



Response of soil moisture to landscape restoration in the hilly and gully region of the Loess Plateau, China

Xueli Zhang¹ · Guodong Zhang² · Caihong Hu¹ · Jianhua Ping¹ · Shengqi Jian¹

Received: 24 April 2019 / Accepted: 8 May 2020 / Published online: 2 June 2020
© Plant Science and Biodiversity Centre, Slovak Academy of Sciences 2020

Abstract

Vegetation restoration was conducted by the Chinese government over the past decades to reduce soil and water loss on the Chinese Loess Plateau. However, vegetation restoration was very blind in plant species selection and had no guidance. Field measurements were conducted from 2009 to 2014 to analyze the influence of land-use conversions from croplands to pastures, native grasslands and planted trees, shrubs and on runoff, soil water dynamics and water stresses in the semi-arid loess hilly area. Our research has led to the following major findings: (1) The soil water stored decreased from 2009 to 2014 among all land cover types. The soil water replenishment by rainfall during rainy seasons was not sufficient to fully recharge the soil water storage. Vegetation restoration by shrub could retain more soil water than other land cover types; (2) The ratio of ET/P (evapotranspiration/precipitation) ranked from high to low was Grassland (1.31) > Shrubland (1.29) > Cropland (1.28) > Alfalfa (1.26) > Woodland (1.20). The ET/P ratio of the pine plantation was the lowest among the five land cover types; (3) Woodlands and shrublands showed the higher infiltration rates and the wetting fronts of croplands and shrublands could reach greater depths than woodland and grassland.

Keywords Infiltration · Landscape restoration · Loess plateau · Soil moisture

Introduction

Soil water content is a key component of the terrestrial system and plays an integrative role in surface hydrological processes, especially in semi-arid areas (Chen et al. 2008; Legates et al. 2011). In such regions, hydrologic viability is considered to be the most important driver of the productivity and sustainability of terrestrial ecosystems (Porporato et al. 2002; Mishra and Singh 2010; Jin et al. 2011).

In arid and semi-arid regions, vegetation restoration is largely controlled by soil water availability (Legates et al. 2011). Plants have strong effects on ecosystem water balances through their contrasting capacity to access, transport, and transpire soil moisture (Qiu et al. 2011). Precipitation is among the most important factors that determine the

occurrence and diversity of species (Benito et al. 2019). 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. 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 (Wang et al. 2008), 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. 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 (Wang et al. 2012).

The Chinese Loess Plateau is facing the severe soil erosion (Han et al. 2009). Vegetation restoration practices had been conducted by Chinese government in order to slow down water and soil losses. The traditional steep slopes farmlands were converted to pasture grasslands, shrublands, and forestlands. The afforestation species are mainly nonnative plants

✉ Shengqi Jian
jiansq@zzu.edu.cn

¹ College of Water Conservancy & Environment, Zhengzhou University, Science road 100, Zhengzhou, China

² Henan Yellow River Hydrological Survey and Design Institute, Chengdong road 100, Zhengzhou, China

that consume more water than no afforestation (Sun et al. 2006; McVicar et al. 2010; Cao et al. 2011). The average annual rainfall ranges from 300 to 650 mm (Chen et al. 2008), the average annual pan evaporation is 1669 mm (Xie and Wang 2007), resulting in a low soil moisture content, which is unable to meet the growth needs of the afforestation species in Loess Plateau (Yang and Tian 2004). Thus, in order to ensure the sustainable provision of ecosystem services, we require a detailed understanding of the eco-hydrological processes in the Loess Plateau. The rainfall patterns of the Loess Plateau are characterized by high intensity rainfall (Liu et al. 2012) with a high runoff ratio and low soil moisture input. Thus, the rainwater infiltration and storage capacity of a soil are important to determine the amount of runoff and soil water storage for plant production (Jones et al. 2002; Wang et al. 2008). Data on the infiltration processes and the effects of cumulative infiltration on different land covers remain scarce. In addition, research indicates that reforestation has a low survival rate (Cao et al. 2011; Jiao et al. 2011). Therefore, additional long-term assessments of vegetation variation are urgently needed to implement a more effective restoration policy.

This study focused on a small catchment in the western Chinese Loess Plateau to test the effects on soil moisture of Chinese pine (*Pinus tabulaeformis* Carr.), korshinsk peashrub (*Caragana korshinskii* Kom.), spring wheat (*Triticum aestivum* L.), Purple alfalfa (*Medicago sativa* L.) and semi-natural grassland (*Stipa breviflora* Griseb. and *Stipa bungeana* Trin.). The aims of this study were to examine (1) the infiltration processes by time series soil moisture content measurements under heavy rainfall and to compare the effects of different soil moisture inputs as a result of the five typical plant species and (2) how soil moisture storage changes among different land covers in a long term.

Materials and methods

Study area

Fieldwork was performed from 2009 to 2014 in the Anjiapo catchment of the western Chinese Loess Plateau (Fig. 1). The area has an average annual precipitation of 420 mm, 60% of which occurs between July and September. The monthly average air temperature varies from -7.4 to 27.5 °C, and the annual mean temperature is 6.3 °C. The average annual evaporation is 1510 mm. The soil belongs to the *Calcic Cambisol* group based on the FAO–UNESCO soil classification system (Chen et al. 2008). It has developed on loess parent material and has a relatively thick profile. The soil in the study area is derived mainly from loess and has a depth of 50–200 m depending on the topography. The loess in this area usually has a composition of more than 50% silt (0.002–0.05 mm) and less

than 20% clay (< 0.002 mm), and a porosity of approximately 50%. The gravimetric field capacity and wilting percentage of soil moisture are 20–24% and 3–6%, respectively (Wang et al. 2010).

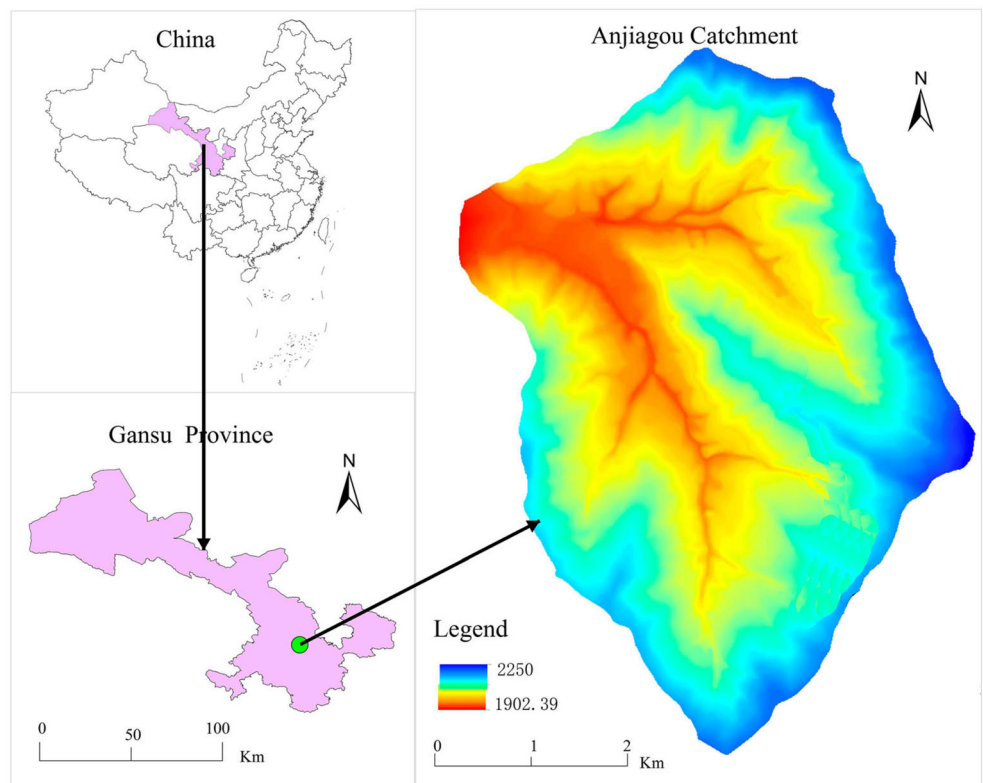
Vegetation restoration has been widely conducted in the area since the late 1970s. Purple alfalfa (*Medicago sativa* L.), Chinese pine (*Pinus tabulaeformis* Carr.), False Acacia (*Robinia pseudoacacia* Linn.), korshinsk peashrub (*Caragana korshinskii* Kom.) and sea buckthorn (*Hipporhae rhamnoides* Linn.) were planted. These species were also used in the Grain-for-Green project, which began in 1998, the Chinese government implemented the project to improve the natural ecosystems in the Loess Plateau region. This project aimed at vegetation recovery due its crucial role in soil conservation (Wei et al. 2007). At present, the study area has arable land, abandoned cropland, alfalfa, semi-natural grassland, shrubland and woodland. The major crops are spring wheat (*Triticum aestivum* L.), soybeans (*Glycine max* Linn.), potatoes (*Solanum tuberosum* L.), millet (*Panicum miliaceum*) and sorghum (*Sorghum bicolor* L.). The major grasses include *S. breviflora* and *S. bungeana*.

Experimental design

Fifteen experimental plots were constructed on hillslopes with similar positions, aspects, and slopes where rainfed crops (i.e., winter wheat and potatoes) were grown previously. The sizes of plots were same, 10×10 m. Each plot was constructed with a cement ridge 30 cm above the ground around the borders, and an H-flume was used to measure surface runoff. The runoff automatic monitors (JZ-NB1700, Jiuzhou, China) were installed for each plot at the top of the H-flume (Fig. 2). For each land cover type, three replications were used (Table 1).

- (1) Cropland: Crops (*T. aestivum*) were sown in April since 1986 with a 15 cm row spacing and were harvested at the end of July. Then a fallow period followed from August to March of the next year. No chemical fertilizer or manure was used.
- (2) Alfalfa: Purple alfalfa (*M. sativa*) was sown in April since 1986 at a rate of 11 kg ha^{-1} , and was harvested for livestock. In rainfall-limited years, alfalfa was harvested only once because of its poor growth, whereas it could be cut twice in years with high rainfall. After 7-years growth, the alfalfa was resown annually.
- (3) Shrubland: Korshinsk peashrub (*C. korshinskii*) saplings were planted at a spacing of 1.0×1.0 m in March 1986. At stand maturation, the shrub (*C. korshinskii*), dense grasses (*Stipa breviflora* Griseb. and *Stipa bungeana* Trin.) and thick litter provided a closed cover.
- (4) Woodland: Chinese pine (*P. tabulaeformis*) was planted at a spacing of 3.0×1.5 m in March 1986. The litter was

Fig. 1 Location of the study area



removed by local farmers for daily heating. No grasses or bushes were observed on the ground.

- (5) Semi-natural grassland: As a dominant native species, *S. bungeana* was sown in March 1986, and the plots were derelict land and retained free from human disturbance.

Volumetric soil moisture was determined using EC-5 sensors (Decagon Devices Inc., Pullman, WA, USA) which were installed at depths of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60,



Fig. 2 Schematic diagram of runoff automatic monitor

70, 80, 90, 100, 120, 140, 160, 180, and 200 cm. We installed the probes in April 2008 (the stabilization period exceed one year). This type of soil moisture sensor is capable of measuring volumetric saturation values between 0% and 100%, with an accuracy of $\pm 1.0\%$ and a resolution of 0.1%.

The surface runoff of each plot was collected from May to September of 2009–2014. The collectors were cleaned after each measurement.

A meteorological tower was installed at the study site (2 m and 3 m above the ground). The meteorological variables recorded 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 2014.

Water balances

The change in soil water content in the growing seasons (ΔSW) was calculated as:

$$\Delta SW = SW_E - SW_B \tag{1}$$

where ΔSW is the change in soil water content in the 0–200 cm layer (mm), SW_B is the soil water content measured at the beginning of each month (mm), and SW_E is the soil water content measured at the end of each month (mm). Soil

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

	Parameter	Sample numbers	Mean ± SD				
			<i>P. tabuliformis</i>	<i>T. aestivum</i>	<i>C. korshinskii</i>	<i>M. sativa</i>	<i>S. bungeana</i>
Biological parameters	Plant height (m)	160	11.42 ± 3.63	0.71 ± 0.16	1.70 ± 11	0.65 ± 0.11	0.66 ± 0.25
	DBH/BD (cm)	200/160	20.11 ± 4.72	–	1.51 ± 0.21	–	–
	Projected area (m ²)	160	17.66 ± 5.29	--	3.02 ± 0.44	--	--
	Cover (%)	50	87 ± 3	68 ± 5	65 ± 5	91 ± 4	74 ± 6
Soil parameters	Clay (< 0.002 mm; %)	15	9.45 ± 2.31	10.22 ± 1.46	9.17 ± 1.20	11.04 ± 2.30	9.44 ± 1.54
	Silt (0.05–0.002 mm; %)	15	75.46 ± 10.03	77.36 ± 10.24	75.59 ± 9.21	76.69 ± 11.34	76.53 ± 8.31
	Sand (0.05–2 mm; %)	15	15.09 ± 1.15	12.42 ± 2.06	15.24 ± 1.16	12.27 ± 2.81	14.03 ± 1.52
	Organic matter (%)	15	0.68 ± 0.09	0.74 ± 0.07	0.95 ± 0.08	0.71 ± 0.04	0.81 ± 0.06
	pH	15	8.20 ± 0.30	8.10 ± 0.50	8.10 ± 0.90	7.90 ± 0.70	7.90 ± 0.60
	Soil bulk density (g cm ⁻³)						1.22
	0–20 cm	15	1.35 ± 0.09	1.38 ± 0.16	1.13 ± 0.08	1.29 ± 0.20	1.24 ± 0.19
	20–40 cm	15	1.37 ± 0.12	1.32 ± 0.18	1.15 ± 0.13	1.20 ± 0.21	1.25 ± 0.12
	40–60 cm	15	1.29 ± 0.16	1.36 ± 0.16	1.17 ± 0.15	1.23 ± 0.19	1.23 ± 0.18
	60–80 cm	15	1.27 ± 0.12	1.29 ± 0.15	1.19 ± 0.14	1.25 ± 0.23	1.21 ± 0.21
80–100 cm	15	1.31 ± 0.14	1.28 ± 0.24	1.10 ± 0.11	1.26 ± 0.18	1.25 ± 0.17	

Each parameter was measured from 2009 to 2014. DBH is the diameter at breast height for trees; DB is the basic diameter for shrubs; Projected area is the area surrounded by a shadow outline

water storage was calculated by volume water content multiplied by soil depth.

The Chinese Loess Plateau is characterized by rare rainfall, high rainfall intensity, low vegetation coverage, and the depth of vadose zone is over hundred meters, belonging to infiltration-excess (Hortonian) overland flow region. There is almost no subsurface runoff (Gao et al. 2018). The total annual surface runoff of each land cover type was determined by averaging the runoff of the three plots for each land cover.

The actual evapotranspiration (*ET*) for each plot was calculated using rainfall (*P*), runoff and the changes in soil water:

$$ET = P - Q - \Delta SW \quad (2)$$

Ecosystem water stress was introduced by comparing evapotranspiration (*ET*) with rainfall (*P*). *ET/P* was used to express water use efficiency, a low water use efficiency is indicated by a low *ET/P* ratio.

Data analysis

Data on the soil moisture of these five land cover types were analyzed using SPSS for Windows 18.0. One-way ANOVA was performed, after verifying the assumptions of normality and homogeneity of variances, to test the effects of land cover types on soil moisture.

Multicollinearity was addressed. Based on the soil water balance principle, the cumulative infiltration of each rainfall event could thus be described as:

$$I = (S_e - S_b) \times Z_f \quad (3)$$

where *I* is the cumulative infiltration (mm); *S_b* is the soil moisture (%) in the beginning of each rainfall event; *S_e* is the soil moisture (%) at the end of each rainfall event; and *Z_f* is the infiltration depth (cm).

Results

Climate factors

261 rainfall events were observed during the experimental period. An individual rainfall event is considered to be a rainfall event separated by dry intervals of at least 5 h (Guastini et al. 2019). The results indicated that low rainfall intensity events dominated (< 0.5 mm h⁻¹, accounting for 43.9% of rainfall events) (Fig. 3a). The annual rainfall averaged 354.2 mm, with the following distribution: ≤ 5 mm, 27.7% of the annual rainfall depth and 74.8% of the events; 5.1–10 mm, 21.3% and 12.7%, respectively; 10.1–15 mm, 18.9% and 6.6%; 15.1–20 mm, 11.2% and 2.8%; 20.1–25 mm, 5.2% and 1.0%; > 25 mm, 15.7% and 2.1% (Fig. 3b). The percentages of the total amount and frequency of

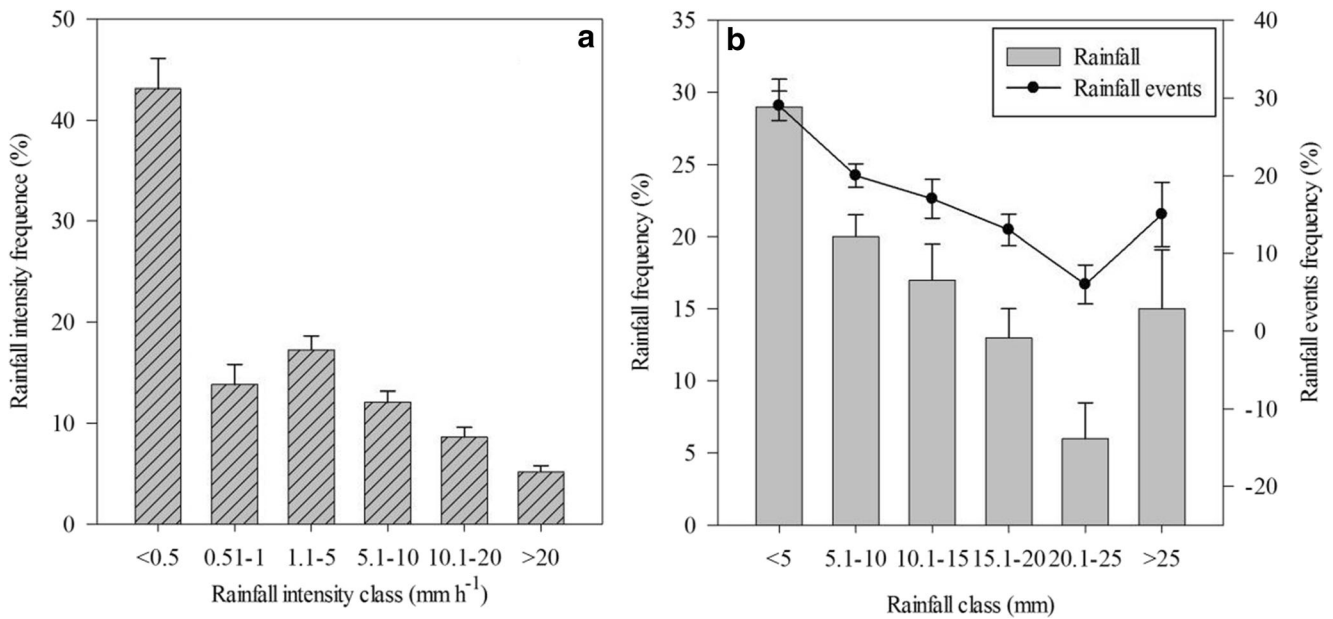


Fig. 3 The frequency distributions of the rainfall intensity, rainfall and rainfall events from 1st May to 30th September of 2009–2014 (The rainfall intensity was grouped based on the standard of the China Meteorological Administration on rainfall level)

events decreased with increasing rainfall, during the experimental period. Small events (≤ 5 mm) were the most frequent, whereas larger events (≥ 10 mm) were infrequent but had a greater influence on total rainfall. The heaviest rainfall event that occurred on 12th August, 2012 and resulted in a total rainfall depth of 31 mm, with a maximum 30-min rainfall intensity of 4.21 mm/h, a duration of 569 min and an average intensity of 3.5 mm/h, was used to analyze the advance of the wetting front.

The annual climate factors values of the study period (2009–2014) and long-term period (1975–2008) were presented in Table 2.

Soil water variation

The monthly soil water content in the different land cover types during the experimental period was determined by Eqs. (1) and (2). Soil water storage varied greatly during the study period from May to September of 2009–2014 (Fig. 4). However, no significant differences were found among the five land cover types (Table 3). Soil water replenishment usually occurs from the end of autumn to the end of spring (Fig. 4). In general, a

decreasing trend was found for all land cover types during the experimental period (Fig. 4). The ΔSW was negative in most months from May to September of 2009–2014, water loss exceeded precipitation in these months (Fig. 5).

Runoff

Among the land cover types, woodland produced the largest surface runoff (102 mm), followed by cropland (86 mm), grassland (83 mm), alfalfa (77 mm) and shrubland (66 mm) throughout the 6 years (Fig. 6). This was somewhat surprising since pines were considered as a major species for soil erosion control through reducing surface runoff in the study region. We attributed the large runoff to the soil compaction and lacking understory in the pine stands. High runoff frequency occurred in July and August, which accounted for 66.4% of the total surface runoff. The May and September had the lowest surface runoff, accounting for 7.2% and 8.6%, respectively. Especially, no runoff was observed in May of 2009 and 2011.

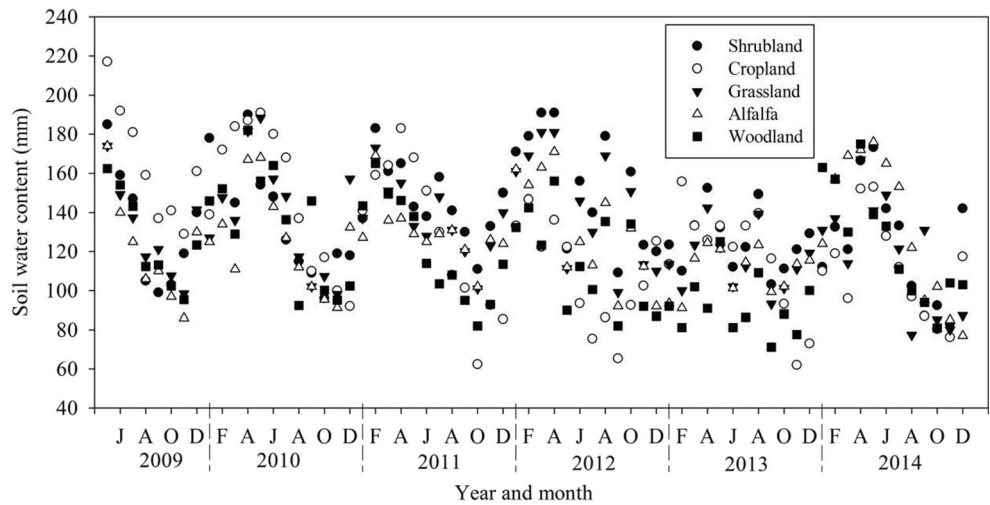
The monthly runoff increased with increasing monthly rainfall depth and followed by significantly positive linear relationships in the five land cover types (Fig. 7). The monthly rainfall

Table 2 The annual climate factors values of the study period (2009–2014) and long-term period (1975–2008)

Climate factors	Rainfall (mm)	Air temperature (°C)	Evaporation (mm)	Wind speed (m/s)	Relative humidity (%)	Solar radiation (MJ/m ²)
2009–2014	354 ± 31	6.5 ± 1.1	1496 ± 112	2.53 ± 0.57	65 ± 12	5419 ± 142
1975–2008	420 ± 85	6.3 ± 1.5	1510 ± 131	2.36 ± 0.61	61 ± 16	5322.1 ± 346

Data = Mean ± S.D. The data from 1975 to 2008 were from Dingxi institute of soil and water conservation

Fig. 4 Soil water content variations from 2009 to 2014



thresholds to generate runoff are 27.43 mm, 28.47 mm, 30.90 mm, 24.20 mm and 27.53 mm for cropland, Alfalfa, shrubland, woodland and grassland, respectively (Fig. 7).

The monthly runoff-to-precipitation ratios increased with increasing monthly soil water content and followed by significantly positive linear relationships in the five land cover types (Fig. 8). The runoff-to-precipitation ratios in most months were less than 0.1 for all five land cover types.

Characteristics of the ET/P ratio

The ET/P ratios fluctuated during the study period. The ET/P ratios were higher than 1.0 in most months for all land covers during the study period (Fig. 9). For all land covers, the monthly average ET/P ratios ranked from high to low were Grassland (1.31) > Shrubland (1.29) > Cropland (1.28) >

Alfalfa (1.26) > Woodland (1.20). Pine plantation, as a landscape restoration type, its ET/P ratio was the lowest one among the five land cover types. This suggested that pine as an exotic species to the semi-arid Loess Plateau, did not use the rainfall resource adequately, perhaps due to greater water loss by overland flow. However, the slope of declining trend of ET/P for the landscape restoration types was: Grassland > Woodland > shrubland (Fig. 9).

Infiltration characteristics

The heaviest rainfall event, that occurred on 12th August 2012, was used to determine the advances of the wetting front (Fig. 10a). The wetting front of cropland reached 5 cm after 140 min of rainfall. The wetting front took approximately 60 min to move from 5 cm to 10 cm, 10 cm to 15 cm and

Fig. 5 Soil water content change for different land cover types from May to September in the period from 2009 to 2014. Box-and-whisker diagrams showed standard deviation 25th, 50th, 75th and abnormal value percentiles

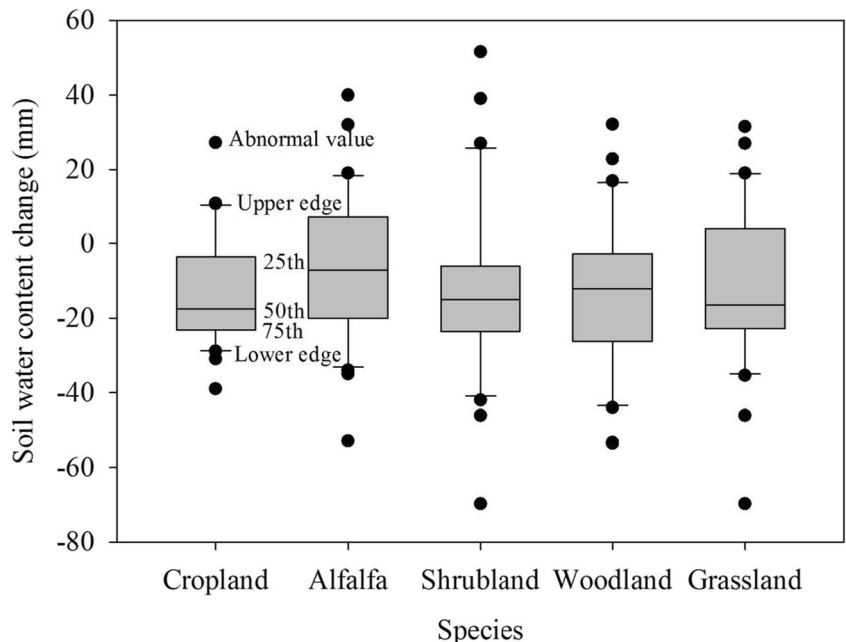
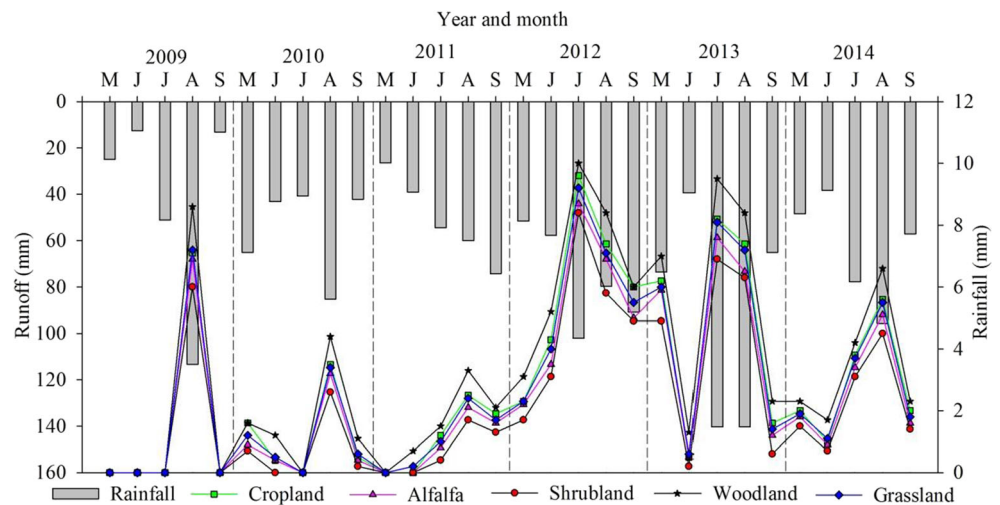


Fig. 6 Time series of runoff in different landscapes from May to September in the period from 2009 to 2014



15 cm to 20 cm, respectively, and achieved the stable soil moisture of 27.4%, 23.2% and 20.5%, respectively. After approximately 130 min of slowly increase, the stable value of soil moisture is 14.0% at a depth of 25 cm. The wetting front reached a depth of 30 cm after 12 h. The soil moisture reached approximately 12.1% at a depth of 50 cm after a period of slowly increase. Finally, the wetting front stopped at a depth of 120 cm deep after 7 days in the cropland (Fig. 10b).

In alfalfa, the wetting front reached 5 cm approximately 90 min later than that in cropland and took a longer time to achieve a depth of 10 cm, i.e., 25.6% after the initial 10.8%. The wetting front of alfalfa reached a depth of 15 cm after 13 h. The soil water ultimately infiltrated depth was 50 cm (Fig. 10c).

The wetting front reached a depth of 5 cm after 60 min in the shrubland. After 220 min of rapidly increase, the soil moisture achieved at 23.0% at a depth of 10 cm. The wetting fronts reached 15 cm and 20 cm after 7 and 9 h, respectively. The soil water finally infiltrated depth was 100 cm (Fig. 10d).

The initial soil moisture in woodland was the lowest among the five land covers. The wetting front reached a depth of 5 cm

after 70 min. The soil moisture showed a stable value of 22.4% after 360 min. The wetting front took 190 min to move from 5 cm to 10 cm. The wetting front arrived at 15 cm after 14 h and reached 50 cm 4 days later (Fig. 10e).

In the grassland, it took about 300 min to reach 5 cm. The soil moisture reached 20.9% after 150 min. After 370 min, The soil water infiltrated to 10 cm. The water finally reached a depth of 60 cm after 5 days (Fig. 10f).

The cumulative infiltration I (mm) (upper 2 m) increased with increasing rainfall depth P (mm) and followed by significantly positive linear relationships in the five land cover types (Fig. 11). The regression equations were as follow:

$$\begin{aligned}
 I_{\text{Cropland}} &= 0.44P - 1.39, & R^2 &= 0.93 \\
 I_{\text{Alfalfa}} &= 0.46P - 1.04, & R^2 &= 0.77 \\
 I_{\text{Shrubland}} &= 0.51P - 1.42, & R^2 &= 0.89 \\
 I_{\text{Woodland}} &= 0.49P - 1.80, & R^2 &= 0.87 \\
 I_{\text{Grassland}} &= 0.46P - 1.79, & R^2 &= 0.90
 \end{aligned}
 \tag{4}$$

Fig. 7 The relationship between monthly rainfall and runoff from May to September, 2009–2014 (Sig. level < 0.001)

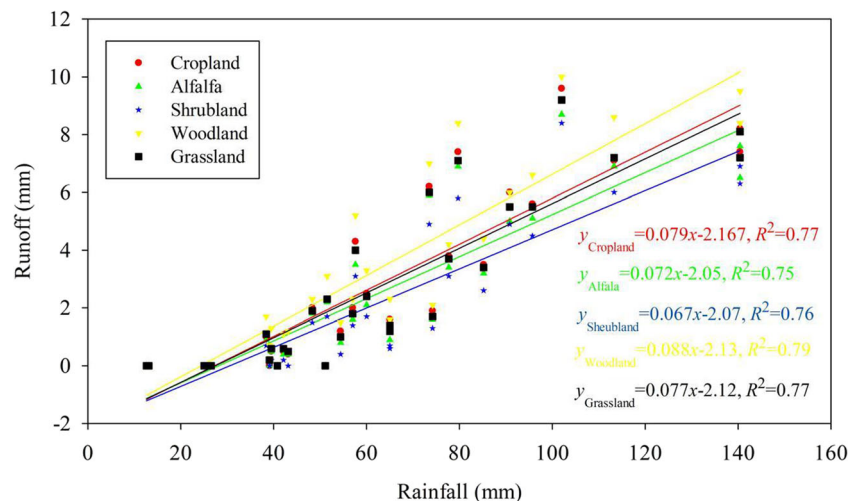
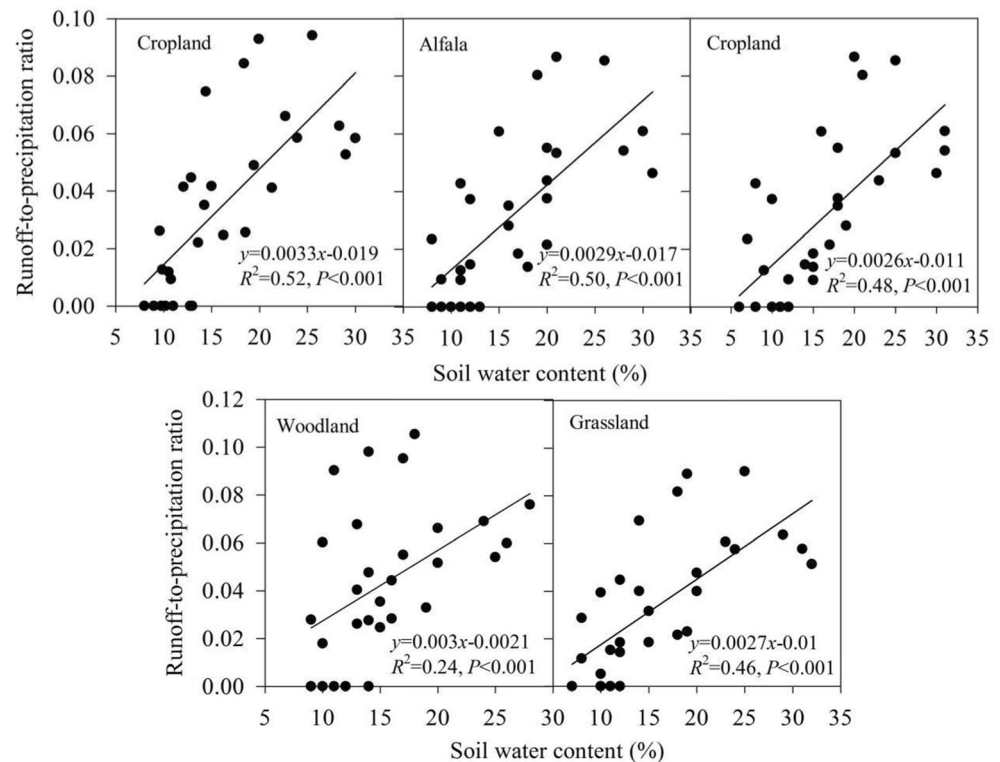


Fig. 8 The relationship between runoff-to-precipitation ratio and soil water content from May to September, 2009–2014



Discussion

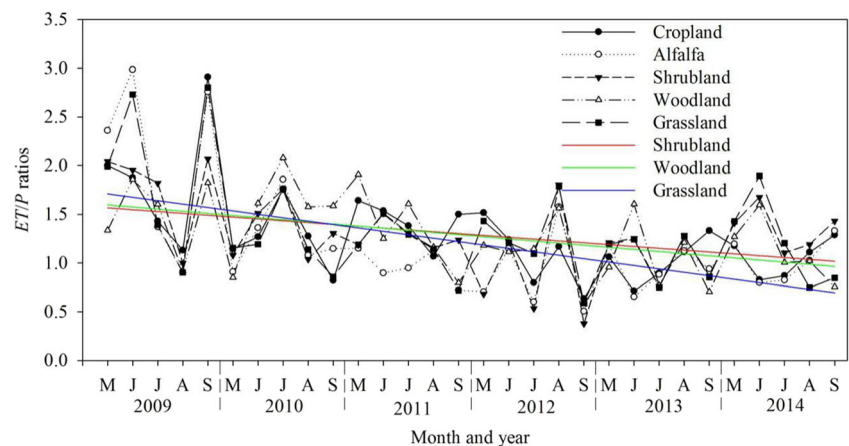
Effect of land covers on soil water variation

In the pine plantation, lower infiltration and higher surface runoff were found during the experimental period. This was mainly due to the soil compaction caused by the pine plantation (Table 1) (Fu et al. 2005). These results were also confirmed by Kosmas et al. (1997) and Vörösmarty et al. (2000), they found that in a *Eucalyptus* forest, runoff and erosion increased with decreased understory vegetation. Gutierrez and Hernandez (1996) described a positive correlation between soil bulk density and surface runoff. High soil bulk density usually resulted in lower infiltration rates and higher

surface runoff (Descheemaeker et al. 2006; Velísková et al. 2017). However, shrub lands and native grassland had more understory than pine woodland, which showed the more effective soil water conservation (Wang et al. 2005; Gong et al. 2006). Subshrubs had a higher efficiency to acquire and retain soil water resources than trees and shrub (Figs. 5 and 6), which is attributed to the effective barrier effects, lower soil compactness, and higher clay content (Wang et al. 2012).

Generally, land cover types have different influences on the variations of soil moisture. However, the current study did not find a significant difference for the land cover types (Table 3). The different results were found in other studies of the Loess Plateau. For example, Liu et al. (2008) found that the available soil water of 0–10 m depth decreased in an apple plantation

Fig. 9 Time series of *ET/P* ratios of different landscapes from May to September in the period from 2009 to 2014



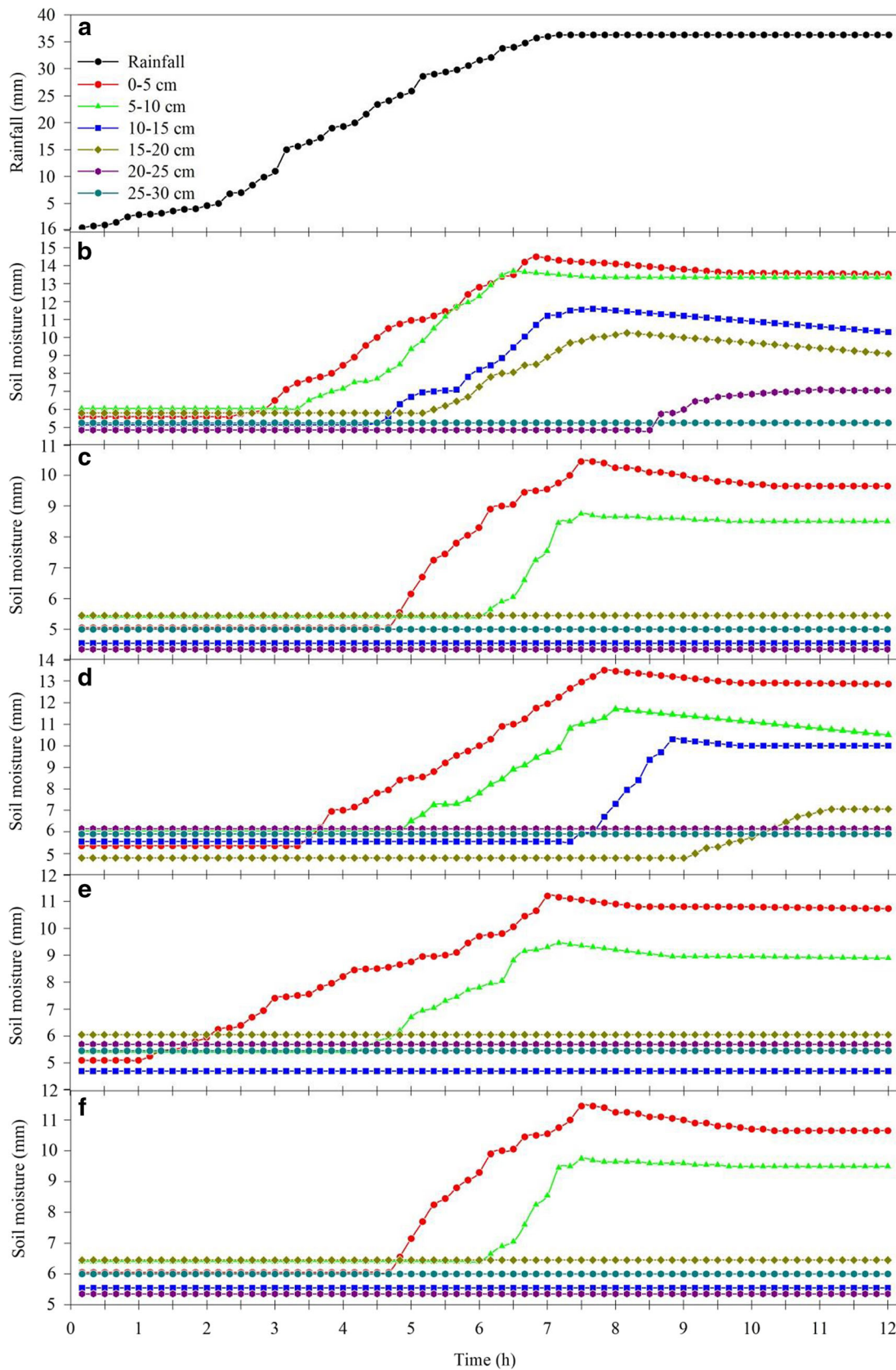
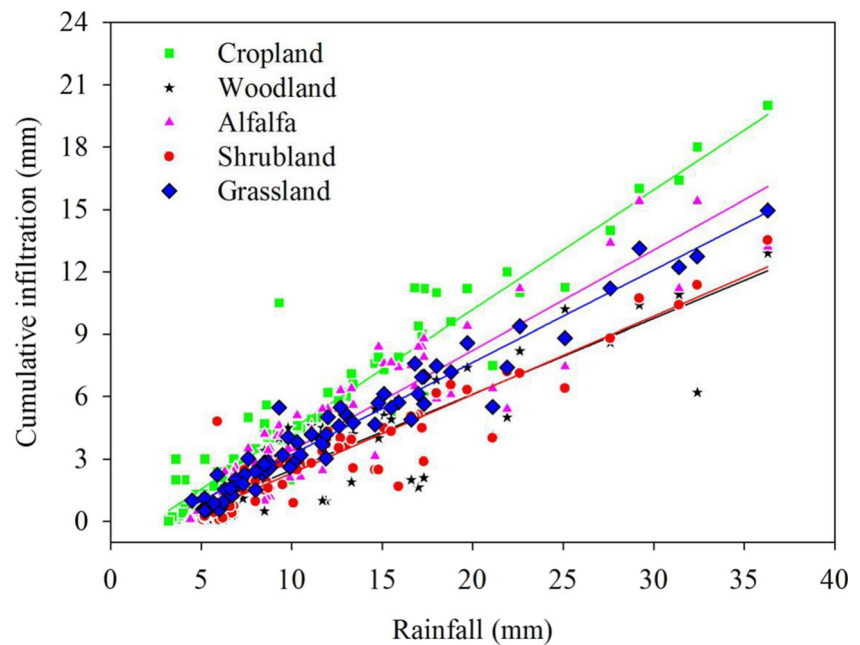


Fig. 10 The characteristics of infiltration beneath the five land cover types. **a** rainfall processes; **b** cropland; **c** alfalfa; **d** shrubland; **e** woodland; **f** grassland. The frequency of soil moisture is 10 min

Fig. 11 The relationship between precipitation and cumulative infiltration



over time. Nosetto et al. (2007) reported that native species had higher soil moisture than those introduced exotic species and vegetation restoration may cause soil drying if exotic species were planted on the Loess Plateau. The difference between the above-mentioned studies and our results is due to the difference in rainfall and soil properties. In our study, almost all of the rainfall was consumed by evapotranspiration, and little for soil water enhancement. However, other studies focused on the Loess Plateau under higher rainfall may show the differences in evapotranspiration for different land covers (Huang and Gallichand 2006; Liu et al. 2008). Soil porosity and soil bulk density contribute 86.2% to the change of soil moisture (Li et al. 2016). During the growth process of vegetation roots, soil bulk density can be reduced and soil structure can be improved, and then improves the soil moisture (Luo et al. 2010). Soil organic matter and biological activities can effectively improve soil moisture. Soil organic matter can promote the formation of aggregates and the pores in and between aggregates can improve soil porosity. Many studies have shown that there is a positive correlation between soil organic matter content and soil moisture (e.g. Zhao et al. 2010; Ruan et al. 2015).

Table 3 The results of One-way ANOVA in soil water storage for all land cover types

	Sum of squares	df	Mean square	<i>F</i>	Sig.
Between groups	1296.3	4	324.1	0.776	0.543
With groups	60,580.2	145	417.8		
Total	61,876.5	149			

Apart from shrub lands, soil water was not recharged for the other land covers over the experimental period (Fig. 5). The soil moisture of pine woodlands and native grasslands had obvious decreasing trend from 2009 to 2014. However, soil water of shrub lands in May was nearly balanced. Normally, woodlands have strong evapotranspiration, and soil water decreases obviously in the deep soil layers during the dry season (Yang and Rong 2007). Planting pine is not always appropriate on the Loess Plateau. Wei et al. (2007) indicated that the young stage of a tree plantation has a higher soil water content than the mature stage. Also, some studies found that soil desiccation developed under a 28-year-old tree plantation, whereas natural forest or grassland often has the better soil moisture status (Zheng et al. 2008). In our study, all ecosystems had a poor soil water condition during the experimental period.

Effect of land cover on *ET/P*

The *ET/P* ratios varied during the study period (Fig. 9). The monthly averaged *ET/P* ratios were bigger than 1.0 for the five land covers during the experiment period. The results indicated that the water is not sufficient for evapotranspiration and growth during the experimental period. The *ET/P* ratios had declining trends indicated that water stress became increasingly severe with the growth of vegetation. Chen et al. (2007) and Liu et al. (2008) also found that afforestation species would degrade after a few years due to water depletion. The potential evapotranspiration is higher than annual rainfall with high runoff on the semi-arid Loess Plateau, which is not suitable for vegetation growth. The runoff-to-precipitation ratio is negatively correlated with the actual

evapotranspiration (Chen et al. 2007). Some studies had indicated that plant evapotranspiration decreased with decreasing soil water and water use efficiency in the Loess Plateau (Yang and Tian 2004). Thus, afforestation species plantations may result in growth retardation (Huang and Gallichand 2006). This result is not the original intention of vegetation restoration and may dampen public enthusiasm to vegetation restoration.

Pine plantations had a lower *ET/P* ratio among the five land cover types due to the soil compaction (Table 1). Our results were different from other studies conducted in the regions rich in rainfall. Li and Shao (2006) reported that vegetation restoration would increase aggregate stability, soil porosity, saturated hydraulic conductivity and water-holding capacity, and decrease soil bulk density. However, it showed the opposite trend under pine stands in the semi-arid Loess Plateau (Gong et al. 2006; Lichner et al. 2017). Much more water loss through runoff, little rainfall enhanced the deep soil water. Some studies have proven that vegetation restoration would increase surface runoff (Zheng et al. 2008; Vanclay 2009). Zhou et al. (2002) also found *Eucalyptus* trees had the higher runoff coefficient, which attributed to a poor understory.

Differences in infiltration among land cover types

The different vertical structures in soil moisture profiles were displayed among the five sites (Table 1). The wetting fronts reached 10 cm more quickly for the cropland than other land cover types may be attributed to the surface tillage. The shrub site had the dense shrub layer resulted in the advance of the wetting front was slower, and the alfalfa site showed the slowest speed due to the lower initial soil moisture. The wetting front reached 80 cm only in the grass site and to a depth of 60 cm in the other sites. The grass site usually produces more runoff and lower infiltration rate may be attributed to lower soil bulk density (Liu et al. 2012; Iovino et al. 2018). These factors provided subshrubs a competitive advantage for a long time, causing the subshrubs to adapt to the local environment. The rainwater at the shrub and crop sites took the shortest time to reach 20 cm, but the two land covers took a longer time to infiltrate into deeper soil layers (Fig. 10).

The woodland had the lowest cumulative infiltration and the most runoff for all land covers. It was surprised that trees have always been considered the preferred species for afforestation. Soil and water loss has gradually decreased on the Loess Plateau during the 20 years that the Grain-for-Green project was conducted. Therefore, the water inputs and utilization characteristics of afforestation species would be the research focus. Dam land always had high moisture content to provide the effective water use for crop growth. Afforestation areas usually consumed more water, especially when they are covered with rich understory to generate interception loss and reduce rainfall infiltration. The natural

vegetation had higher infiltration rates and deeper wetting front, particularly in the subshrub communities, which had the highest cumulative infiltration during the experimental period. Native vegetation seems to be more suitable for vegetation restoration.

Conclusions

On the Loess Plateau, rainfall is the only water input to the soil. However, our results indicated that such replenishment was not effective, and soil water deficits frequently occurred from 2009 to 2014. This was attributed to low rainfall, strong evapotranspiration and runoff to restrict plant transpiration and growth, especially in the pine plantation. With respect to landscape restoration, pine plantation produced the highest surface runoff compared with the shrubs and native grasses. Although pine plantations may control water and soil loss, they compound soil compaction and desiccation, resulting in landscape degradation.

Infiltration is an important process of soil water balance. Most of the sloping farmlands of Loess Plateau were abandoned during recent decades in favour of grass or subshrub species or planted forests and shrubs. Different plant communities have varied water interception, root and soil properties, leading to various soil water input characteristics. Crops and Alfalfa often have high infiltration rates, and deeper wetting front. Pine plantation should not be the first choice for vegetation restoration in such a semi-arid loess hilly area.

Acknowledgements This project was supported by National Natural Science Foundation of China (31700370); The National Key Research Priorities Program of China (2016YFC0402402); National Natural Science Foundation of China (51409116); Startup Research Fund of Zhengzhou University (1512323001); Institution of higher learning key scientific research project, Henan Province (16A570010); Foundation of drought climate science (IAM201705); China postdoctoral science foundation (2016 M602255); Henan province postdoctoral science foundation; National Natural Science Foundation of China (91025015). We would like to thank LetPub (www.letpub.com) for providing linguistic assistance during the preparation of this manuscript.

Compliance with ethical standards

Conflict of interest The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

References

- Benito E, Varela E, Rodríguez-Alleres M (2019) Persistence of water repellency in coarse-textured soils under various types of forests in NW Spain. *J Hydrol Hydromech* 67:129–134. <https://doi.org/10.2478/johh-2018-0038>

- Cao SX, Chen L, Shankman D, Wang CM, Wang XB, Zhang H (2011) Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. *Earth Sci Rev* 104:240–245. <https://doi.org/10.1016/j.earscirev.2010.11.002>
- Chen LD, Huang ZL, Gong J, Fu BJ, Huang YL (2007) The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China. *Catena* 70:200–208. <https://doi.org/10.1016/j.catena.2006.08.007>
- Chen HS, Shao MA, Li YY (2008) Soil desiccation in the Loess Plateau of China. *Geoderma* 143:91–100. <https://doi.org/10.1016/j.geoderma.2007.10.013>
- Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S (2006) Runoff on slopes with restoring vegetation: a case study from the Tigray highlands, Ethiopia. *J Hydrol* 331:219–241. <https://doi.org/10.1016/j.jhydrol.2006.05.015>
- Fu BJ, Zhao WW, Chen LD, Zhang QJ, Lu YH, Gulnick H, Poesen J (2005) Assessment of soil erosion at large watershed scale using RUSLE and GIS: a case study in the Loess Plateau of China. *Land Degrad Dev* 16:73–85. <https://doi.org/10.1002/ldr.646>
- Gao G, Fu BJ, Zhang J (2018) Multiscale temporal variability of flow–sediment relationships during the 1950s–2014 in the loess plateau, China. *J Hydrol* 563:609–619. <https://doi.org/10.1016/j.jhydrol.2018.06.044>
- Gong J, Chen LD, Fu BJ, Huang YL, Huang ZL, Peng HJ (2006) Effect of land use on soil nutrients in the loess hilly area of the Loess Plateau, China. *Land Degrad Dev* 17:453–465. <https://doi.org/10.1002/ldr.701>
- Guastrini E, Zuecco G, Errico A, Castelli G, Bresci E, Preti F, Penna D (2019) How does streamflow response vary with spatial scale? Analysis of controls in three nested Alpine catchments. *J Hydrol* 570:705–718. <https://doi.org/10.1016/j.jhydrol.2019.01.022>
- Gutierrez J, Hernandez II (1996) Runoff and inter-rill erosion as affected by grass cover in a semi-arid rangeland of northern Mexico. *J Arid Environ* 34:287–295. <https://doi.org/10.1006/jare.1996.0110>
- Han X, Tsunekawa A, Tsubo M, Li S (2009) Effects of land–cover type and topography on soil organic carbon storage on northern Loess Plateau, China. *Acta Agric Scand Sect B-Soil Plant Sci* 60:326–334. <https://doi.org/10.1080/09064710902988672>
- Huang MB, Gallichand J (2006) Use of the SHAW model to assess soil water recovery after apple trees in the gully region of the Loess Plateau, China. *Agric Water Manag* 85:67–76. <https://doi.org/10.1016/j.agwat.2006.03.009>
- Iovino M, Pekárová P, Hallett PD, Pekár J, Lichner L, Mataix-Solera J, Alagna V, Walsh R, Raffan A, Schacht K, Rodný M (2018) Extent and persistence of soil water repellency induced by pines in different geographic regions. *J Hydrol Hydromech* 66:360–368. <https://doi.org/10.2478/johh-2018-0024>
- Jiao F, Wen ZM, An SS (2011) Changes in soil properties across a chronosequence of vegetation restoration on the Loess Plateau of China. *Catena* 86:110–116. <https://doi.org/10.1016/j.catena.2011.03.001>
- Jin T, Fu BJ, Liu GH, Wang Z (2011) Hydrologic feasibility of artificial forestation in the semi-arid Loess Plateau of China. *Hydrol Earth Syst Sci* 15:2519–2530. <https://doi.org/10.5194/hess-15-2519-2011>
- Jones SB, Wraith JM, Or D (2002) Time domain reflectometry measurement principles and applications. *Hydrol Process* 16:141–153. <https://doi.org/10.1002/hyp.513>
- Kosmas D, Danalatos N, Cammeraat LH, Chabart M (1997) The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena* 29:45–59. [https://doi.org/10.1016/S0341-8162\(96\)00062-8](https://doi.org/10.1016/S0341-8162(96)00062-8)
- Legates DR, Mahmood R, Levia DF, DeLiberty TD, Quiring S, Houser C, Nelson FE (2011) Soil moisture: a central and unifying theme in physical geography. *Prog Phys Geogr* 35:65–86. <https://doi.org/10.1177/0309133310386514>
- Li YY, Shao MA (2006) Change of soil physical properties under long-term natural vegetation restoration in the Loess Plateau of China. *J Arid Environ* 64:77–96. <https://doi.org/10.1016/j.jaridenv.2005.04.005>
- Li TC, Shao MA, Jia YH (2016) Application of X-ray tomography to quantify macropore characteristics of loess soil under two perennial plants. *Eur J Soil Sci* 67:266–275. <https://doi.org/10.1111/ejss.12330>
- Lichner L, Rodný M, Marschner B, Chen Y, Nadav I, Tarchitzky J, Schacht K (2017) Comparison of various techniques to estimate the extent and persistence of soil water repellency. *Biologia* 72: 982–987. <https://doi.org/10.1515/biolog-2017-0112>
- Liu JG, Li SX, Ouyang ZY, Tam C, Chen XD (2008) Ecological and socioeconomic effects of China's policies for ecosystem services. *Proc Natl Acad Sci U S A* 105:9477–9482. <https://doi.org/10.1073/pnas.0706436105>
- Liu Y, Fu BJ, Lü YH, Wang Z, Gao GY (2012) Hydrological responses and soil erosion potential of abandoned cropland in the Loess Plateau, China. *Geomorphology* 138:404–414. <https://doi.org/10.1016/j.geomorph.2011.10.009>
- Luo LF, Lin H, Li SC (2010) Quantification of 3-D soil macropore networks in different soil types and land uses using computed tomography. *J Hydrol* 393:53–64. <https://doi.org/10.1016/j.jhydrol.2010.03.031>
- McVicar T, Niel T, Li LT, Wen ZM, Yang QK, Li R, Jiao F (2010) Parsimoniously modeling perennial vegetation suitability and identifying priority areas to support China's re-vegetation program in the Loess Plateau: matching model complexity to data availability. *Forest Ecol Manag* 259:1277–1290. <https://doi.org/10.1016/j.foreco.2009.05.002>
- Mishra AK, Singh VP (2010) A review of drought concepts. *J Hydrol* 391:202–216. <https://doi.org/10.1016/j.jhydrol.2010.07.012>
- Nosetto MD, Jobbagy EG, Toth T, Di Bella CM (2007) The effects of tree establishment on water and salt dynamics in naturally salt-affected grasslands. *Oecologia* 152:695–705. <https://doi.org/10.1007/s00442-007-0694-2>
- Porporato A, D'Odorico P, Laio F, Ridolfi L, Rodriguez-Iturbe I (2002) Ecohydrology of water-controlled ecosystems. *Adv Water Resour* 25:1335–1348. [https://doi.org/10.1016/S0309-1708\(02\)00058-1](https://doi.org/10.1016/S0309-1708(02)00058-1)
- Qiu GY, Xie F, Feng YC, Tian F (2011) Experimental studies on the effects of the conversion of cropland to grassland program on the water budget and evapotranspiration in a semi-arid steppe in Inner Mongolia, China. *J Hydrol* 411:120–129. <https://doi.org/10.1016/j.jhydrol.2011.09.040>
- Ruan XZ, Cheng JH, Zhang HJ, Du SC, Li SY, Zhang FM (2015) Soil macropore characteristics of different wood land and their influencing factors on Simiansan mountain in Chongqing. *J Soil Water Conserv* 29:68–74. <https://doi.org/10.13870/j.cnki.stbcbx.2015.03.014>
- Sun G, Zhou GY, Zhang ZQ, Wei XH, McNulty SG, Vose JM (2006) Potential water yield reduction due to reforestation across China. *J Hydrol* 328:548–558. <https://doi.org/10.1016/j.jhydrol.2005.12.013>
- Vanclay JK (2009) Managing water use from forest plantations. *Forest Ecol Manag* 257:385–389. <https://doi.org/10.1016/j.foreco.2008.09.003>
- Velísková Y, Dulovičová R, Schügerl R (2017) Impact of vegetation on flow in lowland stream during the growing season. *Biologia* 72: 840–846. <https://doi.org/10.1515/biolog-2017-0095>
- Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289:284–288. <https://doi.org/10.1126/science.289.5477.284>
- Wang ZQ, Liu BY, Wang XL (2005) Effects of natural shrub of *Caragana Opulens* on soil moisture in a semiarid area on the Loess. *Geogr Res* 24:113–120 (In Chinese with English abstract). <https://doi.org/10.11821/yj2005010013>

- Wang XP, Cui Y, Pan YX, Li XR, Yu Z, Young HM (2008) Effects of rainfall characteristics on infiltration and redistribution patterns in revegetation–stabilized desert ecosystems. *J Hydrol* 358:134–143. <https://doi.org/10.1016/j.jhydrol.2008.06.002>
- Wang YQ, Shao MA, Shao HB (2010) A preliminary investigation of the dynamic characteristics of dried soil layers on the Loess Plateau of China. *J Hydrol* 381:9–17. <https://doi.org/10.1016/j.jhydrol.2009.09.042>
- Wang S, Fu BJ, Gao GY, Yao XL, Zhou J (2012) The hydrological responses of different land cover types in a re-vegetation catchment area of the Loess Plateau, China. *Hydrol Earth Syst Sci* 9:5809–5835. <https://doi.org/10.5194/hessd-9-5809-2012>
- Wei TX, Zhu JZ, Zhang JJ, Bi HX, Zhu QK (2007) Protective forest system at small watershed in the gullied–hilly loess area based on water balance on the Loess Plateau. *Res Soil Water Conserv* 14: 179–183 (In Chinese with English abstract). <https://doi.org/10.3969/j.issn.1005-3409.2007.01.057>
- Xie XQ, Wang L (2007) Changes of potential evaporation in northern China over the past 50 years. *J Nat Resour* 22:683–691 (in Chinese with English abstract). <https://doi.org/10.3321/j.issn:1000-3037.2007.05.002>
- Yang G, Rong LY (2007) Effects of artificial vegetation types on soil moisture, carbon and nitrogen in the hill and gully area of the Loess Plateau. *Bulletin Soil Water Conserv* 27:30–33 (In Chinese with English abstract). <https://doi.org/10.3969/j.issn.1000-288X.2007.06.008>
- Yang WZ, Tian JL (2004) Essential exploration of soil aridization in Loess Plateau. *Acta Pedol Sin* 41:1–6 (in Chinese with English abstract). <https://doi.org/10.3321/j.issn:0564-3929.2004.01.001>
- Zhao SW, Zhao YG, Wu JS (2010) Quantitative analysis of soil pores under natural vegetation successions on the Loess Plateau. *Sci China Earth Sci* 53:617–625. <https://doi.org/10.1007/s11430-010-0029-8>
- Zheng H, Chan FL, Ouyang ZY, Tu NM, Xu WH, Wang XK, Miao H, Li XQ, Tian YX (2008) Impacts of reforestation approaches on runoff control in the hilly red soil region of southern China. *J Hydrol* 356: 174–184. <https://doi.org/10.1016/j.jhydrol.2008.04.007>
- Zhou GY, Morris JD, Yan JH, Yu ZY, Peng SL (2002) Hydrological impacts of reforestation with eucalypts and indigenous species: a case study in southern China. *Forest Ecol Manag* 167:209–222. [https://doi.org/10.1016/S0378-1127\(01\)00694-6](https://doi.org/10.1016/S0378-1127(01)00694-6)

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.