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

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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),

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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.