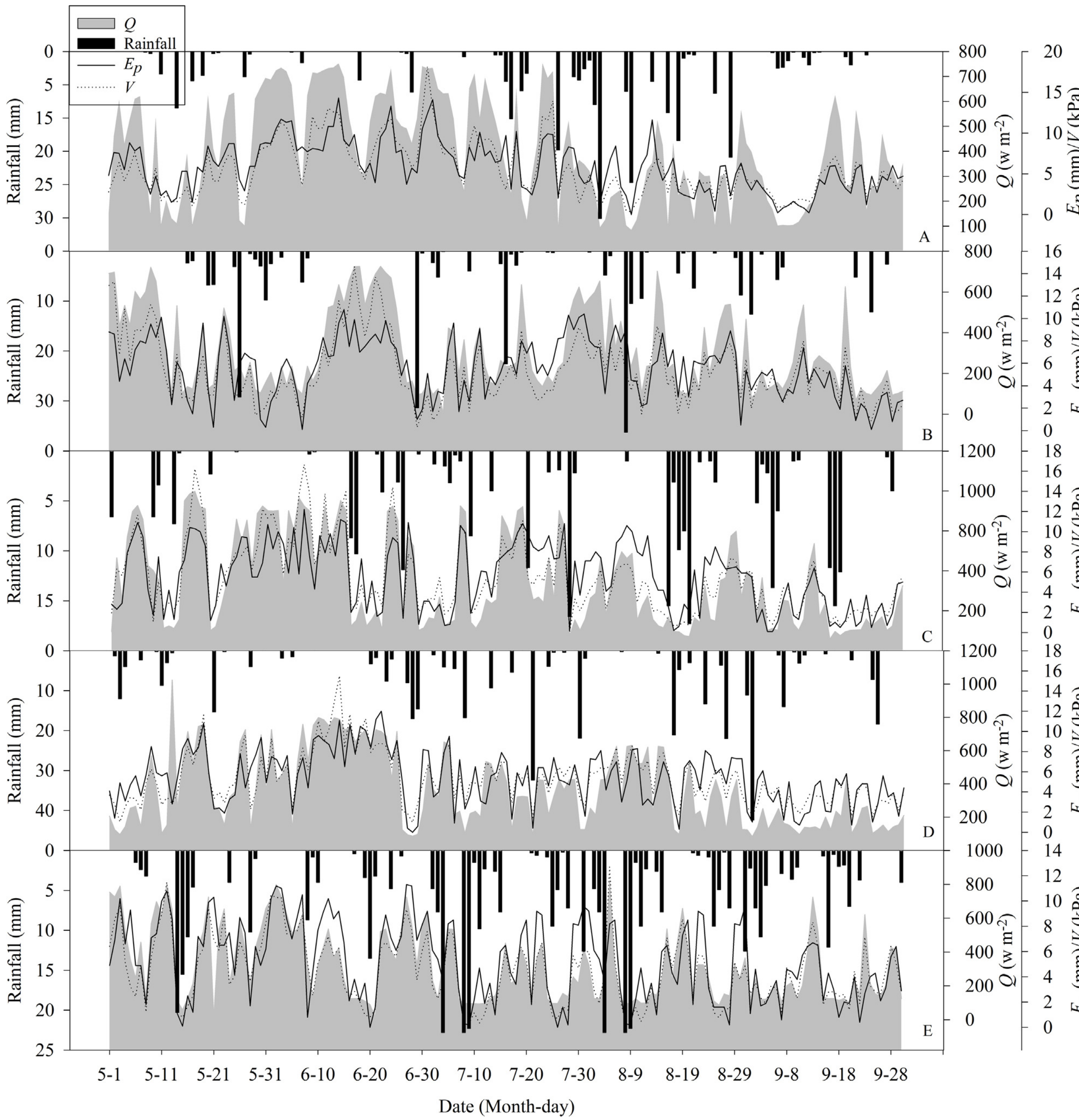

Fig. 1. Daily rainfall, solar radiation (Q), vapor pressure deficit (V) and potential evapotranspiration (E_p) from May to September in the period of 2009–2013. A–E represented the year of 2009–2013.

amount (458 mm) was observed from May to September of 2013, followed by 2012 (381 mm), 2010 (276 mm), 2011 (254 mm), and 2009 (213 mm). The daily precipitation in the five-year study period (from May to September) showed a characteristic pattern of being wet in July and August and very dry in May June, and September (Fig. 1). A high frequency of dry days was observed in May, June, and September of each year. Solar radiation (Q), vapor pressure deficit (V), and potential evapotranspiration (E_p) exhibited similar pattern during the study period.

For each species, the LAI values increased as years passed because of plant establishment (Fig. 2). The LAI values were largest in 2013 for all species. The LAI values of *P. tabuliformis* were always higher than those of *H. rhamnoides*, *R. pseudoacacia*, and *C. korshinskii* for a given month. *C. korshinskii* had the lowest LAI values.

3.2. Canopy interception

Stemflow accounted for only a small proportion of gross rainfall for *P. tabuliformis* (1.1%) and *R. pseudoacacia* (2.2%). *C. korshinskii* had the largest annual stemflow (36.9 ± 12.4 mm), followed by *H. rhamnoides* (25.2 ± 8.5 mm), *P. tabuliformis* (3.3 ± 1.1 mm), and *R. pseudoacacia* (6.8 ± 2.3 mm) (Fig. 3A). The total measured canopy interception values from May to September of 2009–2013 were estimated to be 57.9 ± 18.4, 84.9 ± 22.3, 70.9 ± 22.5, and 66.9 ± 21.3 mm or 18.3 ± 5.8%, 28.0 ± 7.35%, 22.4 ± 7.1%, and 21.1 ± 6.7% of annual rainfall for *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia*, respectively (Fig. 3B). July and August showed higher interception than the other three months in each year during the experimental period.

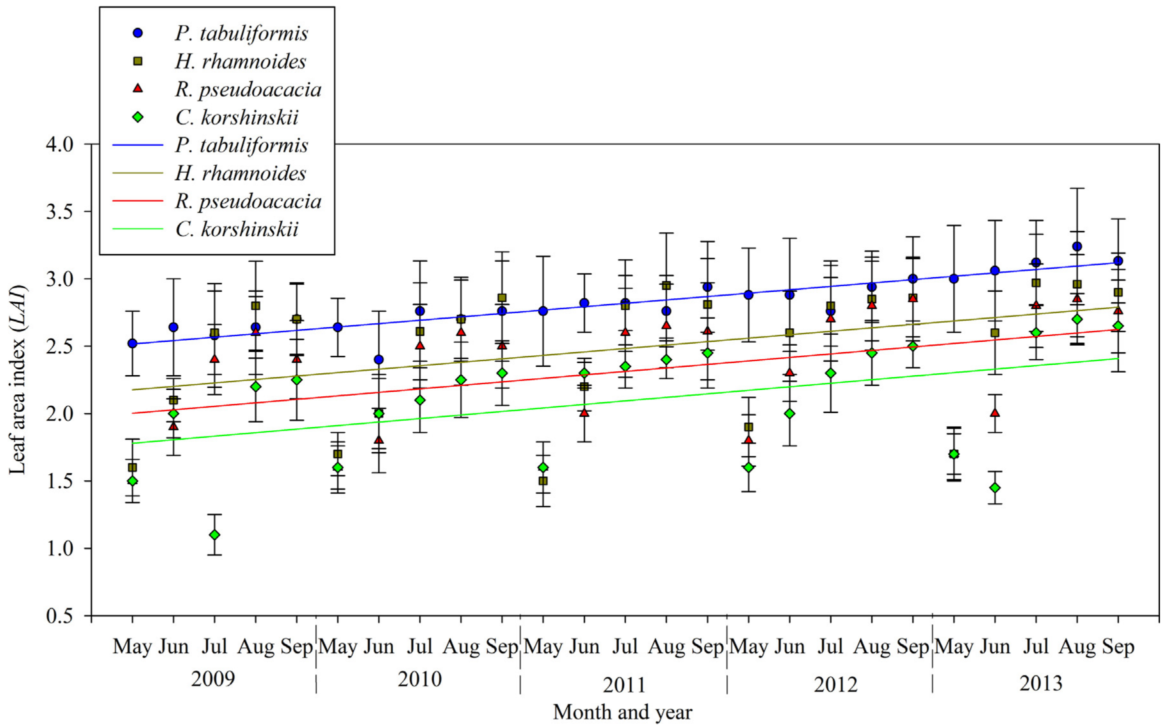

Fig. 2. Monthly changes in LAI of *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis* and *R. pseudoacacia* from May to September in the period of 2009–2013. Data = mean ± SD, $n = 3$. The change trend is in significant level when the R^2 is bigger than 0.423 when the number is 25. *P. tabuliformis*, $P < 0.001$; *H. rhamnoides*, $P < 0.01$; *R. pseudoacacia* and *C. korshinskii*, $P < 0.05$.

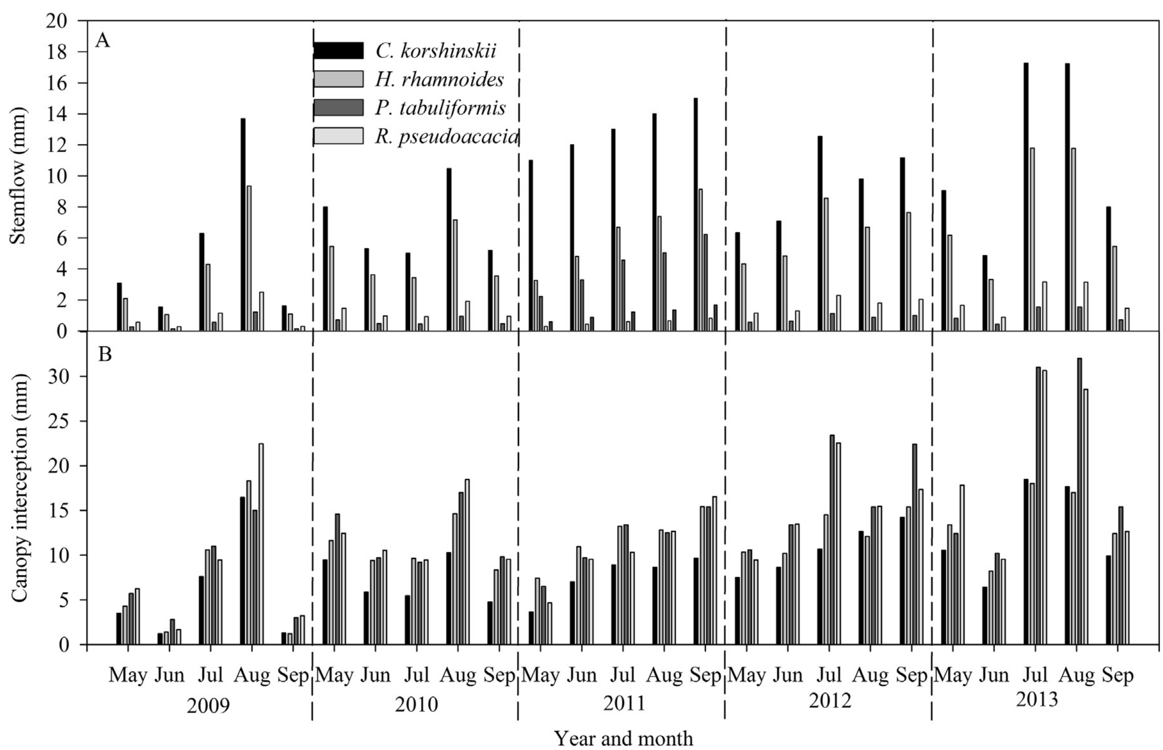

Fig. 3. Monthly changes in stemflow (A) and canopy interception (B) of *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis* and *R. pseudoacacia* from May to September in the period of 2009–2013.

3.3. Soil evaporation

Soil evaporation ranged within 0.06–3.49, 0.03–3.58, 0.05–2.76, and 0.29–1.84 mm per day from May to September of 2009–2013 for *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia*, respectively (Fig. 4). The mean annual soil evaporation values for the five-year study period were 256.48 ± 25.09, 225.84 ± 39.63, 179.69 ± 40.76, and 169.19 ± 27.42 mm for *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia*, respectively. August exhibited the largest soil evaporation during the study period,

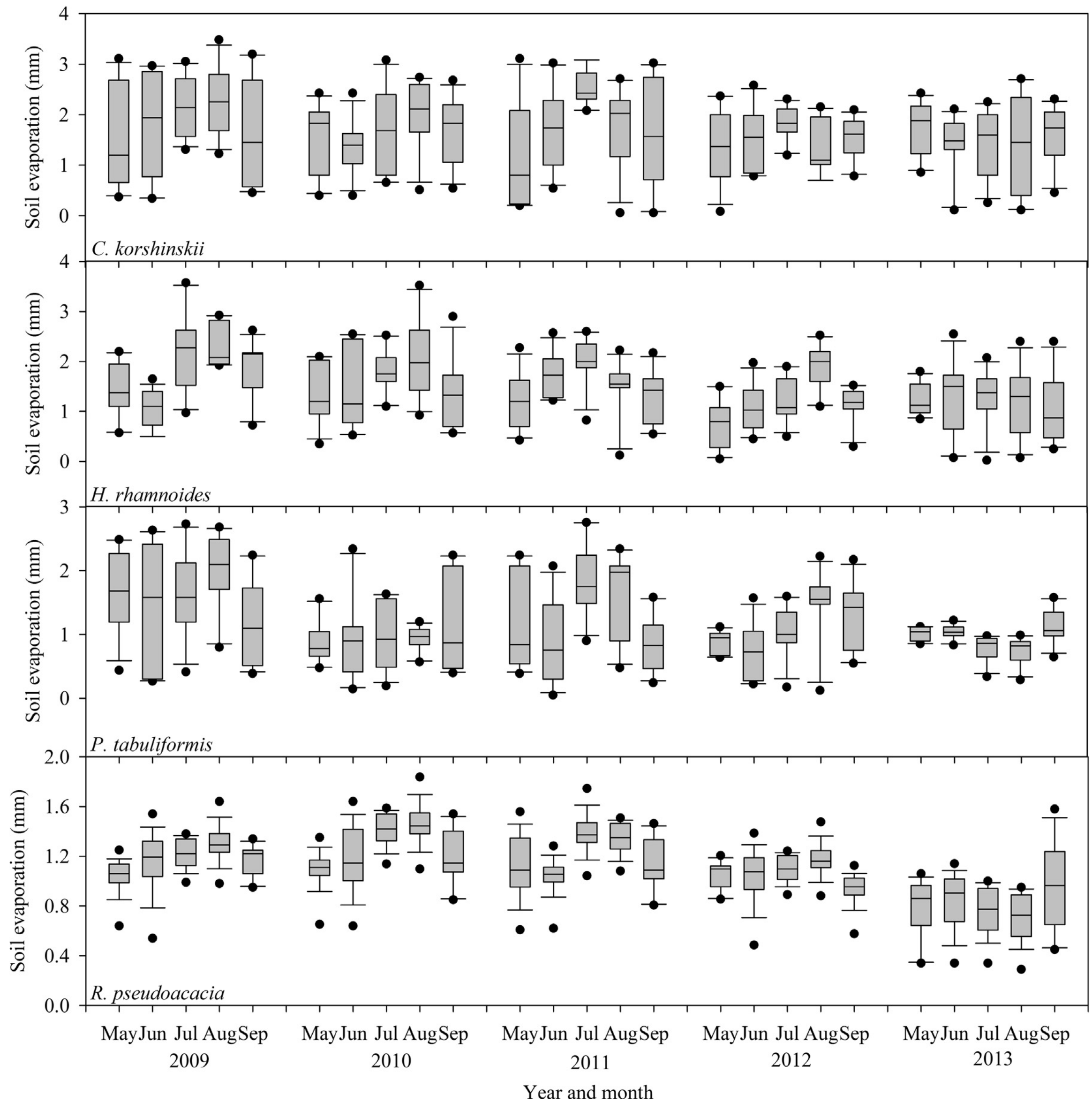

Fig. 4. Box plots for mean daily site micro-lysimeters soil evaporation from May to September in the period of 2009–2013.

followed by July, September, May, and June for the four species. The daily soil evaporation was highly linearly correlated with *Q* (R^2 = 0.91, 0.89, 0.82, and 0.88) and *V* (R^2 = 0.90, 0.85, 0.92, and 0.82) for *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia*, respectively.

3.4. Plant transpiration

The transpiration over the study period had annual mean values of 223.21 ± 12.27, 295.06 ± 20.84, 188.57 ± 7.74, and 167.81 ± 7.42 mm, ranging within 0.12–3.95, 0.29–4.38, 0.05–3.32, and 0.2–3.04 mm day^{-1} for *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia*, respectively. Cumulative transpiration occupied 70.50%, 93.19%, 59.56%, and 53.00% of annual mean rainfall during this period for *C. korshinskii*, *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia*, respectively. The transpiration increased in the beginning and then decreased from May to September of 2009–2013 (Fig. 5).

Low actual evapotranspiration (ET)/E_p ratio values were found for all land cover types, typical of semi-arid regions (Fig. 6). Monthly variability was observed (Fig. 6), and the peak value appeared in August of 2013 and the lowest value in June of 2009. For instance, the ET/E_p ratio for *C. korshinskii* was 0.320 in August of 2009, and a sharp decrease appeared in September of 2009 (0.159). Among all land covers, the ET/E_p ratios followed the order (from highest to lowest) *C. korshinskii* > *R. pseudoacacia* > *H. rhamnoides* > *P. tabuliformis*. When the monthly rainfall amount was less than 50 mm, *H. rhamnoides* had the lowest ET/E_p ratio among the four land cover types, but high ET/E_p ratio was observed in *H. rhamnoides* with larger rainfall amount (>70 mm).

3.5. Runoff

Among the land cover types, *P. tabuliformis* produced the largest surface runoff (87.13 mm), followed by *H. rhamnoides* (72.2 mm), *R. pseudoacacia* (64.3 mm), and *C. korshinskii* (55.7 mm) throughout the 5 years (Fig. 7). High runoff frequency appeared in July and August, and most rainfall events did not generate runoff in three other months.

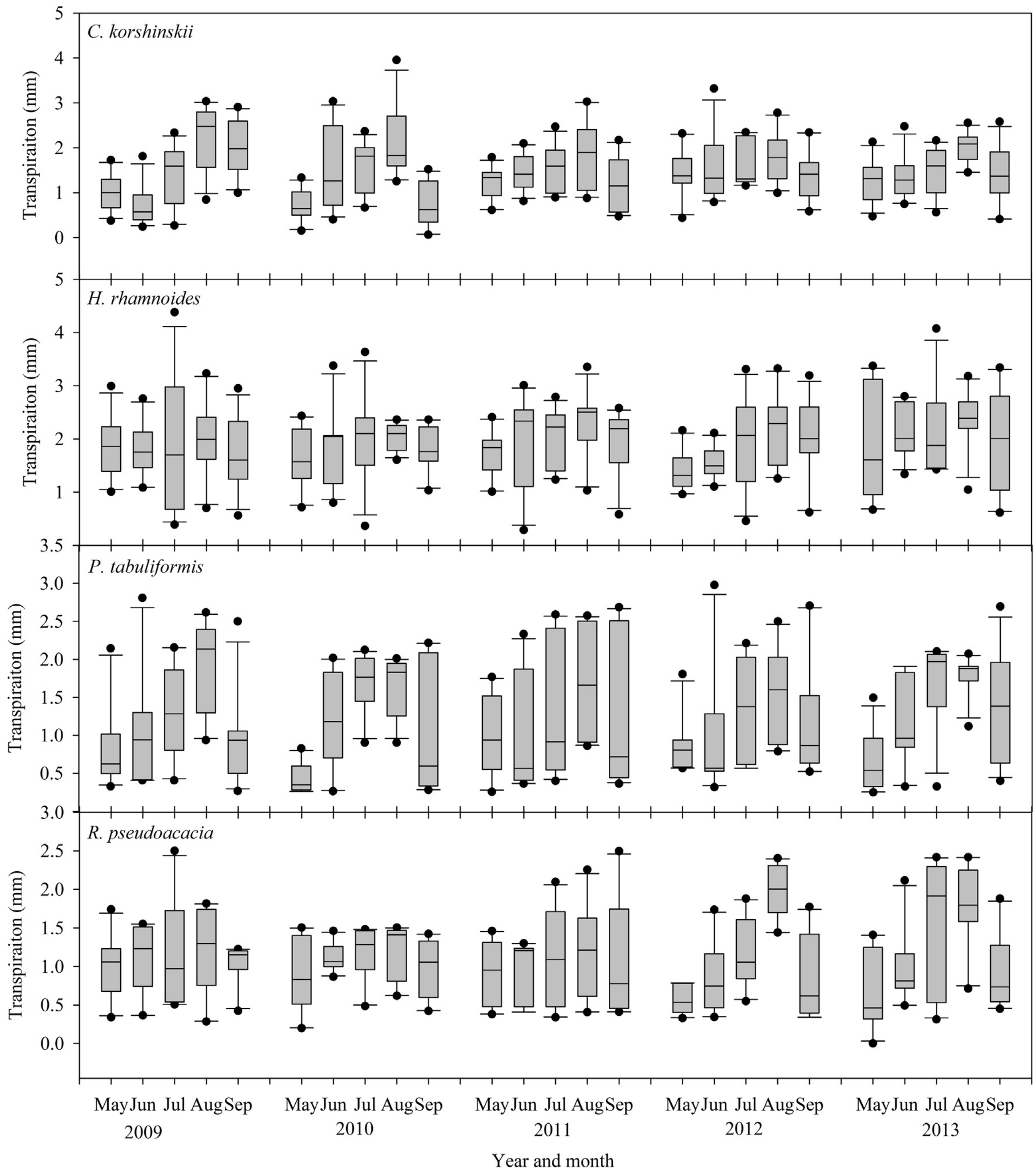

Fig. 5. Box plots for mean daily transpiration for the four species from May to September in the period of 2009–2013.

3.6. Water balance

The daily soil water content in the different land cover types during the growing season was calculated using the water balance Eq. (1), and the results are presented in Table 2. The net soil water storage (ΔSW) was negative in most months from May to September of 2009–2013. Water loss exceeded precipitation in these months, which is notable in this semiarid climate. *P. tabuliformis* and *R. pseudoacacia* had a soil water surplus in 2013, but not the other land cover types (Table 2). Water replenishment in the soil usually occurs from the end of autumn to the end of spring in the Anjiapo catchment (Fig. 8). In general, a decrease trend was found for all land cover types from 2009 to 2013 (Fig. 8). Land cover examination showed that the slope of the decline trend of the soil water storage for *C. korshinskii* was much lower than that of the other land cover types. However, *P. tabuliformis* had the largest decline slope among the four land cover types (Fig. 8).

4. Discussion

4.1. Validity of hydrological budgets

High rainfall interception was found among the four land cover types. The average interception loss in *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia* was greater than 20% of the annual rainfall (Fig. 3). High rainfall interception by forest canopies is frequently associated with high LAI (Carlyle-Moses and Price, 2006). Zimmermann et al. (2007) found that high evaporation rates of intercepted rainfall from tall trees lead to low throughfall. This hypothesis depends on long canopies with greater “roughness”

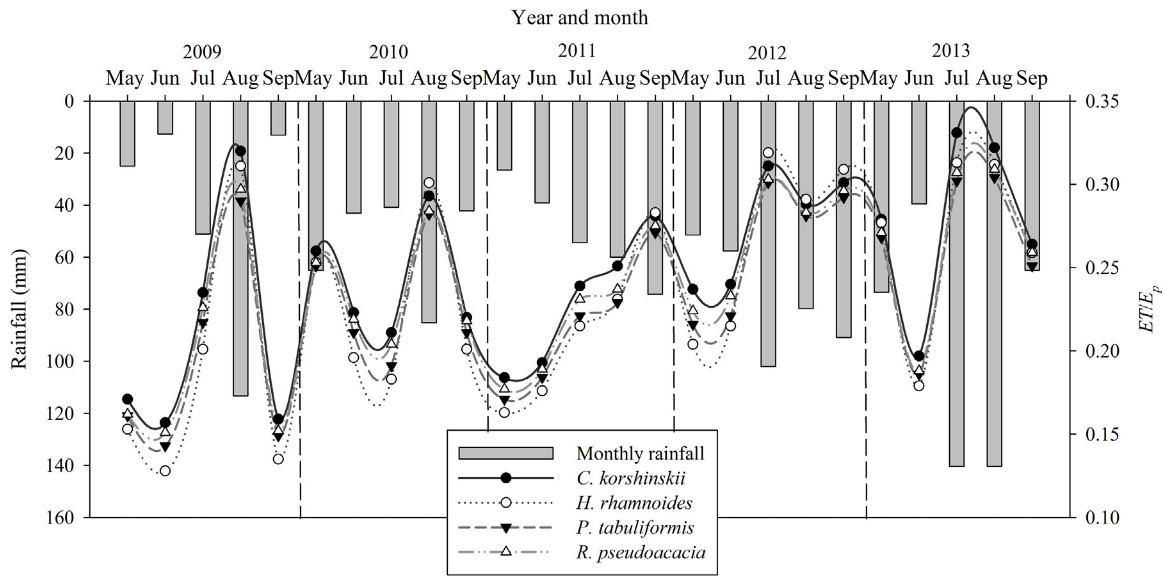

Fig. 6. Variation ET/E_p ratio of different land cover types from May to September in the period of 2009–2013. ET is the actual evapotranspiration (soil evaporation + plant transpiration).

(Raat et al., 2002) than short ones. In this case, high evaporation would be the product of the high rates of turbulent exchange with the atmosphere in tall canopies relative to short trees with similar LAI. Stemflow can be an important source of soil moisture in arid and semi-arid lands (Tromble, 1987). Mauchamp and Janeau (1993) reported that *Flourensia cernua* is capable of channeling approximately 50% of the incident gross precipitation to the plant stem. Navar and Bryan (1990) calculated that the stemflow inputs to the soil area around three semi-arid shrub stems in northeastern Mexico represent a water input that is five times that received by other areas below the canopies. The relatively high efficiency of *C. korshinskii* in producing stemflow (Fig. 3) is most probably a consequence of the smooth bark associated with this species. *C. korshinskii* is a thorny shrub with small strip- or linear-shaped leaves and wax layers on the twigs, branches, and leaves, forming a smooth "funnel" to channel stemflow. Rough barked tree species similar to most conifers and a few hardwood species have low stemflow amounts (André et al., 2008).

C. korshinskii showed the largest soil evaporation, followed by *H. rhamnoides*, *P. tabuliformis*, and *R. pseudoacacia* and had the lowest LAI (Figs. 2 and 4). The large soil evaporation in the plots with low LAIs may be contributed to several factors. Soil evaporation occurs in two stages: (1) the constant rate stage controlled by energy input as influenced by light penetration through the canopy, atmospheric turbulence, and soil albedo, and (2) the falling rate stage controlled by overall soil moisture and hydraulics (Suleimann and Ritchie, 2003). As such, direct evaporation from soil is generally constrained to the upper soil layers (Suleimann and Ritchie, 2003) and is highest in open sites because the shade from overstory canopy cover and forest floor litter reduces light penetration (Morecroft et al., 1998) and soil temperature (Scholes and Archer, 1997). *C. korshinskii* with low LAI increases light penetration to the floor (Suleimann

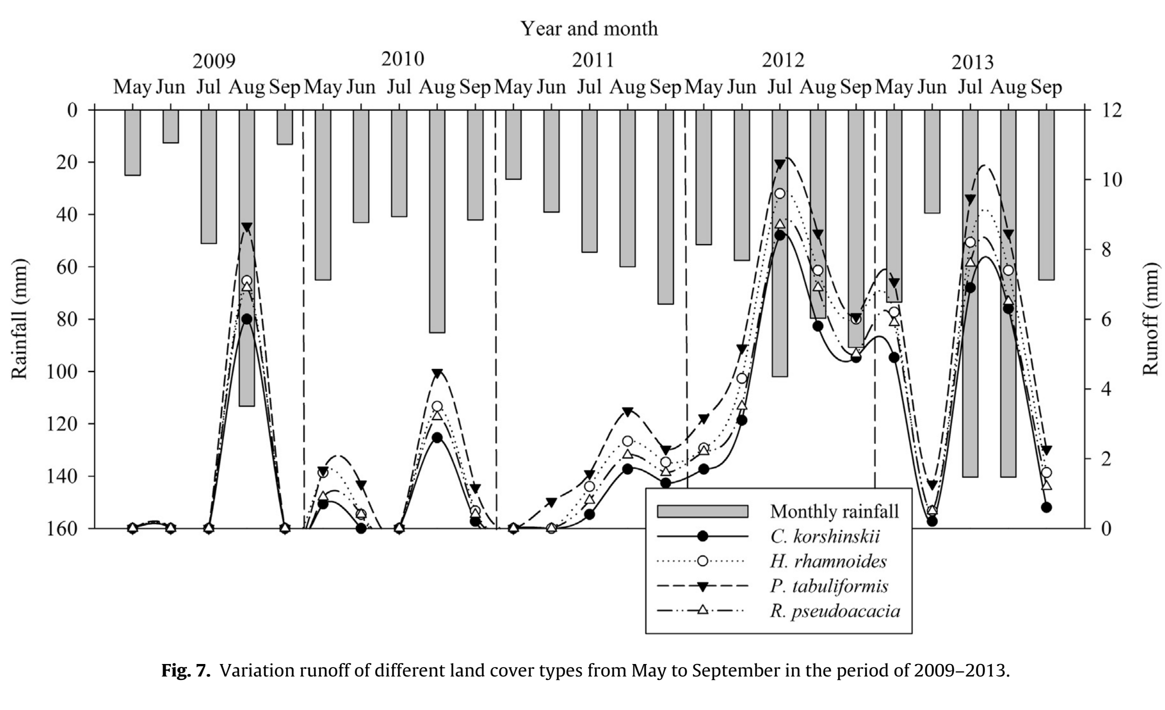

Fig. 7. Variation runoff of different land cover types from May to September in the period of 2009–2013.

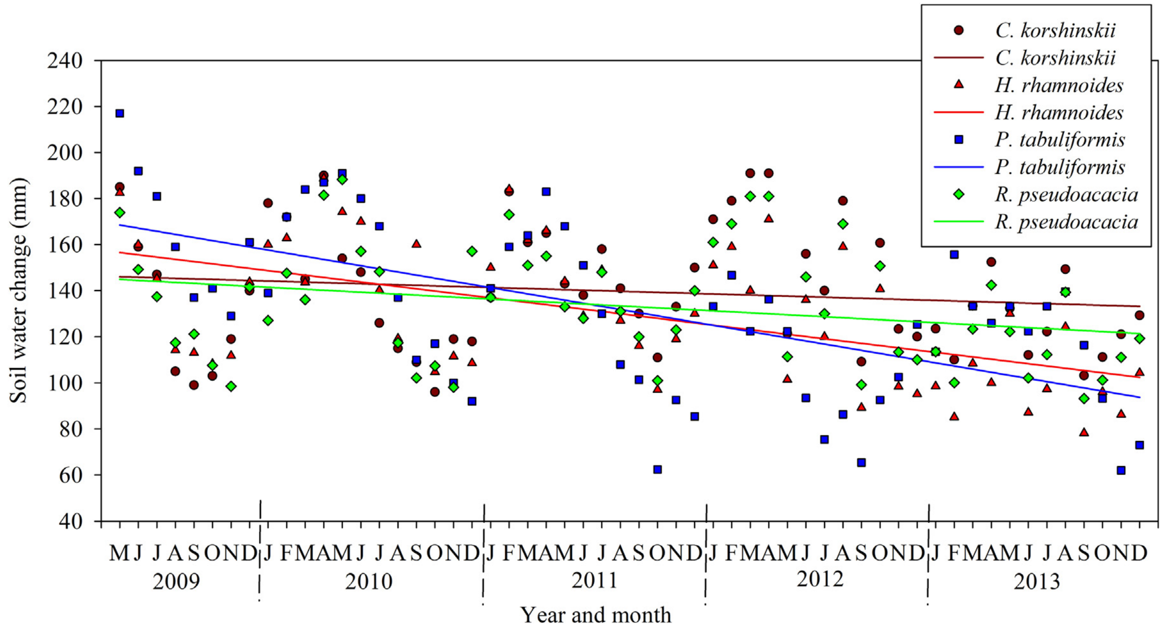

Fig. 8. Soil water variations from May to September in the period of 2009–2013. The change trend is in significant level when the R^2 is bigger than 0.503 when the number is 56. *P. tabuliformis*, *H. rhamnoides*, *R. pseudoacacia* and *C. korshinskii*, $P < 0.05$.

and Ritchie, 2003), resulting in high soil temperature (Scholes and Archer, 1997) and increased throughfall precipitation (this study); these findings contribute to significant potential soil evaporation. A study on stand water balance in a ponderosa pine plantation in California (Kurpius et al., 2003), where soil evaporation accounted for approximately 50% of stand evaporation during summer and fall, supports our interpretation that low LAI increases the evaporation of soil water.

The imbalance between water supply and water demand was particularly acute in *C. korshinskii* plantation (Table 2). During the experimental period, soil water replenishment by rainfall cannot meet the demand for water use in this area. Although transpiration is frequently restricted by soil water availability in the upper soil profile, the *C. korshinskii* shrub could still meet its evaporative demand because of its deep and developed rooting systems. Our previous study reported the root distribution patterns of *C. korshinskii* in the same area (Jian et al., 2014). The roots can reach as deep as 2.8 m. The majority of absorbing roots are concentrated in the upper 1.0 m of soil (Jian et al., 2014). Root water uptake from the deep and moist soil layer as well as transport to the dry upper soil layer are carried out at night. This phenomenon is important in arid and semi-arid areas (Gao et al., 2011).

P. tabuliformis had greater surface runoff than the other three land cover types, although it had the highest LAI values. This finding is surprising because *P. tabuliformis* is considered a major species for soil erosion control through reducing surface runoff in the study region. The large runoff is attributed to soil compaction and lack of understory in the *P. tabuliformis* stands (Chen et al., 2007). By contrast, the low surface runoff of shrub lands had good ground coverage, low soil bulk density, and high infiltration rates (Table 1). These results also agreed with other studies. For example, Chen et al. (2008) reported that the favorable conditions for runoff and erosion under a eucalyptus forest are related to the prevailing bare soil conditions caused by decreased understory vegetation. A positive relationship was found between soil bulk density and surface runoff (Gutierrez and Hernandez, 1996). High soil bulk density is usually observed with low infiltration rates and high runoff depths (Descheemaeker et al., 2006). Shrub lands had better soil water conservation than *P. tabuliformis* woodland because of the lower soil bulk density and better understory.

4.2. Effect of land cover on soil water variation

Land cover types had different effects on soil water dynamics. However, in the current study, no significant difference was found among the land cover types (Table 2). Other studies also showed different results in the other areas of the Loess Plateau. Liu and Huang (2002) reported that soil water decreases with apple trees growing at 0–10 m depth. Wang et al. (2011) found that native species have higher soil moisture than exotic species, and vegetation restoration may result in soil desiccation in the Loess Plateau. The difference between our studies and the above mentioned studies may be due to the difference in rainfall. In our studies, the annual rainfall was almost all used by evapotranspiration, and only a small amount was used for soil water recharge during the growing season. However, other studies that focused on the Loess Plateau with more rainfall show differences in evapotranspiration among different land cover types.

Except for *C. korshinskii*, soil water was not appropriately replenished for the other land uses from May to September of 2009–2013 (Fig. 8). The soil water for *P. tabuliformis* woodlands had a clear declining trend during the experimental period because of the high LAI of *P. tabuliformis* (Fig. 2 and Table 1), which were associated with more evapotranspiration and reduced soil water infiltration by canopy interception. Large evapotranspiration combined with small soil water infiltration could give rise to soil desiccation (Guo and Shao, 2004). These observations support the results of Guo and Shao (2009), which showed that dry soil layers can be formed in *P. tabuliformis* plantations. The soil water in the *C. korshinskii* plantation at the beginning of the growing season was nearly balanced. Planting *P. tabuliformis* was not considered suitable for the Loess Plateau. Wei et al. (2007) found that soil water is higher at the early stage of tree plantation than that in the late stage. Zheng et al. (2008) also reported that soil desiccation was developed under a 28-year-old tree plantation; however, good soil moisture was often observed under natural forests or grasslands. In our study, all land uses exhibited poor soil water condition during the growing seasons.

A comparison of the land cover types shows that *P. tabuliformis* plantations had low ET/E_p ratio, which is attributed to soil compaction. This finding is different from the other studies conducted in

Table 2
Soil water change (ΔSW), canopy interception (*I*), soil evaporation (*E*), transpiration (*T*), surface runoff (*R*) and rainfall (*P*) for different land cover types from May to September in the period of 2009–2013. Unit: millimeter.

	C. korshinskii						*H. rhamnoides*					*P. tabuliformis*					*R. pseudoacacia*				
	P	*I*	*E*	*T*	*R*	ΔSW	*I*	*E*	*T*	*R*	ΔSW	*I*	*E*	*T*	*R*	ΔSW	*I*	*E*	*T*	*R*	ΔSW
2009 May	25	3.51	37.15	31.15	0	−46.81	4.3	43.77	55.62	0	−78.69	5.7	49.22	25.39	0	−55.32	6.2	31.	29.4	0	−41.86
Jun	12.6	1.21	43.34	21.75	0	−53.7	1.4	32.34	52.73	0	−73.87	2.8	43.72	32.06	0	−65.98	1.6	34.7	33.1	0	−56.98
Jul	51.1	7.6	45.56	42.55	0	−44.61	10.6	65.65	54.15	0	−79.31	11	49.89	40.51	0	−50.31	9.5	36.5	33.9	0	−28.89
Aug	113.3	16.45	46.31	47.31	6	3.23	18.3	50.34	49.34	7.1	−11.78	15	59.26	56.13	8.6	−17.08	22.4	38.9	36.0	6.9	8.96
Sep	13.1	1.3	40.04	37.71	0	−65.95	1.2	34.65	39.46	0	−62.21	3	37.46	27.84	0	−55.19	3.2	35	31.2	0	−56.5
2010 May	65	9.45	48.54	21.81	0.7	−14.8	11.64	40.84	49.44	1.6	−38.53	14.6	26.79	12.7	1.6	10.94	12.4	33	26.1	0.9	−7.56
Jun	43.1	5.88	41.37	45.17	0	−49.32	9.4	44.18	45.46	0.4	−56.34	9.7	28.67	36.03	1.2	−31.3	10.5	35.4	33.7	0.4	−37.08
Jul	40.8	5.46	47.52	41.22	0	−53.4	9.64	53.79	49.13	0	−71.77	9.2	28.74	50.42	0	−47.55	9.5	42.4	35.2	0	−46.31
Aug	85.2	10.26	50.24	55.53	2.6	−30.83	14.62	43.33	50.06	3.5	−26.31	17	27.84	49.8	4.4	−9.45	18.4	43.5	35.7	3.2	−15.75
Sep	42.1	4.76	49.24	22.73	0.2	−34.63	8.34	40.15	53.86	0.5	−60.75	9.8	38.19	34.79	1.1	−40.69	9.5	36	29.4	0.4	−33.35
2011 May	26.5	3.65	32.65	37.09	0	−46.89	7.42	37.09	34.78	0	−52.79	6.5	35.89	28.77	0	−44.67	4.6	33.7	27.5	0	−39.39
Jun	39.1	7	45.34	39.13	0	−52.73	10.95	52.23	43.36	0	−67.44	9.7	25.83	28.47	0.7	−24.89	9.5	31.3	29.1	0	−30.96
Jul	54.4	8.91	5.98	45.62	0.4	−6.1	13.22	51.46	53.16	1.2	−64.64	13.4	55.48	39.22	1.5	−53.7	10.3	41.3	33.6	0.8	−31.8
Aug	60	8.64	52.75	49.12	1.7	−50.51	12.8	43.7	59.33	2.5	−58.33	12.5	47.94	49.93	3.3	−50.37	12.6	40.3	34.8	2.1	−29.92
Sep	74.2	9.64	49.09	36.59	1.3	−21.12	15.41	38.66	1.9	1.9	−40.67	15.4	25.5	38.72	2.1	−5.42	16.5	34.2	32.7	1.6	−10.88
2012 May	51.5	7.49	39.58	42.16	1.7	−37.73	10.34	23.11	41.12	2.3	−25.38	10.6	26.65	26.55	3.1	−12.29	9.4	31.5	17	2.2	−8.8
Jun	57.6	8.64	46.01	46.17	3.1	−43.22	10.2	31.70	46.8	4.3	−35.41	13.4	22.23	31	5.2	−9.03	13.5	31.2	25	3.5	−15.65
Jul	102	10.67	55.48	48.45	8.4	−12.6	14.5	36.68	59.12	9.6	−17.91	23.4	32.11	38.21	10	8.27	22.5	32.9	35.4	8.7	−2.37
Aug	79.7	12.64	42.04	52.8	5.8	−27.78	12.1	47.33	67.37	7.4	−54.50	15.4	43.7	46.06	8.4	−25.46	15.4	35.0	59.2	6.9	−36.96
Sep	90.8	14.21	40.06	42.13	4.9	−5.6	15.4	33.48	54.44	6	−18.52	22.4	38.66	35.67	6	−5.93	17.3	28.0	25.3	5	15.01
2013 May	73.5	10.54	51.27	37.51	4.9	−25.83	13.4	37.43	48.12	6.2	−31.65	12.4	30.49	18.85	7	11.76	17.8	23.5	19.5	5.9	6.66
Jun	39.5	6.41	41.92	39.68	0.2	−48.51	8.21	36.41	46.34	0.5	−52	10.2	31.42	35.05	1.3	−37.17	9.5	25.3	29.1	0.5	−25.05
Jul	140.4	18.45	41.22	44.23	6.9	36.49	18.	39.48	57.47	8.2	17.25	31	23.07	48.93	9.5	37.39	30.6	23.1	46.5	7.6	32.47
Aug	140.4	17.64	45.09	59.15	6.3	18.56	17	34.57	55.1	7.4	26.33	32	22.06	53.88	8.4	32.46	28.5	21.6	54.1	6.5	29.53
Sep	65	9.9	46.99	40.69	0.6	−32.57	12.41	32.8	46.24	1.6	−28.05	15.4	34.18	40.38	2.3	−24.97	12.6	28.6	27.2	1.2	−4.67

humid regions, where the soil bulk density significantly decreases after vegetation restoration along with the increase in soil porosity, saturated hydraulic conductivity, aggregate stability, and water-holding capacity (Huang et al., 2011). However, in the semi-arid Loess Plateau, the soil bulk density increases with trees growing under *P. tabuliformis* plantations (Chen et al., 2008). Consequently, limited rainfall infiltrated into the soil to supply deep soil water, thereby producing much more runoff. The results also indicate that rainfall had a strong effect on the ET/E_p ratio in *H. rhamnoides* plantation; hence, *H. rhamnoides* is suitable for afforestation in areas with high levels of rainfall.

5. Conclusions

Precipitation is considered the only water source to replenish soil water in the Anjiapo catchment. However, the current study showed that such replenishment was insufficient, and soil water deficits frequently occur from May to September of 2009–2013. This finding was attributed to low rainfall, strong plant evapotranspiration, and surface runoff, especially for the *P. tabuliformis* plantation. *P. tabuliformis* plantation produced the largest surface runoff among the studied species. *P. tabuliformis* plantations may be conducive to soil conservation, but it compounded soil compaction and desiccation, thereby resulting in landscape degradation. The soil water for *P. tabuliformis* woodlands also showed a clear declining trend during the experimental period because of the high LAI of *P. tabuliformis*, which were associated with more evapotranspiration and reduced soil water infiltration by canopy interception. Large evapotranspiration combined with small soil water infiltration could give rise to soil desiccation. An extremely low ET/E_p ratio in the growing seasons was found for all land cover types, especially for *P. tabuliformis* woodlands in our study. Therefore, *P. tabuliformis* plantation should not be the first choice for vegetation restoration in a semi-arid loess hilly area. *H. rhamnoides* is suitable for afforestation in areas with high levels of rainfall. *C. korshinskii* and *R. pseudoacacia* are highly recommended for vegetation restoration.

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