Journal of Hydrology 528 (2015) 152–160

Contents lists available at ScienceDirect

Journal of Hydrology

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

Regional temporal persistence of dried soil layer along south–north transect of the Loess Plateau, China

Xiaoxu Jia [a], Ming'an Shao [a,b,*], Chencheng Zhang [b], Chunlei Zhao [b,c]

[a] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China
[c] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China

ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form 12 June 2015
Accepted 14 June 2015
Available online 17 June 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Joanna Crowe Curran, Associate Editor

Keywords:
Soil desiccation
Regional transect
Temporal persistence
Spatial distribution
The Loess Plateau

SUMMARY

The occurrence of dried soil layer (DSL) threatens the sustainable development of restored ecosystems in the Loess Plateau of China. Knowledge of the regional spatiotemporal characteristics of DSL in water-deficient regions is critical for optimal water management and vegetation restoration. This study assessed regional temporal persistence of DSL using Spearman's rank correlation coefficient (r_s) and relative difference (RD) analyses and determined the dominant driving factors. Two DSL evaluation indices [DSL thickness (DSLT) and DSL soil water content (DSL-SWC)] were calculated by measuring volumetric SWC of the 0–500 cm soil layer at 86 locations along a south–north regional transect of the Loess Plateau in 2013–2014.

Based on the study, there was DSL formation at most of the sites (61 out of 86 sites) along the transect. The level of DSL was severe, with mean DSLT of 273 cm and mean DSL-SWC of only 10.8% (v/v) [field capacity (FC) = 22.5% (v/v)]. Mean DSL-SWC generally decreased from south to north, while no obvious trend was noted in DSLT along the transect. Derived r_s values indicated a good temporal persistence of spatial patterns of DSL. Also RD analysis showed that DSL with thicker DSLT and/or lower DSL-SWC had much stronger temporal persistence, implying higher possibility for the formation of permanent DSL. The representative locations of each DSL index well represented the regional means of DSLT and DSL-SWC. This suggested that there was the feasibility of directly estimating regional patterns of DSL from theoretical temporal stability. The temporal persistence of DSL patterns was mainly controlled by soil texture, soil organic carbon, field capacity, mean annual precipitation, precipitation seasonal distribution (PSD) and mean annual temperature. We concluded that soil- and climate-related factors dominated regional temporal persistence of DSL. Lower soil water holding capacity, fewer rainfall and more concentrated PSD could intensify the formation and/or development of permanent DSL in the Loess Plateau. This is especially true under worsening global climate change conditions.

1. Introduction

The formation of dried soil layer (DSL) is common phenomenon across the globe. For instance, DSL has been detected in the Loess Plateau of China (Li, 1983), Russia (Yang and Han, 1985), Eastern Amazonia (Jipp et al., 1998) and Southern Australia (Robinson et al., 2006). DSL is recognized as a serious ecological phenomenon in the Loess Plateau (Li, 1983; Chen et al., 2008a; Wang et al., 2010a, 2011a) that has deep loess deposits, unique landscapes and intensive soil and water erosion (Shi and Shao, 2000). The occurrence of DSL potentially interferes with water cycle in soil–plant-atmosphere systems by preventing water flow between shallow (soil moisture) and deep (groundwater) soil layers (Chen et al., 2008a). In addition, prolonged soil desiccation could lead to soil degradation, regional vegetation die-off and aridity of local climatic environments (Breshears et al., 2005; García et al., 2008). Thus DSL affects hydrological conditions and threatens sustainable development of restored ecosystems in the Loess Plateau and beyond. Understanding the development processes of DSL and developing corresponding land management strategies are critical for long-term soil and water ecosystem services in the Loess Plateau and other fragile ecosystems.

* Corresponding author at: Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China. Fax: +86 29 87012210.
E-mail address: shaoma@igsnrr.ac.cn (M. Shao).

http://dx.doi.org/10.1016/j.jhydrol.2015.06.025
0022-1694/© 2015 Elsevier B.V. All rights reserved.

After the first discovery of soil desiccation in the semi-arid regions in Shaanxi and Gansu provinces of China in the 1960s (Li, 1983), numerous studies have since been conducted on DSL in the Loess Plateau. Studies have been conducted on the definition and classification (Yang, 2001; Chen et al., 2008a), formation and development processes (Wang et al., 2009, 2010b), spatial distribution patterns at various scales (Wang et al., 2010a, 2011a, 2012a) and sustainable recovery (Fan et al., 2004; Wang et al., 2011b, 2012b) of DSL.

DSL varies in space and time due to the heterogeneity in soil type, climate, vegetation and topography. Wang et al. (2010a) mapped the spatial distribution of DSL for the entire Loess Plateau, and showed that DSL was generally thicker (>170 cm) in the western and central Loess Plateau region (170–220 cm) than in around the Yellow River and flood plains in the interior irrigation regions. Wang et al. (2010a) concluded that precipitation and soil type were respectively the primary and secondary factors with significant impact on DSL formation and/or development. The rate of formation and thickness of DSL depend largely on vegetation type at regional scale and vegetation age at site scale (Wang et al., 2010b).

Soil desiccation is divided into two types based on dynamic characteristics – temporary type and permanent type (Li, 1983). Permanent DSL typically occurs in arid and semi-arid regions where there is low soil water content due to long-term soil desiccation. Temporary DSL, however, mostly occurs in semi-humid regions. Permanent DSL is difficult to reclaim in the Loess Plateau due to generally limited rainfall, deep groundwater, vegetation consumption and intense evaporation (Wang et al., 2011b). The formation of permanent DSL could have profound and long-term impact on ecological and hydrological processes. Although there exist numerous studies on DSL in the Loess Plateau at various scales, little has been done on the spatiotemporal characteristics of DSL and the related factors at regional scale. The unique regionalized variability of the Loess Plateau makes it specifically difficult to study in terms of sample collection cost and time. Thus there is need for sufficient information on regional temporal persistence of DSL for policy decisions for sustainable soil water management and ecological restoration.

It has recently been demonstrated that the theory of temporal stability is an effective tool for analyzing temporal persistence of properties that vary in space and time. Vachaud et al. (1985) first proposed the concept of temporal stability and defined it as the time-invariant association between spatial location and classical statistical parameters of a given soil property. The definition of the stability of soil water content over time was later expanded to describe temporal persistence of spatial patterns (Kachanoski and de Jong, 1988). This concept has been broadly used to study soil water around the world. This includes the Loess Plateau of China (Hu et al., 2010a,b, 2012; Gao and Shao, 2012; Jia et al., 2013a,b; Liu and Shao, 2014), where soil water content is the most crucial factor for ecological restoration. One of the most useful applications of the concept of temporal persistence is its potential to identify representative locations that rapidly and effectively estimate mean conditions of a given property within the entire study area of interest. Studies on soil water in the Loess Plateau confirm and support the application of temporal persistence. The theory of temporal persistence could therefore provide a useful understanding of regional spatiotemporal characteristics of DSL and the driving factors in the Loess Plateau.

There is widespread occurrence and severity of DSL with potential negative impacts on hydrological processes and ecological environments in the Loess Plateau. There is therefore the need for information on regional spatiotemporal characteristics of DSL and the driving factors. This could guide policy decisions and vegetation restoration strategies to optimize soil and water management. To deepen insight into regional temporal persistence of DSL, this study analyzed neutron probe data collected on 10 occasions along the south–north transect of the Loess Plateau from June 2013 to September 2014. The specific objectives of the study were to deepen insight into the spatiotemporal characteristics of DSL along the south–north transect, and to determine the primary factors that control regional temporal persistence of DSL in the Loess Plateau of China.

2. Materials and methods

2.1. Study area description

This study was conducted in the typical Loess Plateau region. The typical Loess Plateau area covers a total area of *ca.* 430,000 km^2 (Fig. 1), with loess as the most continuous soil in horizontal and vertical space. This area has the most typical loess geomorphic landforms and erosion terrains, such as Yuan (a large flat surface with little or no erosion), ridges, hills and various gullies (Yang et al., 1988). Most of the study area is subject to severe soil and water erosion, causing land degradation and loss of soil fertility. In order to control soil and water erosion and to restore the ecosystem, an extensive ecological rehabilitation program (the "Grain-for-Green") was initiated by the Chinese government in 1999. The program has now been operating for 15 years and the natural environment in most parts of the Plateau is progressively improving.

To effectively measure the characteristics and dynamic properties of DSL at regional scale, a south–north transect (*ca.* 800 km) within latitudes 34.09°N–39.38°N and longitudes 108.62°E–110.32°E was determined in the Loess Plateau (Fig. 1). This transect crosses the moderate-temperate and semi-arid zones, with mean annual precipitation of 400 mm in the north and 620 mm in the south. The mean annual temperature along the transect is 6.8 °C in the north and 12.3 °C in the south.

The soils are mainly of loess with clay-loam as the most common soil texture, sandier soils in the north and clayier soils in the south. The transect has complex topography, including plains, sub-plateaus, hills and gullies with altitude rang of 380–1600 m above mean sea level. From south to north, the land use type generally changes from cropland to forestland and then to grassland. The cropland is often cultivated with winter wheat and summer maize, with irrigation. All the forestlands are artificial with different tree species, including apple (*Maluspumila*), black locust (*Robiniapseudoacacia* L.), apricot (*Armeniacasibirica* L.), jujube (*Zizyphusjujuba*) and korshinsk peashrub (*Caraganakorshinskii*). The grasslands are both artificial, mainly comprised of purple alfalfa (*Medicago sativa* L.), and natural, comprised of *Stipabungeana*, *Lespedeza davurica* and *Heteropappusaltaicus*.

2.2. Sampling location and profile soil water content

Along the south–north transect, 86 aluminum neutron probe access tubes (5.2 m in length) were installed at approximate intervals of 10 km (Fig. 1), measured by vehicle milometer during travel. Each sampling point was randomly selected and located using GPS receiver (5 m precision in the horizontal direction) to represent the main land uses, topography and vegetation types within the range of vision. Volumetric soil water content (SWC) was measured using neutron probe at the 86 locations during the growing season in the period from June 2013 to September 2014. Each measurement process took 3–4 days. There was a total of 10 sampling occasions during the entire sampling period. Slow neutron counts were taken at intervals of 0.2 m to depth of