Pol. J. Environ. Stud. Vol. 23, No. 2 (2014), 511-520

Original Research

Soil Moisture Status under Deep-Rooted and Shallow-Rooted Vegetation in the Semiarid Area of Loess Plateau in China

Xuyan Wang[1]*, Wanjun Zhang[1], Zhiqiang Wang[2], Xiuping Liu[1], Shufen Wang[3]

[1]Key Laboratory of Agricultural Water Resources, Hebei Key Laboratory of Agricultural Water-Saving, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, University of Chinese Academy of Sciences, Shijiazhuang, 050021, China
[2]State Key Laboratory of Earth Surface Processes and Resource Ecology, School of Geography, Beijing Normal University, 100875, Beijing, China
[3]Institute of Seashore Agriculture, Hebei Academy of Agriculture and Forestry Sciences, Tangshan, 063200, China

Received: 2 August 2012
Accepted: 2 October 2013

Abstract

Deep loessial soil stores water recharged in a rainy season or wet year, and supplies water to vegetation for evapotranspiration in a dry season or dry year in the semiarid area of the Loess Plateau, China. However, this function of "soil water reservoir" may be weakened by deep-rooted shrub and forests that often extract deep soil waters and form a dry soil layer. The purpose of this study was to evaluate soil moisture status and variation under deep and shallow-rooted vegetation. The hypothesis was that the mature deep-rooted vegetation in this area may deplete deep soil water to such an extent that the plants could not further extract water from the deep soil layer, and the plants live mainly on present year precipitation. Soil moisture of shallow-rooted annual crops and natural grasses, planted deep-rooted caragana shrub, arborvitae forest, pine forest, and the mixture forest of pine and arborvitae were tested in late 2001 and 2005-08 to 10 m depth. The maximum rain water recharge depths under shallow-rooted vegetation was 2.4-3.0 m, and those under deep-rooted vegetation were 1.2- 2.2 m in a relatively wet year of the five years. Within the maximum recharge depths, annual recharge depths and soil moistures were changed inter-annually dependent on rainfall. The average recharge depths for deep-rooted vegetation were 0.6, 1.0, 1.2, 1.4, and 1.8 m in 2005, 2008, 2006, 2007, and 2001, according to the ascending June-October rainfall amount order. In the inter-annually rechargeable layer, soil moistures under shallow-rooted vegetation were 6.7-13.6% in the five years, belonging to the easily or most easily available level in four out of five study years, the moistures under deep-rooted vegetation were 4.5-12.0%, varying from hard-unavailable to easily available moisture levels dependent on rainfall. Below the inter-annually changeable layer to the tested 10 m, there were no significant inter-annual moisture changes ($p<0.001$) under both shallow-rooted and deep-rooted vegetation, but the moisture of shallow-rooted vegetation was >10%, belonging to easily available moisture level, those of deep-rooted vegetation were <5%, close to permanent wilting point, and the water belonged to or near to hard-unavailable moisture levels.

Keywords: semiarid area, Loess Plateau, shallow-rooted vegetation, deep-rooted vegetation, soil moisture

*e-mail: laly997@163.com

Introduction

Deep-rooted shrubs and forest normally transpire more water and can extract water more deeply from soil than many shallow-rooted annual crops and grasses [1-3]. The hydraulically lifted water may be a water source to neighboring plants [4-7], but in semiarid or arid environments, deep-rooted shrubs or forest, especially artificial ones, could often have adverse effects on nearby crops [8, 9] and could decrease groundwater recharge, hence influencing the water cycle [10, 11]. However, in some cases the reduction in ground water recharge by deep-rooted vegetation may be beneficial [12]. The soil water stored in deep loess on the Loess Plateau in northwest China functions as a "soil water reservoir" regulating crop growth [13], but deep-rooted artificial shrubs and forests often exhaust deep soil water and form dry soil layers [14-16] which in turn restrain healthy growth of the planted vegetation [17-19]. Almost all planted mature shrubs and forest in the semiarid area of the Loess Plateau could result in dry soil layers [20], which might reach more than 10 m in soil depth [21]. A studied 23-year old caragana brush and a pine forest had formed dry soil layers as deep as 22.4 and 21.5 m, respectively, and planted 7-year-old alfalfa had formed a 15.5 m deep dry soil layer [22].

Although many studies have investigated the extent of soil moisture depletion by deep- and shallow-rooted vegetation in the Loess, much of these studies were based on one-time testing. There had been some studies on seasonal and/or inter-annual soil moisture changes under deep- and/or shallow-rooted vegetation on the Loess. However, the tested depths of much these studies were limited to 2 or 4 m, or the timespans were limited to 2 or 3 years even if the tested depths were deep enough. Initial studies showed that in rainfall rechargeable depth, soil moistures were changed seasonally and inter-annually, but below the rechargeable depths, soil moistures were stable under both shallow- and deep-rooted vegetation [16, 21, 23]. In a wet year (644.1 mm) of an area with average annual precipitation of 558.4 mm, soil moistures under a Black Locust (*Robinia pseudoacacia* L.) forest in June, August, and October were changed above 1.5 m, but unchanged to the tested 1.5-5 m profile on which the soil was very dry [24]. In another area with average annual precipitation of 500 mm, in 2002 (precipitation was 372.4 mm) water recharge depths were 1.2 m and 1.8 m under Manchu Rose (*Rosa xanthina* Lindl) shrub and planted pine forest, respectively. Below these depths to the studied depth of 9.9 m, soil moistures were the same in August and October [25]. In an area with average annual precipitation of 437.4 mm, soil moisture changed above 2.2 m under planted alfalfa, but changed above 3 m in bare land during the period from June 2004 to October 2005 [26]. In the same area, rainfall recharge depths were different under the same vegetation type but with different soil texture. The maximum recharge depths under caragana shrubs during 2004-05 in sand soil and loess soil were 2.5 and 2.2 m, respectively. Below these depths of both soil textures, soil moistures were stable to the tested 6 m [23]. In an area with average annual precipitation of 414.9 mm, the maximum recharge depths under caragana shrub in 2002 (precipitation 384.8 mm) and 2003 (precipitation 623.3 mm) were 1.7, 2.1 m, respectively [27]. It seems that, by initial short time studies, in the semiarid area of the Loess Plateau, the present year rainfall recharge depth under shallow-rooted crop and natural grassland were limited to 3 m, and the recharge depths under deep-rooted mature shrubs and forest were limited to 2 m. But in an extremely wet year, water recharge depth might be deeper. In a long-term study (1988-90, 1992-95) in an area with average annual rainfall of 447.5 mm, water recharge depths of populous hopeiensis forest, caragana shrub, and *Robinia pseudoacacia* were 2, 1.2, 0.8 m, respectively, in normal years [28], but at an extremely wet year in which the growing season (April- October) rainfall was 651.6 mm, the rainfall recharge depth under caragana shrub reached to 3.1 m [29]. In a simulation study, simulated precipitations were 345.8, 595.8, and 889.4 mm, standing for very dry, normal, and very wet years, the recharge depths in bare soil were 1.8, 2.4, and 3.8 m, respectively, when simulated rainfall were 377.8, 639.5, and 838.2 mm, recharge depths of natural grassland were 1.6, 2.4, and 3 m, respectively [30].

A common issue concerning many scientists and planners is whether deep soil moistures in dry layers were changeable or not under mature planted forests and shrubs. If deep soil moisture is stable in a dry layer, it might mean that deep soil has lost its function as a "soil water reservoir," and the planted trees and shrubs grow using present-year precipitation. Because the ground water was 40-100 m below the deep loess deposit, it is impossible for planted forests or shrubs to extract ground water [31]. This might lay unfavorable living conditions for planted vegetation in consecutively dry years.

Some short-term studies have indicated that below rainfall recharge depth, there were no inter-annual moisture changes under mature artificial forests and shrubs in the semiarid area of the plateau [23, 26, 32]. Our initial study also showed that there were no inter-annual changes in deep soil moisture under both shallow- and deep-rooted vegetation, and there were no significant moisture differences in deep soil layers between cropland and grassland, neither among forest of different species [16]. But in a short period the range of annual precipitation was limited. Thus long-term study is needed to evaluate the status and variability of soil moisture in dry soil layers under planted forest and shrub. This paper reports the results of 5 years of tests of soil moisture of deep- and shallow-rooted vegetation in the semiarid area of the Loess Plateau in a period of eight years from 2001-08. The main purpose was to evaluate the moisture status and its variability under deep- and shallow-rooted vegetation in the area. The results of this study may provide valuable data for sustainable land use planning.

Method

Study Sites

The study was carried out in the middle reaches of the Yellow River, near the county town of Suide, Shannxi Province, which is located within the semi-arid area of the

Table 1. Annual precipitation (mm) from 2000-08.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	Average
Precipitation	277.6	457.5	353.7	439.0	320.0	306.6	434.9	470.1	355.1	379.4

Table 2. Site characteristics of soil water sampling.

Site	Slope position	Slope aspect	Slope degree	Elevation/m	Time of moisture measurement
C	Middle	East	36°	960	2001.10.25, 2005.10.23, 2006.11.6, 2007,11.15, 2008.11.16
G	Up middle	East	36°	1021	2001.10.28, 2005.10.19, 2006.11.4, 2007.11.14, 2008.11.16
SH	Middle	East	32°	980	2001.10.24, 2005.10.21, 2006.11.3, 2007.11.10, 2008.11.17
F1	Middle	East	32°	980	2001.10.29, 2005.10.21, 2006.11.4, 2007.11.15, 2008.11.17
F2	Middle	East	32°	980	2001.10.28, 2005.10.18, 2006.11.4, 2007.10.25, 2008.11.17
F3	Middle	East	32°	980	2001.10.25, 2005.10.22, 2006.11.3, 2007.11.16, 2008.11.18

Loess Plateau in northwestern China, the geographical location of the study area was proximately 37º31'16" N, 110º17'05" E. Mean annual precipitation is 438.3 mm (1960-2008), with 70% falling in June-September, and the annual precipitation varied from 254.4 mm (1965) to 745.2 mm (1964). The annual precipitation from 2000-08 varied from 277.6 to 470.1 m with average of 379.4 mm (Table 1). The mean annul temperature was 9.7ºC and mean annual potential evaporation was about 1,900 mm/a. The soil type is a sandy silt loam (32.1, 60.5, and 7.4% of sand, silt and clay content, respectively) developed on deep loess. The main soil characteristics in 0-1 m depth were summarized as 1.25 g/cm^3 of bulk density, 54.0% of porosity, 1.15-1.30 mm·min^{-1} hydraulic conductivity, 15.8% field capacity, and permanent wilting points of 4% [32]. The slope of the area is very steep and about 62% of the total land is greater than 25º. The area belongs to an ecotone from typical steppe to broadleaved deciduous forest (forest-steppe), from northwest to southeast. Extant vegetation were mainly crops and planted grasses, brush, and forest. The planted forest species are mainly pine (*Pinus tabulaeformis*) and arborvitae (*Platycladus orientalis*), planted separately and in mixtures, and the caragana (*Caragana microphylla* Lam.) was the main planted shrub. In recent years some cropland has been abandoned and returned to natural grasses, in which the components are semi-perennial herbaceous grasses mainly consisting of *Artemisia gmelini*, *Artemisia grandii*, and common forbs (*Lespedeza devurica* and *Aster altaicus*). An important gramineous grass is *Stipa bungeana*, scattered in the herbaceous grasses or dominant at rather drier situations.

Sampling Sites

According to the length of roots and their influence on deep soil moisture, two groups of vegetation were selected. The first group was shallow-rooted vegetation: crops and natural grasses. The second group was deep-rooted vegetation, mainly planted brushes and area forests. One site on cropland (C) and another site on natural grass land (G) were selected and referred to as replications because both crop and natural grasses were shallow-rooted compared to shrub and forest, and they had similar soil-water consumption intensity and depth [16]. For the deep-rooted group, each site in planted caragana shrub (SH), planted arborvitae forest (F1), pine forest (F2), and the mixture of pine and arborvitae forest (F3) was selected. These four sites also were replications because all four vegetation elements had deep roots and also had similar water consumption intensity and depth, though the deep soil moisture of caragana was slight lower than the other three forests, the absolute difference was very small [16]. For the representative of the regional topographic properties, all sites were located on the middle or upper-middle slope positions with similar topographic characteristics (Table 2).

All forests and caragana were planted in 1985. The forest density was 5,400 trees/ha. The average height of arborvitae was 5.5 m and that of pine was 5 m, but in the mixture the height of pine tree was 3.3 m and that of arborvitae was still 5.5 m. The density of caragana was about 4,500 clusters/ha with average 1.3 m in height. Under the arborvitae and pine forest, there were little grass species presented but with about 2 mm thick ground litter, under the mixture of pine and arborvitae, there were many herbaceous grass species mainly *Artemisia gmelini*, *Artemisia grandii*, *Lespedeza devurica*, and *Aster altaicus*. The ground coverage of all planted forest was over 90%.

Soil Water Testing and Data Analysis

Soil moisture was measured one time in late October to early or middle November in each of 2001, 2005, 2006, 2007, and 2008 (Table 2). By the time of late October to early November in a year, the rainy season had just passed and soil water recharge reached its maximum. In addition, this is typically the start of a period when the abundance and distribution of soil moisture remains relatively constant [34], so the inter-annual differences in soil moisture at a specific site could be ascribed to annual rainfall recharge differences or water consumption differences between years.

The soil moisture of all sites was measured to a depth of 10 m. Soil water samples were tested at 0.2 m intervals to a depth of 3 m, and at 0.3 m intervals from 3 to 10 m. Soil samples were extracted using a subsoil probe, and oven-dried to determine soil moisture. Results were reported in percent gravimetric soil moisture. Relative soil moisture was the ratio of gravimetric soil moisture to field capacity.

SPSS (SPSS Inc., Widows ver. 10.0) was used to obtain descriptive statistics of soil moisture, and to compare moisture difference on soil profile among years using a non-parametric test program (K-related samples).

Results and Analysis

Inter-Annual Moisture Change

Soil moisture under all the six sites varied greatly from surface soil to certain depths among the study years, but below these depths, soil moisture distribution lines became close and repeatedly intersected (Fig. 1), which meant there were few moisture differences among the study years. Here we refer to the soil layers in which moisture was changeable inter-annually as moisture changeable layer, and those soil layers on which moisture had no or little inter-annual changes were referred as moisture-stable layers.

The depth or thickness of inter-annually changeable layer we directly read from Fig. 1 was about 3 or 4 m for cropland, and about 1.3 m for the mixture of pine and arborvitae, and about 2 m for all other vegetation types. To establish uniform criteria we used moisture variance as an indicator to evaluate moisture-changeable depths for all sites. Variance was calculated as follows:

$$S_z^2 = \frac{1}{n-1}\sum_{j=1}^{5}\left(w_{ijz}-\overline{w}_{iz}\right)^2, \quad j = 1,2,3,4,5 \qquad (1)$$

...where S_z^2 was moisture variance of z site, w_{ijz} was soil moisture at i depth of j year of z site, and $\overline{w}_{iz}$ was the average moisture of 2001, 2005, 2006, 2007, and 2008 at i depth of z site. Fig. 2 was moisture variance distribution on soil profiles.

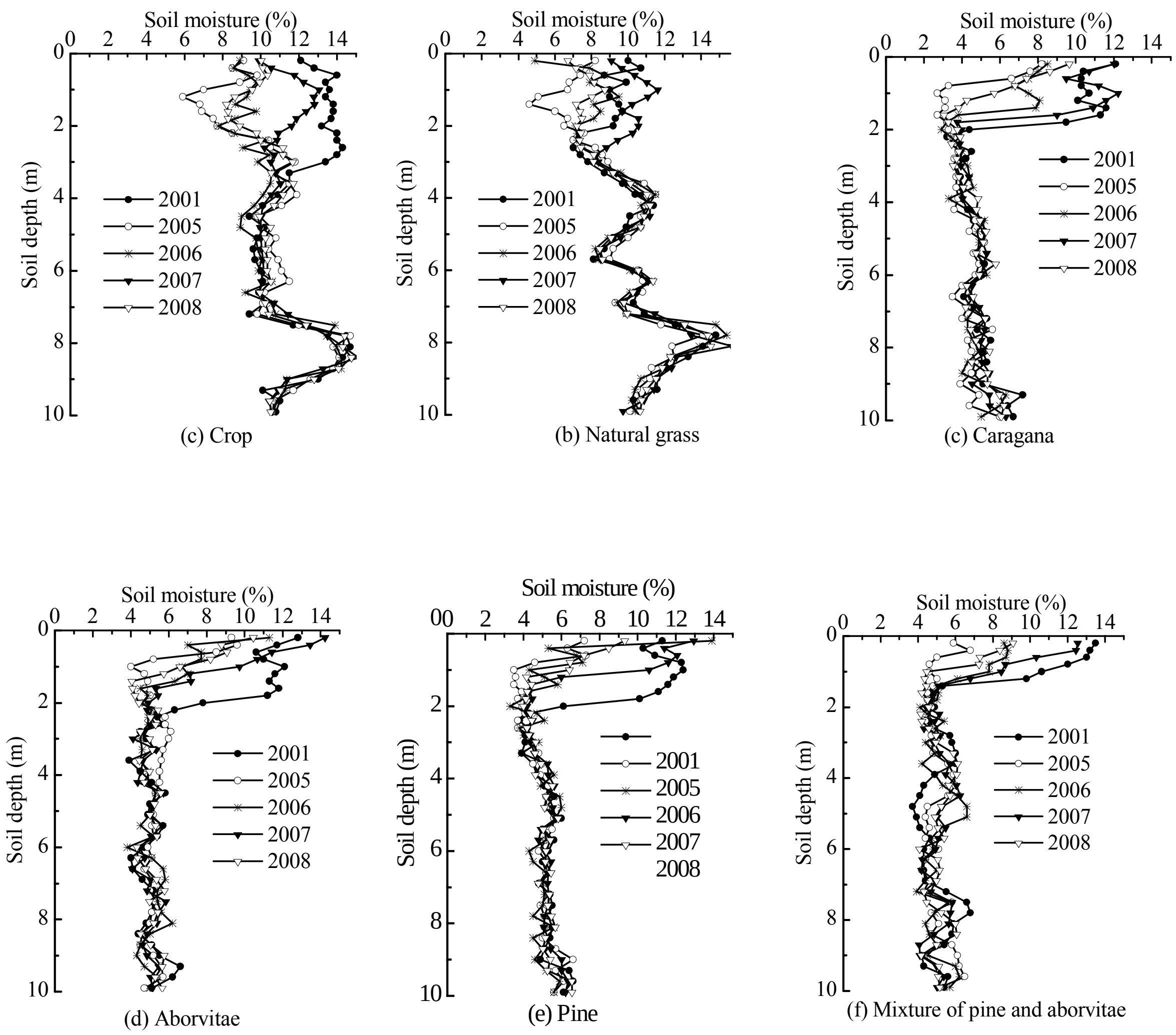

Fig. 1. Moisture change with soil depth of different vegetations types.

Table 3. Statistical significance of moisture differences among study years.

Vegetation	Inter-annually changeable layer		Inter-annually unchangeable layer	
	Soil layer (m)	Significance	Soil depth (m)	Significance
Crop	0-3	**	3-10	NS
Natural grass	0-2.4	**	2.4-10	NS
Caragana	0-1.8	**	1.8-10	NS
Arborvitae	0-2	**	2-10	NS
Pine	0-2	**	2-10	NS
Pine+arborvitae	0-1.2	**	1.2-10	NS

**significant at p<0.01, NS – not significant (p>0.05), (Friedman Test)

The moisture variances were changed greatly above certain depths of all sites, indicating great moisture changes among years, but below these depths, on most soil profiles, the moisture variances were less than 1 and became rather stable (Fig. 2), which indicated that there were few changes in soil moisture among the study years. We set variance 1 as a critical value. The soil layer on which moisture variance was greater than 1 was referred to as the annually changeable layer. Otherwise, the section where moisture variance was less than 1 was looked at as a stable layer. According to this criteria, the inter-annually changeable depth under crop, natural grass, planted caragana brush, arborvitae forest, pine forest, and the mixture of pine and arborvitae forest in the five study years was 3, 2.4, 1.8, 2.0, 2.0, and 1.2 m, respectively. Nonparametric tests (K-related samples Friedman test) showed that there were significant moisture differences in the inter-annually changeable layer, but no significant differences in stable layers under each vegetation site (Table 3).

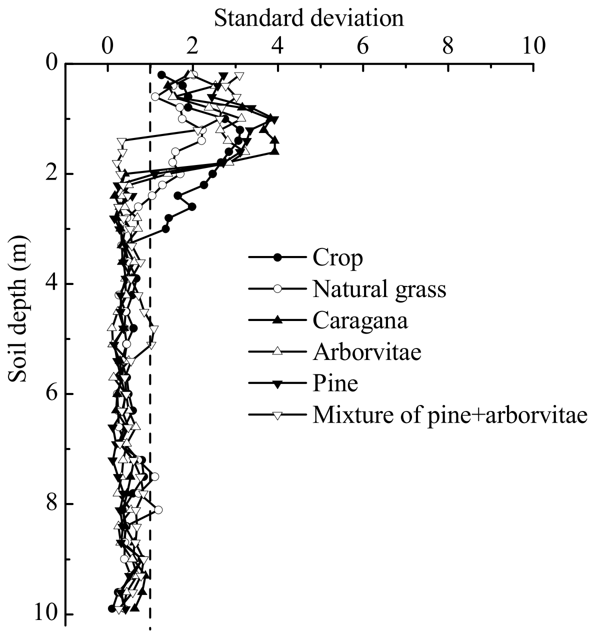

Fig. 2. Distribution of moisture variance among 2001, 2005-08 study years along soil profile.

In the inter-annually stable layers of cropland and natural grassland, though there were no inter-annual moisture changes among the study years, there were moisture changes along the profiles. However, the moisture distribution lines under the deep-rooted plants were rather straight along the stable layer (Fig. 1). The changes under shallow-rooted crops were mainly caused by the differences in soil clay content. There were also differences in soil clay content under deep-rooted plants, but the strong water consumption capability of deep roots diminished the influence of the difference in clay content and made the moisture distribution lines relatively straight along soil profiles [35].

Net Rainfall Recharge Depth

Because there were no moisture changes below the inter-annually changeable layer, the lower boundary of inter-annually changeable layer should be the maximum rain water recharge depth in the study years. So the maximum recharge depths of the lands under crops, natural grasses, caragana shrubs, arborvitae forest, pine forest, and mixed pine and arborvitae forest 3.0, 2.4, 1.8, 2.0, 2.0, and 1.2 m, respectively, in the five study years.

The changeable layer means rainfall could recharge water at least in relative wet years. The stable layer did not necessarily mean there was no water recharged at all, but it did mean little or no net water recharged at the time when the rainy season had passed. Because of the late time of year, soil water recharge reached its maximum and soil moisture was undergoing a relatively constant period under deep-rooted vegetation [34]. Other studies have also demonstrated that it was very rare for precipitation to recharge water below 2 m once planted shrubs and forest were established [16, 34, 36, 37]. Within the inter-annually changeable layer of the study period, rain water might reach to different depths in different times of a single year, but the maximum depth to where net recharge reached should be limited to the wetting front in the late time of year.

Since there was no inter-annual moisture difference among the study years and rather uniformly distributed on the stable layer under each of the deep-rooted vegetation, the average soil moisture of the stable layer across the five study years could be taken as a critical value for evaluating net annual recharge depth under each deep-rooted vegetation. The average soil moisture in stable layer was calculated as follows:

$$\overline{w}_x = \frac{1}{n}\sum_{j=1}^{5}\left(\overline{w}_{xj}\right), \qquad j = 1,2,3,4,5 \tag{2}$$

...where $\overline{w}_x$ was the average soil moisture in stable layer across the five study years of x site, $\overline{w}_{xj}$ was the average soil moisture in stable layer in j year of x site. If moisture from surface was continuously higher than the average ($\overline{w}_x$) of the stable layer in the late time of a specific year, it implied that net rainfall recharged that part of the profile. But this was not true for shallow-rooted vegetation like crops and

Table 4. Net rainfall recharge depth under deep-rooted vegetation in late 2001, 2005-08.

Vegetation	Net rainfall recharge depth (m)					
	2001	2005	2006	2007	2008	Average
Caragana	1.8	0.6	1.4	1.6	1.0	1.3
Arborvitae	2.2	0.6	1.4	1.4	1.0	1.3
Pine	2.0	0.6	0.8	1.2	1.0	1.1
Mixture of pine and arborvitae	1.2	0.4	1.2	1.2	0.8	1.0
Average	1.8	0.6	1.2	1.4	1.0	1.2

Table 5. Pearson correlation coefficient (r) between net annual rainfall recharge depth and the amount of rainfall of different time periods under deep-rooted vegetation.

Months	8-10	7-10	6-10	3-9	2-9	1-9	6-9	1-10	4-10	3-10	2-10	7-9	4-9	8-9
r	0.843	0.835	0.824	0.785	0.779	0.776	0.775	0.771	0.767	0.762	0.756	0.754	0.713	0.710
Sig.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Months	5-10	5-9	8	7-8	6-8	1-4	3-8	1-8	2-8	2-4	3-4	4-8	4	7
r	0.668	0.632	0.622	0.587	0.546	0.545	0.538	0.533	0.530	0.492	0.490	0.482	0.475	0.421
Sig.	0.001	0.003	0.003	0.007	0.013	0.013	0.014	0.015	0.016	0.027	0.028	0.032	0.034	0.064

natural grass land because there were large moisture changes along the stable layer due to the influence of clay content differences.

The average soil moistures ($\overline{w}_x$) of 2001, 2005-08 across the stable layer under the caragana, arborvitae, pine, and the mixture forest of pine and arborvitae were 4.6, 5.1, 5.1, and 5.0%, respectively (Table 6). We took these data as critical values to evaluate water recharge depths in 2001, 2005, 2006, 2007, and 2008, respectively, for each deep-rooted vegetation. For example, in 2001 soil moisture from surface soil under caragana was continuously higher than 4.6% to a depth of 1.8 m, below which the soil moisture was close to 4.6%, so the recharge depth was determined as 1.8 m for 2001. For 2005, soil moisture in 0-0.6 m was higher than 4.6%, so the recharge depth at the late time of this year was 0.6 m. The recharge depths of all other years and other deep-rooted sites were determined in this same way (Table 4).

Net water recharge depth depended on vegetation type and the amount of rainfall, but differences of recharge depths among the deep-rooted species were much smaller than the differences among study years with different rainfall amounts. The five-year average rainfall recharge depths under the deep-rooted vegetation varied from 1.0-1.3 m, but the average recharge depth of the four deep-rooted species varied from 0.6-1.8 among the five study years (Table 4). There was significant relationship between net rainfall recharge depth and rainfall amount (Table 5). The recharge depths were significantly correlated with rainfalls of many time periods, but the relative higher correlation coefficient (r>0.8) occurred between recharge depth and the rainfall amounts in the months of 8-10, 7-10, and 6-10, and the correlation coefficient of recharge depth and the rainfall of 8-10 was the highest. This was mainly because, on one hand, much annual rain in the area fell after June (Fig. 3).

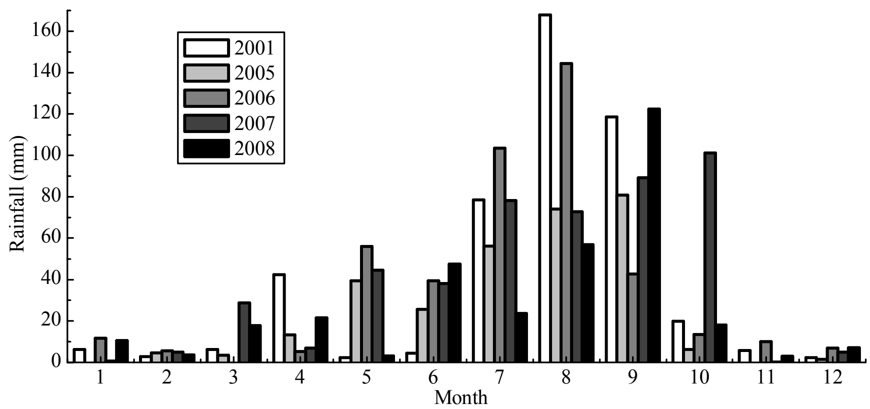

Fig. 3. Monthly precipitation in the study area in 2001, 2005-08.

Table 6. Soil moisture and relative moisture in inter-annually changeable and unchangeable layers under shallow- and deep-rooted vegetation in the five study years.

Vegetation	Year	Inter-annual moisture changeable layer			Inter-annual moisture stable layer		
		Soil layer	Soil moisture	Relative moisture	Soil layer	Soil moisture	Relative moisture
Crop	2001	0-3	13.6	85.9	3-10	11.1	70.5
	2005		8.7	55.1		11.5	72.6
	2006		9.2	58.3		11.0	69.7
	2007		11.5	72.7		11.2	70.7
	2008		9.7	61.6		11.4	72.0
	Average		10.5	66.7		11.2	71.1
Natural grass	2001	0-2.4	9.1	57.7	2.4-10	10.5	66.4
	2005		6.7	42.2		10.5	66.7
	2006		7.8	49.6		10.5	66.7
	2007		10.3	65.2		10.7	67.7
	2008		7.6	51.3		10.6	67.0
	Average		8.3	53.2		10.6	66.9
Caragana	2001	0-1.8	10.7	67.7	1.8-10	4.8	30.2
	2005		4.5	28.5		4.3	26.9
	2006		6.8	43.1		4.5	28.7
	2007		10.1	63.9		4.8	30.1
	2008		5.8	40.0		4.7	29.9
	Average		7.6	48.6		4.6	29.2
Arborvitae	2001	0-2	11.2	70.8	2-10	5.1	32.3
	2005		6.1	38.3		5.3	33.4
	2006		6.8	42.8		5.0	31.6
	2007		9.0	57.0		5.0	31.6
	2008		6.6	46.8		5.1	32.3
	Average		7.9	51.1		5.1	32.2
Pine	2001	0-2	10.8	68.4	2-10	5.1	32.2
	2005		4.7	29.9		5.1	32.0
	2006		6.0	37.8		5.0	31.6
	2007		8.2	51.9		5.2	33.0
	2008		5.9	45.4		5.2	32.7
	Average		7.1	46.7		5.1	32.3
Pine+ arborvitae	2001	0-1.2	12.0	76.1	1.2-10	5.0	31.5
	2005		5.3	33.6		5.0	31.6
	2006		8.0	50.4		5.0	31.9
	2007		9.9	62.5		5.0	32.0
	2008		6.8	58.6		5.0	32.0
	Average		8.40	56.3		5.0	31.8

Table 7. Pearson correlation coefficients (r) between soil moisture and the amount of rainfall in different time periods in moisture changeable layers under shallow-rooted vegetation.

Month	8-10	7-10	6-10	3-10	2-10	1-10
r	0.738	0.671	0.660	0.638	0.632	0.624
Sig.	0.014888	0.034	0.038	0.047	0.050	0.054

The data used in correlation analysis incorporated crop and natural grass data. Note that correlation coefficients (r) were arranged in descending order, and the last one is not significant (p>0.05)

Table 8. Pearson correlation coefficient (r) between soil moisture and the amount of rainfall in different time periods in moisture-changeable layers under deep-rooted vegetation.

Months	8-10	7-10	6-10	3-10	2-10	1-10	4-10	3-9	2-9	7-9	1-9	6-9	8-9	5-10
r	0.960	0.912	0.876	0.828	0.821	0.818	0.814	0.773	0.765	0.755	0.740	0.736	0.733	0.700
Sig.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Months	4-9	2-4	3-4	1-4	5-9	8	4	9-10	7-8	3-8	2-8	6-8	1-8	10
r	0.677	0.646	0.641	0.618	0.573	0.563	0.550	0.535	0.533	0.470	0.461	0.451	0.447	0.425
Sig.	0.001	0.002	0.002	0.004	0.008	0.010	0.012	0.015	0.016	0.036	0.041	0.046	0.048	0.061

The data used in correlation analysis incorporated crop and natural grass data. Note that correlation coefficients (r) were arranged in descending order, and the last one is not significant (p>0.05).

On the other hand, the rain that fell earlier was evapotranspired by vegetation [33] when the temperature was higher than late year. Although the total annual precipitation in 2007 was the highest among the study years (Table 1), the maximum recharge depth occurred in 2001, because the rainfall in 6-10, 7-10, and 8-10 m were the highest in 2001, especially the rainfall in 8-10 m of 306.3 mm, which was 145.1, 105.9, 43.3, 109.0 mm higher than those in 2005, 2006, 2007, and 2008 of the same periods. The water recharge depth in 2005 was the shallowest in the five study years, only equal to or less than 0.6 m under all deep-rooted species because the rainfall in 2005 was 305.4 mm (the lowest in the five study years). The average recharge depths of the four deep-rooted vegetation were in the order of 2001, 2007, 2006, 2008, 2005, which corresponded to the rainfall order in months 6-10 of 2001 (389.2 mm), 2007 (379.3 mm), 2006 (343.4 mm), 2008 (268.3 mm), and 2005 (243.0 mm).

The recharge depths of the mixture of pine and arborvitae were shallower than other deep-rooted vegetation in many of the study years. The herbaceous grass species under the mixture might contribute to the shallower rainfall recharge depth than under other deep-rooted vegetation without so much herbaceous grass species.

Water Availability

The average soil moisture in changeable layers under crop, natural grass, caragana, arborvitae, pine, and the mixture of pine and arborvitae were 9.2-13.6, 6.7-10.3, 4.5-10.7, 6.1-11.2, 4.7-10.8, and 5.3-12.0%, and those in unchangeable layers were 11.0-11.5, 10.5-10.7, 4.3-4.8, 5.0-5.3, 5.0-5.2, and 5.0-5.0% in the five study years (Table 6). In the changeable layer, soil moisture was significantly correlated to the amounts of rainfall of many time periods (Tables 7 and 8), but no significant correlation existed in any time periods in the stable layer under both deep- and shallow-rooted vegetation.

Soil moisture in the plateau study area was classified into four categories according to soil water availability for plants [33]: hard-unavailable soil moisture (relative soil moisture <30%), moderately available soil moisture (relative soil moisture 30-49%), easily available soil moisture (relative soil moisture 50-80%), and most easily available soil moisture (relative soil moisture >80%).

In the changeable layers, according to the above-mentioned soil water availability classification, the five-year average soil moisture of all six sites belonged to moderately or easily available moisture because the average relative soil moistures in the five study years were above 40% (Table 6). For cropland, soil moisture in 2001, 2005, 2006, 2007, and 2008 belonged to easily or most easily available levels irrespective of rainfall amounts because the relative soil moistures in the five years were higher than 50%. For natural grassland, only the soil moisture in 2005 belonged to moderately available levels, those of other years belonged to easily available levels. For deep-rooted vegetation, soil moisture availability was changed from hard-unavailable moisture to easily available moisture level dependent on the amount of rainfall. In 2005 the relative moistures of caragana and pine were less than 30%, belonged to hard-unavailable soil moisture, and the moisture of the mixture of pine and arborvitae was 33.6%, close to hard-unavailable soil moisture, and that of arborvitae was 38.3%, belonging to moderately available moisture levels. In 2007 the relative moisture of the three deep-rooted vegetations were adjacent or greater than 70.0%, belonged to the easily available moisture level.

In inter-annually stable layers, the relative soil moistures of both crop and natural grass land were higher than 65% in every study year, belonging to the easily available level. However, the relative moistures of the deep-rooted vegetation were close or below 30% (Table 6), close to or was hard-unavailable moisture levels.

It seems that the soil moisture under caragana brush was particularly lower than those under other deep-rooted forests in the stable layer. Other studies also showed that deep soil moisture under caragana brush was lower than those under planted forest species [18, 38]. This may be due to the higher transpiration [39] and bigger endurance in drought of caragana than the forests in the study area. It has been observed that when soil moisture was less than 3.5%, the caragana began to wither or to die [40], but when soil moisture was continuously below 4.5-5.2%, the pine tree began to wither or to die [17].

Soil moistures of deep-rooted vegetation below inter-annually changeable layers were equal to or close to permanent wilting point (4%), not further decreased nor increased in the five study years in a period of 8 years, and this kind of desiccated layer has reached more than 20 m in soil profiles (Sci China Ser D-Earth Sci, in press). it can be inferred that the deep soil under deep-rooted vegetation had lost its function of "soil water reservoir," and the vegetation mainly used soil moisture recharged from present years. This may be an explanation for the high tree mortality of reforested forests in the consecutive dry periods in the semiarid area of the Loess Plateau [17, 38].

Conclusions

By analyzing soil moistures in late 2001, 2005-08 under deep- and shallow-rooted vegetation in the semiarid area of the Loess Plateau, the following conclusions could be reached:

1. There were inter-annually moisture changeable layers and unchangeable layers under both deep- and shallow-rooted vegetation. The depths of inter-annually changeable layers under shallow-rooted vegetation were deeper than those of deep-rooted vegetation. In this case study, the inter-annually changeable layer of the shallow-rooted crop and natural grassland were 3.0 and 2.4 m, respectively, and those of deep-rooted vegetation of caragana shrub, arborvitae forest, pine forest, and the mixture of pine and arborvitae forest were 1.8, 2.0, 2.0, and 1.2 m, respectively.
2. Annual rain water recharge depth was significantly correlated to rainfall amount under deep-rooted vegetation. The average rain water recharge depths of caragana brush, arborvitae forest, pine forest, and the mixture of pine and arborvitae forest in the five study years in 2005, 2008, 2006, 2007, and 2001 were 0.6, 1.0, 1.6, 1.4, and 1.8 m, respectively, corresponding to the ascending order of rainfall amounts from June-October of the five study years.
3. Soil moisture in inter-annually changeable layers of shallow-rooted vegetation were in easily or most easily available moisture levels in all the study years except in 2005, a very dry year in which the moisture of natural grassland was in the middle available level. However, the moistures of deep-rooted vegetation in the inter-annually changeable layers varied from hard-unavailable level to easily available level defendant on precipitation. In inter-annually stable layer, soil moisture under shallow-rooted vegetation were in easily available levels, but those of deep-rooted vegetation were in or near the hard-unavailable level.
4. The fact that the deep soil moisture under deep-rooted vegetation were close to the permanent wilting point and belonged or near to hard-unavailable level, not increased nor decreased in the five study years in a period of 8 years, indicated that deep soil under this deep-rooted vegetation had lost the function of "soil water reservoir." These results supported the hypothesis that the mature planted shrubs and forest in the semiarid area of the Loess Plateau survived on present year precipitation.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (31000251).

References

1. INOUYE R.S. Effects of shrub removal and nitrogen addition on soil moisture in sagebrush steppe. J. Arid Environ. **65**, (4), 604, **2006**.
2. LOTT J.E., KHAN A.A.H., BLACK C.R., ONG C.K. Water use in a Grevillea robusta-maize overstorey agroforestry system in semi-arid Kenya. Forest Ecol. Manag. **180**, (1-3), 45, **2003**.
3. NIE Y.P., CHEN H.S., WANG K.L., YANG J. Water source utilization by woody plants growing on dolomite outcrops and nearby soils during dry seasons in karst region of Southwest China. J. Hydrol., **420**, 264, **2012**.
4. BLEBY T. M., MCELRONE A. J., JACKSON R. B. Water uptake and hydraulic redistribution across large woody root systems to 20m depth. Plant Cell Environ. **33**, (12), 2132, **2010**.
5. FERNANDEZ M.E., GYENGE J., LICATA J., SCHLICHTER T., BOND B.J. Belowground interactions for water between trees and grasses in a temperate semiarid agroforestry system. Agroforest. Syst. **74**, (2), 185, **2008**.
6. NADEZHDINA N., FERREIRA M.I., SILVA R., PACHECO C.A. Seasonal variation of water uptake of a *Quercus suber* tree in Central Portugal. Plant Soil **305**, (1-2), 105, **2008**.
7. SEKIYA N., YANO K. Do pigeon pea and sesbania supply groundwater to intercropped maize through hydraulic lift? Hydrogen stable isotope investigation of xylem waters. Field Crops Res. **86**, (2-3), 167, **2004**.
8. MUTHURI C.W., ONG C.K., BLACK C.R., NGUMI V.W., MATI B.M. Tree and crop productivity in Grevillea, Alnus and Paulownia-based agroforestry systems in semi-arid Kenya. Forest Ecol. Manag. **212**, (1-3), 23, **2005**.
9. NIPPERT J.B., WIEME R.A., OCHELTREE T.W., CRAINE J.M. Root characteristics of C-4 grasses limit reliance on deep soil water in tallgrass prairie. Plant Soil, **355**, (1-2), 385, **2012**.

10. EILERS V.H.M., CARTER R.C., RUSHTON K.R. A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria. Geoderma **140**, (1-2), 119, **2007**.
11. WANG Y.Q., SHAO M.A., LIU Z.P., WARRINGTON D.N. Regional spatial pattern of deep soil water content and its influencing factors. Hydrolog. Sci. J., **57**, (2), 265, **2012**.
12. LATTA R.A., COCKS P.S., MATTHEWS C. Lucerne pastures to sustain agricultural production in southwestern Australia. Agr. Water Manage. **53**, (1-3), 99, **2002**.
13. ZHANG Y., ZHAO S.W., LIANG X.F., JIANG Z.W. Review of Soil Water Reservoir and Analysis on Influencing Factors in the Loess Plateau. Research of Soil and Water Conservation, **16**, (2), 147, **2009**.
14. CHEN H.S., SHAO M.A., LI Y.Y. Soil desiccation in the Loess Plateau of China. Geoderma **143**, (1-2), 91, **2008** [In Chinese].
15. WANG J.X., HUANG B.L., LUO W.X. Compensation and rehabilitation characteristics of soil water deficit at a planted forest site of the drought- prone Loess Plateau. Acta Ecologica Sinica **24**, (11), 2395, **2004** [In Chinese].
16. WANG Z.Q., LIU B.Y., ZHANG Y. Effects of Different Vegetation Type on Soil Moisture in Deep Loess Soil Profiles. Acta Geographica Sinica **63**, (7), 703, **2008** [In Chinese].
17. WANG Z.Q., LIU B.Y., XU C.D., FU J.S. Survival capability of four types of artificial forests in the Loess Plateau. J. Soil Water Conserv. **16**, (4), 25, **2002** [In Chinese].
18. YANG J.J., LI H.K., ZHENG G.J., LÜ G.H., SHI Q.D., TAXIFULATI T. Preliminary Research on Countermeasures of Desiccation of Deep Soil Layer in Loess Plateau. J. Soil Water Conserv., **20**, (4), 186, **2006**.
19. WANG G.L., LIU G.B., CHANG X. A study on the efect of soil water on vegetation rehabilitation in watershed of loess hilly area. Journal of Natural Resources **17**, (3), 339, **2002** [In Chinese].
20. LIU G., WANG Z.Q., WANG X.L. Analysis of dried soil layer of different vegetatation types in Wuqi County. Research of Soil and Water Conservation **11**, (1), 126, **2004** [In Chinese].
21. LI J., CHEN B., LI X.F., CHENG J.M., HAO M.D. Effects of deep soil desiccations on alfalfa grasslands in different rainfall areas of the Loess Plateau of China. Acta Ecologica Sinica **27**, (1), 75, **2007** [In Chinese].
22. WANG Z. Q., LIU B. Y., LIU G., ZHANG Y. X. Soil water depletion depth by planted vegetation on the Loess Plateau. Sci. China Ser. D., **52**, (6), 835, **2009**.
23. HUE Z., ZHANG B.L. Study on soil dry layer distribution in the main shrub land of Liudaogou catchment. China Population, Resources and Environment **17**, (5), 95, **2007** [In Chinese].
24. XU X.X., ZHANG B.Y., JU T.J. The Spatial-temporal distribution of rainfall, runoff, and soil water in small watershed and its utilization. Ecology and Environment **14**, (6), 890, **2005** [In Chinese].
25. WANG Z.Q., LIU B.Y., HAI C.X., FU J.S. Analysis of soil water content of different vegetation types in the north western area of Shanxi Province. Journal of Arid Land Resources and Environment **16**, (4), 53, **2002** [In Chinese].
26. FAN J., SHAO M.A., WANG Q.J. Soil water restoration of alfalfa land in the wind-water erosion crisscross region on the Loess Plateau. Acta Agrestia Sinica **14**, (3), 261, **2006** [In Chinese].
27. GUO Z.S., SHAO M.A. Dynamics of soil water supply and consumption in artificial Caragana Shrub Land. J. Soil Water Conserv. **21**, (2), 119, **2007** [In Chinese].
28. WANG M.B., LI H.J. Quantitative study on the soil water dynamics of various forest plantations in the Loess Plateau region in northwestern Shanxi. Acta Ecologica Sinica **15**, (2), 177, **1995** [In Chinese].
29. LI H.J., WANG M.B., CHAI B.B. Study on characteristics of soil moisture of planted forest and its relation to precipitation in northwestern Shanxi. J. Soil Water Conserv. **4**, (4), 60, **1998** [In Chinese].
30. CHEN H.S., SHAO M.A., WANG K.L. Desiccation of deep soil layer and soil water cycle characteristics on the Loess Plateau. Acta Ecologica Sinica **25**, (10), 2491, **2005** [In Chinese].
31. LI Y.S. Effects of forest on water cycle on the Loess Plateau. Journal of Natural Resources **16**, (5), 427, **2001** [In Chinese].
32. WANG L., SHAO M.A., ZHANG Q.F. Distribution and characters of soil dry layer in north Shaanxi Loess Plateau. Chinese Journal of Applied Ecology **15**, (3), 436, **2004** [In Chinese].
33. YANG W.Z., SHAO M.A. Study on Soil Water of Loess Plateau. Beijing, Science Press, **2000** [In Chinese].
34. YANG W.Z., YU C.Z. Regional Management and Evaluation. Beijing, Science Press, **1992** [In Chinese].
35. WANG Z.Q., LIU B.Y., WANG X.Y., HAN Y.F. Soil water restoration of different land use after artificial forest in the semi-arid area of Loess Plateau. Transanctions of the CSAE **23**, (11), 77, **2007** [In Chinese].
36. CHENG J.M., WAN H.E., WANG J. Over depletion and recovery of soil moisture on Astragalus adsurgens grasslands in the loess hilly-gully region. Acta Ecologica Sinica **24**, (12), 2979, **2004** [In Chinese].
37. CHENG J.M., WAN H.E., WANG J., YONG S.P. Growth of *Caragana korshinskii* and depletion process of soil water in semi-arid region. Scientia Silvae Sinicae **41**, (2), 37, **2005** [In Chinese].
38. HOU Q., HAN R., LI H. On the problem of vegetation reconstruction in the Yan'an experimental area. Research of Soil and Water Conservation **7**, 102, **2000** [In Chinese].
39. YUAN H.Y., XU X.M. Soil water dynamics of plantations in Sub-arid gully and hilly regions of the Loess Plateau. Journal of Northwest Forestry University **19**, (2), 5, **2004** [In Chinese].
40. YANG W.B., REN J.M., JIA C.P. Study on the relationship between physiological ecology of drought- resistance in Caragana and soil water. Acta Ecologica Sinica **17**, (3), 239, **1997** [In Chinese].