Agricultural Water Management 159 (2015) 176–184

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

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

Bingxia Liu[a,b], Ming'an Shao[c,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, China
[b] Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang 050021, China
[c] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F University, Yangling 712100, Shaanxi, China

ARTICLE INFO

Article history:
Received 22 December 2014
Received in revised form 14 June 2015
Accepted 15 June 2015

Keywords:
Vegetation restoration
Soil desiccation
Carrying capacity
Plant biomass
SHAW model

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-

---

* Corresponding author.

http://dx.doi.org/10.1016/j.agwat.2015.06.019
0378-3774/© 2015 Elsevier B.V. All rights reserved.

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.