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Modeling soil–water dynamics and soil–water carrying capacity for vegetation on the Loess Plateau, China

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ABSTRACT

The conflict between soil desiccation and the sustainable development of revegetation is increasingly important on the Loess Plateau in China. Quantitative guidelines for the selection of plant species, optimal density or biomass, and appropriate management for vegetative restoration are required to address this conflict. The objective of the study is to simulate soil–water dynamics with using the one-dimensional Simultaneous Heat and Water Transfer (SHAW) model to assess consumption process of soil water with growth of caragana and alfalfa and there optimal carrying capacity. Soil and plant parameters required by the SHAW model were calibrated and validated with meteorological and soil–water data from 2004 to 2005 and 2012, respectively. The data from the calibration and verification trials for soil water content were significantly linearly correlated based on a 95% confidence level and had average root mean square errors of 1.06 and 5.71% for caragana and 0.88 and 1.14% for alfalfa, respectively. The SHAW model was thus sufficiently accurate for simulating soil–water dynamics during 2005–2011 in response to plant growing and corresponding changes in biomass. The simulations indicated that soil water decreased within 1.0–4.0 m profiles and that the depth of water depletion deepened with plant growth after vegetative restoration. Dry soil layers (DSLs) began to develop below 1.0 m after five years for caragana and after three years for alfalfa. The optimal ages of the caragana and alfalfa in the study area were thus five and three years, respectively, and the corresponding soil water carrying capacities that were maximum biomasses were 4800 kg/hm^2 and 1380 kg/hm^2, respectively. These results provide useful information for designing appropriate practices of vegetative restoration to attain sustainable ecological and economic benefits on the Loess Plateau.

1. Introduction

On the Chinese Loess Plateau, the Chinese government has implemented many management programs of vegetative restoration since the late 1990s that have converted cropland to forests, shrubland, or grassland to improve the ecological environment and to conserve both soil and water (Chen et al., 2008). The widespread planting of vegetation, however, has aggravated water shortage and the conflict between the carrying capacity for artificial vegetation and the limited water resources during vegetative restoration on the Loess Plateau. Wang et al. (2008) reported that soil desiccation is a serious problem for loess soils in areas with re-established vegetation. Fast-growing artificial plants such as *Caragana korshinskii* Kom. (caragana) and *Medicago sativa* L. (alfalfa) are water-intensive plants with deep root systems, and could escalate water shortages and desiccate deep soil (>1.0 m depth) in arid and semi-arid regions (Fan et al., 2010; Li and Huang, 2008; Wang et al., 2010a). Artificial revegetation increases the intensity and depth of soil–water consumption and soil desiccation, but crops and natural grass do not excessively consume deep soil water (Fu et al., 2012b; Wang et al., 2008). Soil desiccation has a detrimental effect on environmental and hydrological processes and prevents vegetation from maintaining normal growth rates (Chen et al., 2008; Wang et al., 2010a,b). Information on the distributions and dynamics of soil water within soil profiles is vital for the sustainable management of soil water resources and strategies of revegetation (Josa et al., 2012; Wang et al., 2013). It is essential to predict soil–water dynamics with vegetation growth and quantify the available soil water to maintain plants survive.

Adjusting plant productivity to an appropriate carrying capacity is urgently needed in the current restoration of the ecological envi-

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ronment of the Loess Plateau to slow or prevent the formation of dry soil layers (DSLs). The concept of soil–water carrying capacity for vegetation (SWCCV) was introduced to quantify the appropriate plant density or biomass for vegetative restoration for addressing the conflict between soil-water conservation and soil desiccation (Guo and Shao, 2004; Xia and Shao, 2009; Wang et al., 2009). The limited water resource is the most significantly factor to restrict the growth of planted vegetation and plant coverage in the semi-arid and arid region (Fu et al., 2012a; Xia and Shao, 2008). The vegetative carrying capacity is thus mainly determined by the availability of soil water in the water limited region. Thus, accurately simulating long-term soil–water dynamics under revegetation land is the critical basis of quantifying SWCCV. The SWCCV can be an effective tool for managing vegetation to avoid soil desiccation in arid and semi-arid regions (Xia and Shao, 2009). Based on the water balance between water supply and consumption, Guo and Shao (2004) developed a semi-empirical model to determine the optimal coverage for planting vegetation in the Loessial hilly region of the plateau. Xia and Shao (2008) then developed a process-based model to calculate the optimal plant coverage using 2–3 years of contiguous climatic data. Previous studies have only measured SWCCVs for 1–3 years and for plants with young-age or old-age period, few researches study SWCCVs for long-term with different growth ages. The biomasses of the vegetation, however, differed significantly among the growth periods, producing large differences even in same planting densities for the same species (Guo and Shao, 2004; Guo and Shao, 2004a; Wang, 2009; Xia and Shao, 2008). In our study, soil–water dynamics and biomass changes were continuously monitored with for 10 years from 2004 to 2013 with different growth ages for caragana and alfalfa. The caragana experienced young- and middle-age periods, and the alfalfa experienced stages from vigorous growth to degeneration, respectively.

The SHAW model has been tested under a wide range of conditions for predicting soil water dynamics (Huang and Gallichand, 2006; Gribb et al., 2009; Fu et al., 2012a), and the surface energy and water balance (Yin et al., 2010; Zhao et al., 2010). The model also has a wide variety of applications beyond its original intended use, because its detailed physical system through the soil-plant-atmosphere continuum incorporated into the SHAW model (Flerchinger et al., 2012). Researchers have used the model for various applications: revegetation (McDonald, 2002); soil water budgets (Kang et al., 2005; Chauvin et al., 2011); irrigation and water use efficiency (Qin et al., 2005; Yin et al., 2009; Li et al., 2010). However, the model exist limitations with respect to the current applications including no spatial component beyond its one-dimensional nature, no plant growth simulation (the user must input temporal changes in plant characteristics), and no provisions for preferential flow and limited to the Campbell soil moisture release curve (Flerchinger et al., 2012). Even so, soil moisture observations revealed no obvious influence of preferential flow. Simulations of SMs in the study was in vertical one-dimensional system of plant canopy, residue and soil layers, and the parameters of growing plants inputting in the model are the measured values. McDonald (2002) reported that the Simultaneous Heat and Water (SHAW) model was a cost-effective method for assessing revegetation. The SHAW model has been applied on the Loess Plateau to accurately simulate the movement of soil water, soil–water dynamics and water balance (Cheng et al., 2007; Huang and Gallichand, 2006; Fu et al., 2012a) and can accommodate variations of the air-plant-residue-soil system. Thus, the physics-based model was used to simulate one-dimensional soil–water dynamics and to determine the optimal SWCCVs for caragana and alfalfa. The main objectives of this study were: 1) to simulate and investigate soil–water dynamics and soil–water depletion in deep soil (1.0–4.0 m) with plant growth using the SHAW model, and 2) to mathematically model the SWCCVs for the two dominant plant species (*C. korshinskii* and *M. sativa*) during revegetation on the Loess Plateau. These results can be used in future research on optimal use of soil water and maintain the sustainable development of a program of revegetation through quantifying the SWCCV.

2. Materials and methods

2.1. Description of the study site

The study was conducted at the Shenmu Erosion and Environmental Experimental Station (38°46′–38°51′N, 110°21′–110°23′E), Shenmu County, Shaanxi Province, China, in the water-wind erosion crisscross region of the Loess Plateau. The climate is semi-arid temperate with a mean annual temperature of 8.4 °C (ranging from −9.7 °C in January to 23.7 °C in July). The average annual precipitation is 437 mm (minimum of 109 mm and maximum of 891 mm), with significant seasonal and inter-annual variations. Approximately 80% of the rain falls from May to September (Fig. 1). Most of the natural vegetation and residual natural meadows have been destroyed by long-term human activities.

C. korshinskii (caragana) and *M. sativa* (alfalfa) were chosen for this study because they are currently the dominant species used for vegetative restoration at the experimental station. Two plots, one of each species, were established in 2004 with two-year-old caragana and alfalfa seeds on sloped land (approximately 12°). The survival planting spacing for caragana and alfalfa in 2012 were approximately 1.0 m × 1.5 m and 0.2 m × 0.5 m, respectively. The two species received only natural precipitation without irrigation. The soil in the plots is an Aeolian loess, a Camisole (FAO-UNESCO soil classification system) composed of 45.4–50.9% sand, 30.1–44.5% silt, and 11.2–14.3% clay (USDA soil textural classification) in 2004 for the two plots on the same slope land (Zeng et al., 2006). Basic information for the experimental plots in 2012 is presented in Table 1. The soil texture had no significant changes among the period of 2004 to 2012 for the plots with caragana and alfalfa.

2.2. Field measurements

Soil moisture (SM) was measured volumetrically biweekly or monthly during the growing seasons from July 2004 to October 2013 to depths of 4.0 m at increments of 0.1 m from 0 to 1.0 m and of 0.2 m below 1.0 m using a CNC 503DR Hydroprobe neutron moisture meter (Beijing Super Power Company, Beijing, China).

Data for the characteristics of the vegetation (plant height, aboveground biomass, and leaf area index) were collected monthly during the growing seasons. Plant heights were measured with a steel tape. The leaf area index (LAI) was calculated from photographs with Image-J software (National Institutes of Health, USA). The aboveground biomasses for 2012–2013 were obtained by destructively sampling twelve representative branches for caragana, and harvesting the grass in three 1.0 × 1.0 m quadrats alfalfa, respectively. These samples were oven-dried at 75 °C for 72 h and then weighed. The biomasses for 2004–2005 and 2008–2009 were taken from a previous study (Zeng, 2006; Fu, 2010). The biomasses for 2006–2007 were obtained from plants of the same age in other stands at the study site.

Precipitation, wind speed, solar radiation, dew-point temperature, and maximum and minimum air temperatures were recorded at a meteorological station. The meteorological variables were converted to represent daily mean values for wind speed, dew-point temperature, and maximum and minimum air temperatures. Precipitation and global radiation are presented as daily accumulated values. All these data were used as input variables for modeling the SM dynamics of the two plots.

Table 1
Soil properties and plant coverage of the experimental sites in 2012.

Plant	Depth m	Clay (%)	Silt (%)	Sand (%)	ρ_b (g/cm^3)	Ks (mm/min)	SSM (cm^3/cm^3)	Coverage (%)
Caragana	0–0.1	9.6	36.6	53.8	1.44	0.376	0.35	70
	0.2–1.0	9.8	38.8	51.4	1.34	0.446	0.45	
	1.0–4.0	10.7	43.1	46.2	1.40	0.408	0.43	
Alfalfa	0–0.1	9.8	38.6	51.5	1.40	0.412	0.44	45
	0.2–1.0	11.2	42.3	46.5	1.45	0.365	0.39	
	1.0–4.0	11.3	43.1	45.6	1.49	0.335	0.36	

ρ_b – bulk density; Ks – saturated hydraulic conductivity; and SSM – saturated soil moisture.

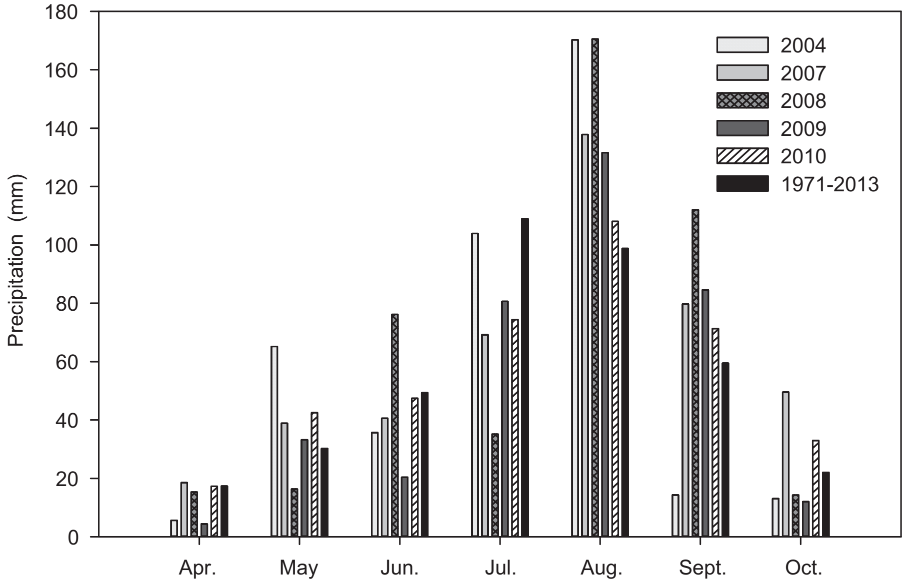

Fig. 1. Monthly precipitation at the study site from April to October for 2004, 2007–2010 and the means for 1971–2013.

2.3. Description of the SHAW model

The Simultaneous Heat and Water (SHAW) model can simulate the one-dimensional movement of water and heat within a vertical profile (Flerchinger, 2000; Preston and McBride, 2004). This study used version 3.0b of the SHAW model which was freely available for download from an anonymous ftp site (ftp.nwrc.ars.usda.gov/public/ShawModel/). Detailed descriptions of the physical processes represented in the model are given in the technical documentation (Flerchinger, 2000). The SHAW model has been extensively demonstrated to simulate heat and water movement within a vertical, one-dimensional system extending from vegetation canopy to a specified soil depth and may include snow and plant residue with random nodes division (Hymer et al., 2000; Flerchinger and Hardegree, 2004; Huang and Gallichand, 2006).

The model can be driven by daily meteorological data: maximum and minimum air temperatures, dew-point temperature, wind speed, precipitation, and solar radiation. The soil profile under plots of caragana and alfalfa was discretized into 16 nodes: 0.2 m increments were used from the 1.0 to 4.0 m depth with specified depths, pore-size distributions, air-entry pressures, saturated hydraulic conductivities, soil bulk densities, saturated water contents, and soil textures. The parameters of plant growth for the model included height, dry aboveground biomass, LAI, and effective rooting depth, all collected as described by Kang et al. (2003) and Shao et al. (1987). Water flux at the lower boundary was assigned to free drainage, and soil temperature was estimated by the model.

To improve the accuracy of the simulations, we selected various soil and plant parameters to manually adjust for model calibration. A simplified systematic sensitivity analysis was performed before calibration to determine the effects of parameter variations on the model outputs and then to select the most sensitive parameters (Cheng et al., 2007). Flerchinger and Hardegree (2004) presented the sensitivity of soil water content to soil hydraulic parameters. Because the SHAW model is physics-based, most of the input parameters can often be either measured or gleaned from the literature (Flerchinger et al., 2012). The selected parameters were calibrated based on field measurements and relevant published data, and default values were used for the other parameters in the model. All parameter values optimized by experimental data during July 2004 to December 2005 and April to October of 2012 used to calibrate the SHAW model were presented in Table 2. The SHAW model was constructed on the basis of the equilibrium adjustment of the growth of the vegetation to soil–water deficits and was used to simulate SM and assess the effects of plant species and aboveground biomass on soil–water dynamics. The soil and plant parameters were calibrated for each species, using SM values measured from July 2004 to December 2005 and were then validated using data from 2012. The simulation ran from 2005 to 2010, with daily outputs. The field monitoring period was from July 2004 to October 2013. The calibrated soil and plant parameters were used to simulate the effect of plant biomass on the soil–water dynamics for determining the optimal SWCCV for each species.

2.4. Determination of SWCCVs

The SWCCV can be defined as the largest acceptable aboveground biomass of a given type of planted vegetation where the plants can sustain normal growth using the available soil water without desiccating deep soil (>1.0 m) under specific climatic con-

Table 2
The initial values of soil and plant parameters for the SHAW model.

Parameters		Unit	Caragana	Alfalfa
Soil parameters	Air entry pressure	m	–0.21*	–0.25*
	Pore-size distribution parameter	/	3.2*	3.0*
	Saturated hydraulic conductivity	mm/min	0.43	.045
	Saturated soil moisture	cm^3/cm^3	0.43	0.44
	Stomatal resistance	s/m	100*	75*
Plant parameters	Empirical coefficient	/	5*	5*
	Critical leaf water potential	m	–100*	–100*
	Leaf resistance to water flow	m^3 s/kg	2.5×10^{5}*	2.3×10^{5}*
	Root resistance to water flow	m^3 s/kg	1.5×10^{5}*	1.4×10^{5}*

* Represents the values from Cheng (2008) and Fu (2010). The other values are measured values.

ditions in arid and semi-arid regions. The timing and amount of precipitation can vary intra- and inter-annually in such regions, but the frequency of dry or rainy years is much lower than normal years. The study period of 2004–2013 had five normal years, and the monthly precipitation distribution for 2010 was similar to the mean precipitation distribution for 1971–2013 (Fig. 1). Study had showed that the effect of precipitation on soil–water changes was mainly within 1.0 m for caragana and alfalfa in dry years and normal years, and exceeded 1.0 m in rainy years (Liu, 2015). In current study, 2010 was thus selected as a representative year, and the SWCCVs would be more representative and typical using the climatic parameters of 2010 than using those of dry or rainy year, to model daily SM in the 1.0–4.0 m profiles. Fu et al. (2012b) and Liu (2015) reported that the depth of infiltration of rainwater was generally within 1.0 m for caragana and alfalfa, and the maximum depth was within 2.0 m under extreme rainy year. The upper 1.0 m of soil tends to be replenished by the infiltration of rainwater (Wang et al., 2010a,b), so a depth of 1.0 m was assigned as the upper boundary of DSLs. Based on the definitions of the SWCCV and DSLs, the study mainly simulated SM in the 1.0–4.0 m soil profiles using the SHAW model under a representative normal climate.

DSLs have a range of SM between the permanent wilting point and the stable soil moisture (SSM) (Yang, 2001; Wang et al., 2008; Wang et al., 2010a,b). The SSM has generally been considered to be equivalent to about 60% of the field capacity (FC), based on the textures of the soils on the northern Loess Plateau, and a layer with an SM lower than the SSM would thus be considered a DSL (Wang et al., 2004; Yang and Tian, 2004). We assigned an SSM of 11.1%, which was equal to 60% of the FC. The previous studies calculated SWCCVs mainly in the depths of plant roots can absorb and make use of the soil water through evaluating soil water balance with calculating soil water storage in the depths (Guo and Shao, 2004; Xia and Shao, 2008, 2009). However, previous studies showed that the depth of infiltration of rainwater is generally about 1.0 m and less than 2.0 m for shrubland and grassland (Huo and Zhang 2007; Fu et al., 2012b). The previous studies on SWCCV within the depths of plant roots can absorb could over-estimate the SWCCV. We thus defined the upper and lower DSL boundaries as 1.0 m and 2.0 m, respectively, for determining the optimal SWCCVs, with the SM in the 1.0–2.0 m layer near or at the SSM (11.1%) during the growing season.

2.5. Analytical methods

The simulated performance of the SHAW model was evaluated by statistical analyses. Simple linear regression analyses were applied to calculate Pearson's correlation coefficients of explanation (R^2) between simulated and observed values. The relationships between simulated and observed values were deemed significant if $R^2 > R^2_{\text{crit 95\%}}$, where $R^2_{\text{crit 95\%}}$ is based on a 95% confidence level, implying that $P \leq 0.05$, and available from tables of critical Pearson's coefficients of explanation. The mean error (ME), root mean square error (RMSE), and relative mean absolute error (RMAE) were also determined to assess the agreement between the simulated and observed values.

The values of ME, RMSE, and RMAE were calculated by:

$$\text{ME} = \frac{1}{N}\sum_{i=1}^{N}\left(\text{SM}'_i - \text{SM}_i\right) \tag{1}$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(\text{SM}'_i - \text{SM}_i)^2\right]^{1/2} \tag{2}$$

$$\text{RMAE}(\%) = \frac{\frac{1}{N}\sum_{i=1}^{N}|\text{SM}_i - \text{SM}'_i|}{\frac{1}{N}\sum_{i=1}^{N}\text{SM}_i} \times 100 \tag{3}$$

where SM and SM′ are the observed and simulated values, respectively, at depth i, and N is the number of observations.

3. Results and discussion

3.1. Model evaluation

The SHAW model was run in daily steps from July 2004 to December 2005 for model calibration and July to October in 2012 for validation. The model performance was evaluated by a linear regression between the simulated SMs and the corresponding observed values at each soil node in the 1.0–4.0 m profiles of each plot (Figs. 2 and 3). The simulated and observed SM values generally agreed well both for caragana and alfalfa in 1.0–4.0 m profile during the calibration and validation periods. Some measured and simulated values had relatively large errors, mainly from shallow layers, because the measured SMs in 0–2.0 m layers were variably affected by precipitation and evapotranspiration (Fu et al., 2012b; Huo and Shao, 2007; Wang 2010a). And the measured SM were the instantaneous values at a moment, while the simulated SMs represented averaged daily values. The coefficients of determination (R^2) between simulated and measured SMs for both plots were all above 0.8 during the calibration period and above 0.6 during the validation period. These values were much higher than the $R^2_{\text{crit 95\%}}$ of 0.3, indicating that the measured and simulated values were significantly correlated. The simulated SMs thus generally agreed well with the measured values in the two plots.

The model was further evaluated by ME, RMSE, and RMAE (Table 3). During the period of calibration, the ME, RMSE and RMAE for SM in the 1.0–4.0 m profile were 0.34, 1.06, and 3.81% for caragana and 0.17, 0.88, and 3.12% for alfalfa, respectively, indicating that the performance of SHAW for the calibration period was also well both for caragana and alfalfa. Compared with simulated results in calibration stage, the model precision

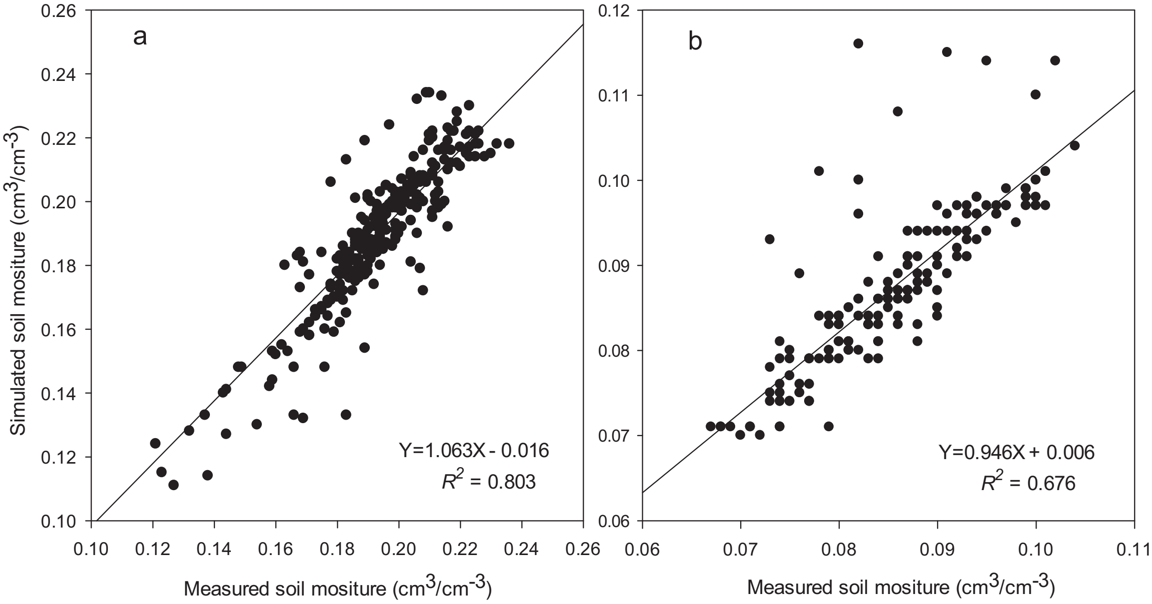

Fig. 2. Comparisons of the simulated and observed soil moistures in the 1.0–4.0 m profile for caragana for calibration (a) and validation period (b).

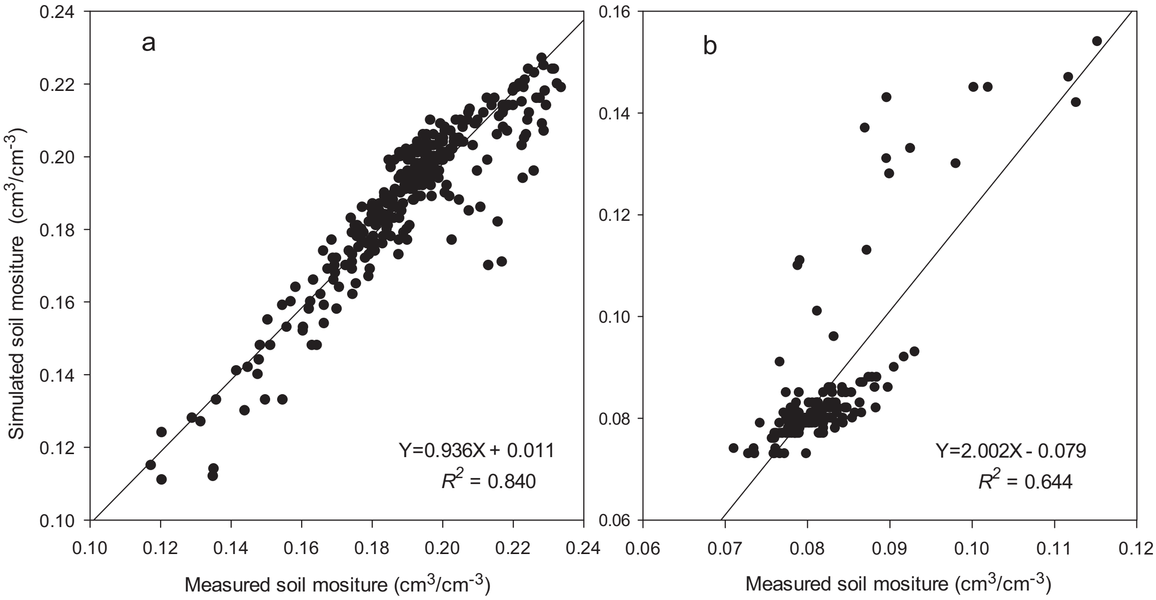

Fig. 3. Comparisons of the simulated and observed soil moistures in the 1.0–4.0 m profile for alfalfa for calibration (a) and validation period (b).

was lower during the validation period, with RMSEs of 5.71 and 1.14% and R^2 values of 0.68 and 0.64 for caragana and alfalfa, respectively, perhaps due to changes in the properties of the soil and plants with plant growth. The ranges of bulk density, saturated soil moisture and saturated hydraulic conductivity of the top 0–20 cm layer in 2004 were 1.33–1.46 g cm^{-3}, 0.27–0.34 cm^3 cm^{-3}, and 0.17–0.28 mm min^{-1}, respectively (Zeng, 2006), while were 1.34–1.45 g cm^{-3}, 0.35–0.45 cm^3 cm^{-3}, and 0.35–0.46 mm min^{-1} for the two plots in 2012, respectively. Despite the lower precision during validation, the error ranges were consistent with those reported in other modeling studies (Fu et al., 2012a; Huang and Gallichand, 2006; Li et al., 2012). The error analyses indi-

Table 3
Error analysis and linear regression of soil moisture in the experimental plots.

Vegetation	Period	N	ME (cm^3/cm^3)	RMSE (cm^3/cm^3)	RMAE (%)	R^2	$R^2_{\text{crit 95\%}}$
Caragana	Calibration	288	0.34%	1.06%	3.81	0.80	0.30
	Validation	176	−0.19%	5.71%	3.76	0.68	0.30
Alfalfa	Calibration	304	0.17%	0.88%	3.12	0.84	0.30
	Validation	176	−0.31%	1.14%	5.91	0.64	0.30

ME – mean error; RMSE – root mean square error; RMAE – relative mean absolute error; R^2, and $R^2_{\text{crit95\%}}$ – critical coefficient of determination based on a 95% confidence level implying that $P \leq 0.05$.

cated that the simulated SM values showed well agreement with measured values during the calibration and validation periods. The SHAW model can thus be considered to accurately predict the daily dynamics of SM for caragana and alfalfa at the study site, supporting the conclusions of SHAW model application on the Loess Plateau by Cheng et al. (2007), Fu et al. (2012a), and Huang and Gallichand (2006).

3.2. Biomass variations and simulated soil moisture

The aboveground biomasses of caragana and alfalfa varied during the study period as the plant growth age increased (Fig. 4). The aboveground caragana biomass tended to continuously increase with plant age (2–11 years old). Caragana growth has been divided into three stages: young-age (0a–6a), middle-age (7a–13a) and old-age (≥14a) (Cheng et al., 2005). Aboveground biomass would thus increase with plant growth before reaching the old-age, and the caragana in our study only experienced young and middle age. The aboveground biomass of alfalfa tended to increase at first and then decrease with plant age (1–10 years old). The alfalfa grew rapidly after sowing, and the aboveground biomass peaked in the 6th year and then began to decrease. The biomass of 10th year-old alfalfa was very low, due to the alfalfa tended to be physical decline and the deep soil water consumed greatly. This results were consistent with the study by Wang (2009), reported that the peak-growth period of alfalfa was about 5 or 6 years on the Loess Plateau region, after that the production decline year by year, and its economic growth was general within 10 years. The alfalfa biomass was lower than that of caragana during the study period. Li et al. (2006) also reported that the productivity of alfalfa in the Liudaogou catchment on the Loess Plateau was generally low, with only short flourishing phases, and the biomass continuously increased for no more than six years.

The comparison between the measured and simulated SMs during the calibration and validation periods showed good agreement, with significantly linear correlations and low errors. The SHAW model was thus considered to accurately simulate the daily SM for caragana (Fig. 5A) and alfalfa (Fig. 5B) in the 1.0–4.0 m profiles during the growing seasons of 2005–2011 at the study site. The simulated growth ages of caragana and alfalfa for 2005–2011 were 3a–9a and 2a–8a, respectively. Plant biomass varied with plant growth and had an obvious impact on the dynamics and distribution of soil moisture in the soil profile. The simulation showed that SM in the 1.0–4.0 m profile decreased over time and that water was depleted from greater depths with plant growth after vegetative restoration. She et al. (2014) reported that the high evapotranspiration for caragana and alfalfa always led to water losses greater than the annual precipitation. The water stored in deep soil is thus consumed to meet the needs of high evapotranspiration, resulting in DSLs. The distribution of measured SM in the 0–4.0 m profiles for 2004–2012 are shown in Fig. 6a and b for caragana and alfalfa, respectively. The dynamics of the measured SMs in the 0–4 m profiles agreed with the changes of the simulated values as growth age increased, confirming that the SHAW model could be used to simulate daily SM for caragana and alfalfa at the study site.

3.3. Soil-water depletion with plant growth

Nosetto et al. (2005) reported that soil texture had more strongly effect on evapotranspiration (ET) than plant did, implying that the homogeneity of soil texture was necessary for evaluating the effect of land use on soil–water dynamics. The homogeneity of the soil texture among the period of 2004 to 2012 for each plots with caragana and alfalfa, allowed us to evaluate the impacts of plant growth on soil-water dynamics and depletion. The stage of plant growth notably affect the levels and distributions of soil water in soil profiles for caragana and alfalfa. Simulation results showed that SM declined with growth age in the 1.0–4.0 m profiles of both plots (Fig. 5a and b). According the definition of DSL, the SSM was equal to 11.1%, which was viewed as the upper limit of DSLs in this study. DSLs development and soil–water depletion, however, differed significantly at different growth stages and between the caragana and alfalfa plots. DSLs began to develop below 1.0 m by the 5th year (2007) for caragana and by the 3rd year (2006) for alfalfa. The degree of soil desiccation and the depths of the DSLs all increased with plant growth for both species. In 2008, the DSLs exceeded 2.0 m for six-year-old caragana and exceeded 3.0 m for five-year-old alfalfa. DSLs formed in 2011 in the 1.0–4.0 m profiles of the nine-year-old caragana and the eight-year-old alfalfa. The results were agreed with the studies by Nosetto et al. (2005), the study showed a plant had different characteristics of water consumption and rooting depth at different stages of growth, which thus lead to different soil–water regimes. Researches also found that DSLs differed with growth of caragana (Yang, 2001) and alfalfa (Li and Huang, 2008).

The DSLs were thicker in the alfalfa plot in 2006–2009, but after that the depths of DSL was thicker in the caragana plot than in the alfalfa plot. The depths of DSL was 2.6 m in the caragana (eight years old) plot and 2.2 m in the alfalfa (seven years old) plot in 2010. These results indicated that the soil water stored in the 0–1.0 m layer was mainly consumed before the first four years for caragana and the first two years for alfalfa, with no soil desiccation below 1.0 m. These results supported those by Wang et al. (2010a,b) who reported that DSLs formed with two-year-old alfalfa and three-year-old caragana on the Loess Plateau and that the preliminary stage of DSL development occurred in deeper soil with alfalfa than with caragana. These differences were mainly attributed to the earlier period of rapid and exuberant growth for alfalfa (4–6th years) than for caragana (7–13th years). Researches showed that depth of water consumption and thickness of DSL increased rapidly year by year before 6 years growth of alfalfa (Liu et al., 2005), and the development of DSL during the years of 1 to 7 was significantly faster than during the late growth period (7–12a) (She, 2009). Li et al. (2002) reported that caragana consumed soil water mainly from shallow layers (0–1.0 m) in the early growth period, while alfalfa mainly depleted soil water stored in deep soil. Our study confirmed that vegetative restoration with artificial plantings can lead to a reduction in deep soil–water storage and to the formation of DSLs.

3.4. Optimal SWCCV

The simulated soil moistures in the 1.0–4.0 m profile decreased significantly, and the degree of soil desiccation increased with plant growth for both caragana and alfalfa after vegetative restoration. Previous studies have also reported that fast-growing shrubs and alfalfa form DSLs on the Loess Plateau (Chen et al., 2008; Wang et al., 2010a,b). DSLs can significantly restrict land productivity in semi-arid environments. Even though vegetative recovery with fast-growing plants can reduce soil erosion and water losses on the Loess Plateau, artificial revegetation can consume more water than can crops and natural grass and may desiccate deep soil layers if not managed properly (Wang et al., 2008, 2011). Li et al. (2008) reported that the water stored in deep soil was nearly depleted 7–8 years after planting alfalfa and suggested that alfalfa not be grown for more than eight years. Revegetation with caragana caused a serious soil–water deficit after 10 years of growth, and DSLs formed at depths of 1–9 m, with soil moisture nearly reaching the wilting point (Li et al., 2007). Appropriate growth ages and management for artificial revegetation are thus necessary for the sustainable use of the water in deep soil.

We investigated the effect of growth age for caragana and alfalfa on the soil–water dynamics to determine the optimal growth ages

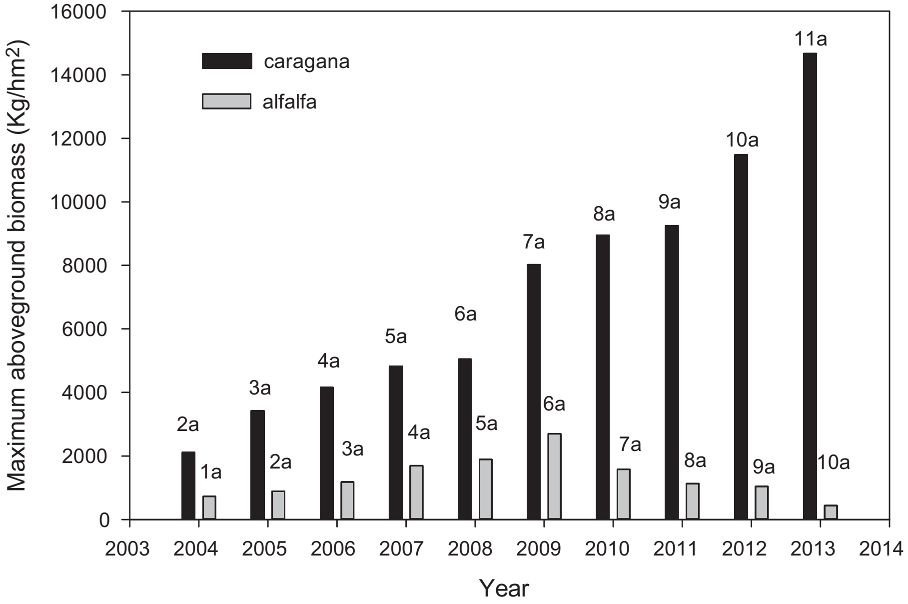

Fig. 4. Changes of the maximum biomass with plant growth for 2004–2013. The growth ages for caragana and alfalfa are identified as 2a–11a and 1a–10a, respectively.

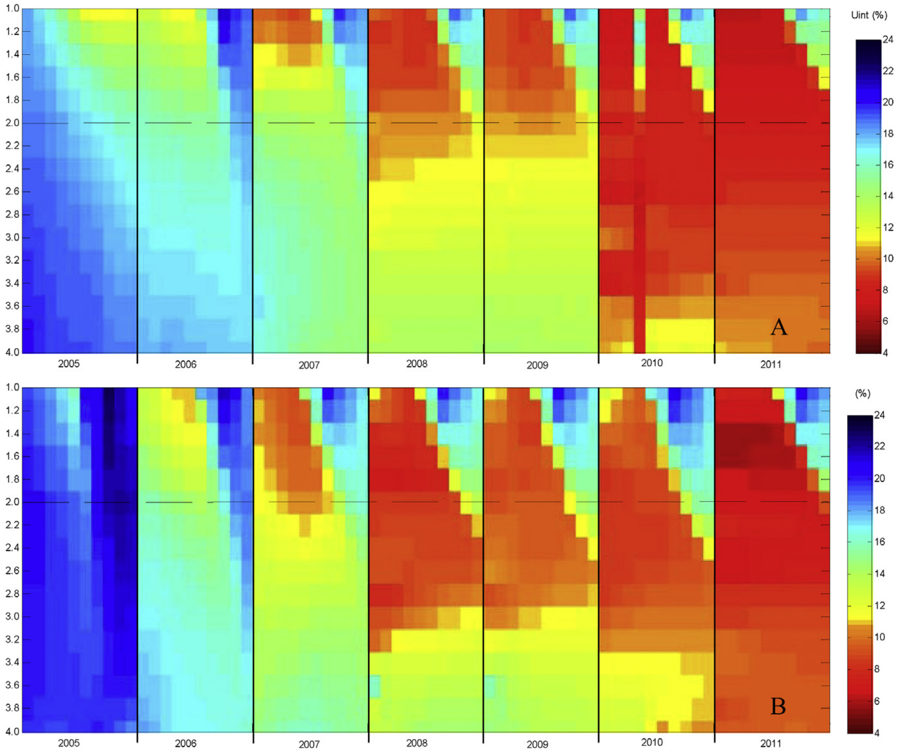

Fig. 5. Simulated volumetric soil moistures in the 1.0–4.0 m profiles for caragana (a) and alfalfa (b) during the growing seasons (form April 1 to October 30) for 2005–2011.

and considered the corresponding biomass as the optimal SWCCV. The optimal SWCCV was the maximum plant biomass when the DSLs formed only at depths of 1.0–2.0 m during the growing season. The simulations indicated that the optimal growth ages were five and three years for caragana and alfalfa, respectively, and that the corresponding maximum biomasses were 4800 kg/hm^2 and 1380 kg/hm^2, respectively, when the SM approached the SSM (11.1%) in the 1.0–2.0 m layer and when no DSLs formed below 2.0 m (Fig. 5). The caragana and alfalfa biomasses in our study differed from those by Xia and Shao (2008), who reported mean SWCCVs of 3460 and 1570 kg/hm^2 for caragana and alfalfa, respectively, in the Liudaogou watershed. These inconsistent results may have been due to differences in climate and/or the growth ages of the plants during the study periods. The study period of Xia and Shao (2008) was only 2–3 years, and the growth ages and stands of the plants were not contiguous. The climatic data for the 2–3 years also did not represent the climatic characteristics of the study area. Annual and inter-annual variations of climate are important, and precipitation can vary widely between dry and wet years. Our study selected a representative year, with an amount of precipitation near the 2005–2011 mean, for simulating the daily SMs for caragana and alfalfa. The optimal caragana and alfalfa biomasses in the study area

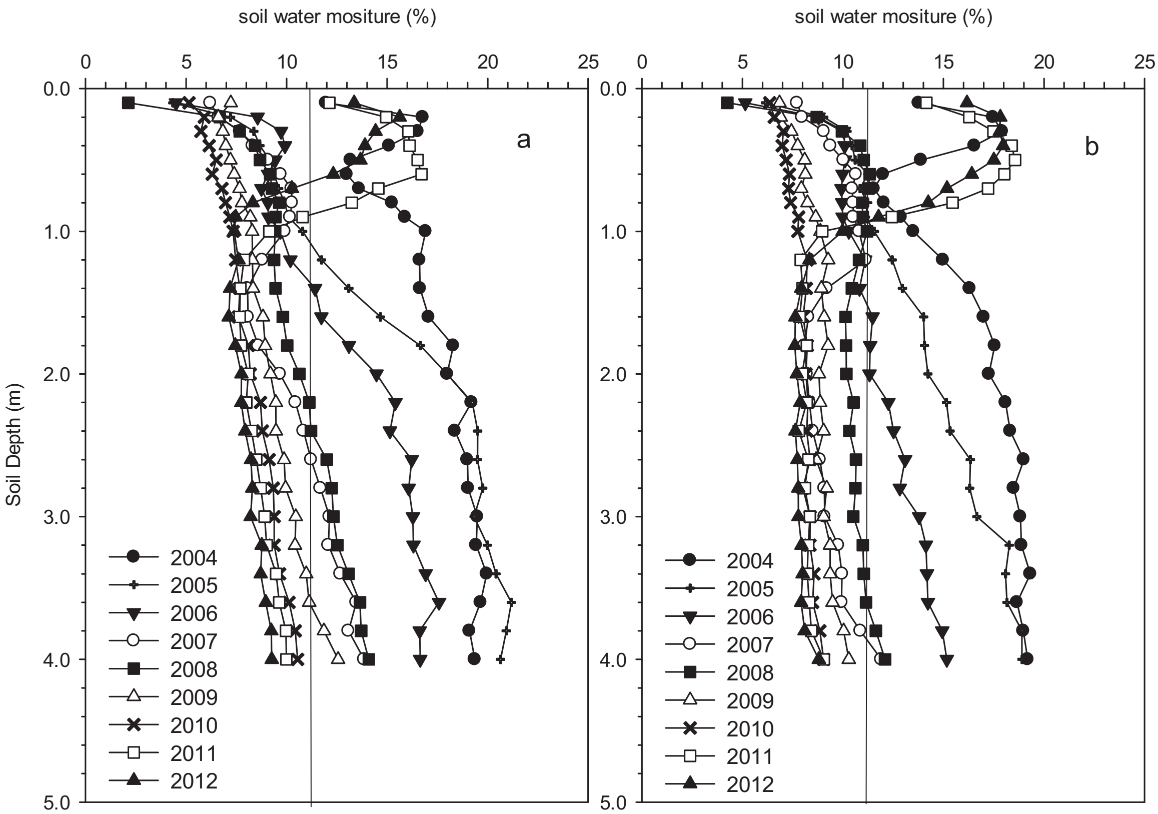

Fig. 6. Distributions of measured soil moisture in the 0–4.0 m profiles for caragana (a) and alfalfa (b) for 2004–2012. The soil moisture in the Fig. 6 was the average values measured April 1 to October 30 for each year of 2004–2012. The vertical lines represent the stable soil–water content of 11.1%.

would thus not likely exceed 4800 and 1380 kg/hm^2, respectively. If plant biomass surpasses the SWCCV, plant density or coverage should be reduced to avoid excessive consumption of the water stored in deep soil. Our results provide representative SWCCVs for caragana and alfalfa and further information for the management of vegetative restorations and use of the water resources on the Loess Plateau in China.

4. Conclusions

The study investigated the effect of plant ages and corresponding biomass on soil moisture variations within 1.0–4.0 m soil profiles simulated by a one-dimensional SHAW model simulated for a representative normal year. These simulated results are helpful to adjust plant age and plant biomass to an appropriate carrying capacity to prevent the formation of DSLs. Field experiments at the Shenmu Erosion and Environmental Experimental Station on the Loess Plateau were also conducted. The following specific conclusions can be drawn from this study.

(1) Soil moisture simulated by the SHAW model was significantly linear correlated with measured values for the caragana and alfalfa during the calibration and validation stages, which were separated by a relatively long span of time. The good correlation implied that the SHAW model could successfully simulate the soil–water dynamics during 2005–2011 on the shrublands and pastures on the Loess Plateau.

(2) Growth age and plant species affected the distribution and depletion of soil moisture in the 1.0–4.0 m profiles. The simulations showed that SM in the profile decreased and that water was depleted from deeper soil after vegetative restoration. DSLs began to develop below 1.0 m for five-year-old caragana and three-year-old alfalfa.

(3) The optimal growth ages for the caragana and alfalfa were five and three years, respectively, and the corresponding optimal SWCCVs were 4800 kg/hm^2 and 1380 kg/hm^2, respectively.

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