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Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China

Yunqiang Wang[a,c], Ming'an Shao[b,*], Yuanjun Zhu[a], Zhipeng Liu[a,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 & Ministry of Water Resources, Yangling 712100, China
[b] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[c] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

A dried soil layer (DSL) formed in the soil profile is a typical indication of soil drought caused by climate change and/or poor land management. The responses of a soil to drought conditions in water-limited systems and the impacts of plant characteristics on these processes are seldom known due to the lack of comparative data on soil water content (SWC) in the soil profile. The occurrence of DSLs can interfere in the water cycle in soil–plant–atmosphere systems by preventing water interchanges between upper soil layers and groundwater. Consequently, a DSL may limit the sustainability of environmental restoration projects (e.g., revegetation, soil and water conservation, etc.) on the Loess Plateau of China and in other similar arid and semiarid regions. In this study, we investigated and compared the impacts of soil type, land use and plant characteristics within each of the three climatic regions (arid, semiarid, semihumid) of the Loess Plateau. A total of 17,906 soil samples from 382 soil profiles were collected to characterize DSLs across the Plateau.

Spatial patterns of DSLs (represented by four indices: (1) DSL thickness, DSLT; (2) DSL forming depth, DSLFD; (3) mean SWC within the DSL, DSL-SWC; and (4) stable field water capacity, SFC) differed significantly among the climatic regions, emphasizing the importance of considering climatic conditions when assessing DSL variations. The impact of land use on DSLs varied among the three climatic regions. In the arid region, land use had no significant effect on DSLs but there were significant effects in the semiarid and semihumid regions ($P < 0.05$). The development of DSLs under trees and grasses was more severe in the semiarid region than in the semihumid region. In each climatic region, the extent of DSLs depended on the plant species (e.g., native or exotic, tree or grass) and growth ages; while only in the semiarid region, the DSL-SWC and SFC ($P < 0.001$) were significantly influenced by soil type. The DSL distribution pattern was related to the climatic region and the soil texture, which both followed gradients along the southeast–northwest axis of the Plateau. Optimizing land use can mediate DSL formation and development in the semiarid and semihumid regions of the Loess Plateau and in similar regions elsewhere. Understanding the dominant factors affecting DSLs at the regional scale enables scientifically based policies to be made that would alleviate the process of soil desiccation and sustain development of the economy and restoration of the natural environment. Moreover, these results can also be useful to the modeling of the regional water cycle and related eco-hydrological processes.

1. Introduction

A dried soil layer (DSL) has been described as having the following three characteristics: (1) located at a certain soil depth, mainly in deeper layers that may extend to 10 m below the soil surface; (2) persistence both spatially and temporally, and cannot be replenished by rainfall infiltration in a normal year; and (3) having a soil water content (SWC) range between the permanent wilting point and the stable field capacity (SFC) which is generally considered to be equivalent to 60% of the field capacity (FC) (Li, 1983; Li et al., 2008; Wang et al., 2008, 2010a; Yang, 2001). Therefore, a soil layer with a SWC lower than the SFC would be considered to be a DSL (Chen et al., 2008b; Wang et al., 2008, 2010a). Many studies have reported DSL formation as a phenomenon typical of the Loess Plateau of China (e.g., Han et al., 1990; Hou et al., 2000; Li, 1983; Wang et al., 2008; Yang, 1996, 2001). However, there are

* Corresponding author. Tel.: +86 29 87012045; fax: +86 29 87016082.
E-mail address: mashao@ms.iswc.ac.cn (M. Shao).

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also reports that similar cases of desiccation in deep soil layers have been observed in other regions of the world such as Russia (Yang and Han, 1985), eastern Amazonia (Jipp et al., 1998), and southern Australia (Robinson et al., 2006).

Global warming is generally, but not universally, expected to increase evapotranspiration, causing declines in SWC that may lead to greater deficits of soil available water in water-limited systems around the world (Breshears et al., 2005; Brown, 2002; Jovanovic et al., 2008; Zavaleta et al., 2003). In recent years, considerable interest has been generated in the assessment of plant responses to drought (Breshears et al., 2005; Engelbrecht et al., 2007; Ji and Peters, 2003; Krishnan et al., 2006). However, the responses of soil to climate change are seldom known. The plant–soil–atmosphere environment is a mutually-interacting system where plants form pathways for water transport to the atmosphere via their roots from the soil around their root zones. Soil water can also transfer to the atmosphere directly by means of soil evaporation. Thus, studying the responses of soil to climate change can help us better understand the water cycle and eco-hydrological processes in terrestrial ecosystems (Scanlon et al., 2005).

The Loess Plateau of China is well-known for having the most severe soil erosion in the world and this has made the region ecologically fragile (Han et al., 2009). Thus, the terrestrial ecosystems of the Loess Plateau may exhibit a comparatively early ecological response to changes in the global climate (Han et al., 2009; Shi and Shao, 2000; Wang et al., 2010a). Furthermore, the natural conditions of the Loess Plateau (i.e., thick loess deposits, unique landscape, large areas containing different climatic regions, etc.) make it appropriate to estimate the responses of soil to climate change (Chen et al., 2007). Generally, the water balance equation on the Loess Plateau can be written as:

$$\Delta W = P - ET \tag{1}$$

where, ΔW is the change in soil water storage, P is precipitation, and ET is evapotranspiration. Decreases in soil water storage may occur in response to the decrease in inputs (P) and/or the increase in outputs (ET).

Annual precipitation on the Loess Plateau has been reported to be decreasing and air temperature to be increasing (Tao et al., 2003, 2006; Thomas, 2000; Yang et al., 2008). Furthermore, to control severe soil erosion on the Loess Plateau, the establishment of forests and grassland has been widely adopted as an effective measure supported by many scientists and policy-makers (Chen et al., 2007; Shi and Shao, 2000) even though intensive vegetation restoration over large areas might also generally increase transpiration (Wang et al., 2010a). Therefore, according to Eq. (1), the combination of declining P inputs and possible increases in ET outputs could potentially lead to decreases in soil water storage on the Loess Plateau.

If the evapotranspiration of plants and soils exceeds the precipitation on the Loess Plateau, the decreasing soil water storage can aggravate soil water scarcity in both upper and deep soil layers (He et al., 2003b). Excessive use of the limited soil water resources, for example, by plant root water uptake, can cause severe soil desiccation that can lead to the formation of DSLs in the soil profile, which may be a serious obstacle to sustainable land use (Wang et al., 2009, 2010a). The occurrence or change in a DSL is one response of the soil to climate change.

In the 1960s, DSLs were first observed in farmland with high yields and under artificial grassland and forests in the semiarid and semihumid regions of Shannxi and Gansu Provinces (Li, 1983). Since then numerous studies on DSLs have been conducted to define and classify them according to their basic characteristics and also on the factors leading to their formation and development (Chen et al., 2008a,b; Han et al., 1990; Huang and Gallichand, 2006; Li, 1983, 2001; Shangguan, 2007; Wang et al., 2008; Yang and Tian, 2004; Yang, 1996, 2001). Since the prevention of water interchanges between upper soil layers and the groundwater by DSLs is often considered to negatively affect the water cycle, the water recharge of DSLs are also a research interest (Huang et al., 2004; Li and Huang, 2008; Wang et al., 2003).

To determine water depletion depth of planted grassland, shrub, and forest, Wang et al. (2009) conducted a study in a semiarid area on the Loess Plateau and found that the depth of soil water depleted by alfalfa (*Medicago sativa*), caragana brush (*Caragana korshinskii*), and pine forest (*Pinus tabuleaeformis*) was as much as 15.5 m, 22.4 m and 21.5 m, respectively. Moreover, Wang et al. (2010a) analyzed the formation and development processes of DSLs under artificial and natural vegetation in the semiarid region of the Loess Plateau and showed that the rate of formation and thickness of DSLs depended on the vegetation type and its growth age. Furthermore, they suggested that the use of natural vegetation succession management principles would possibly reduce soil desiccation during vegetative restoration.

As an important regionalized variable, little work has been done on the spatial distribution characteristics of DSLs and related factors at the regional scale. Chen et al. (2008a,b) pointed out that DSLs were often more severe under forests and grassland than under farmland, in vegetated soils than in bare soils, on steep slopes than on gentle slopes, and on hills and ridges than on tablelands or in gully bottoms. Wang et al. (2008) found that a substantial DSL was formed under an artificial *Robinia pseudoscacia* forest but not under an indigenous *Quercus liaotungensis* forest, and that the SWC on north-facing slopes was significantly larger than on south-facing slopes in the north of Shaanxi Province.

In the literature reporting DSLs on the Loess Plateau, studies were generally based on point monitored data at a small scale and were thus inadequate to reveal the spatial pattern of DSL variation. At the regional scale (i.e., the entire Loess Plateau region), there was no information about the DSL's spatial distribution, which was needed by policy makers for sustainable land use planning and scientifically based vegetation restoration. In previous work (Wang et al., 2010b), we produced a spatial distribution map of DSLs across the entire Loess Plateau. We also concluded that large-scale factors such as climate condition (precipitation) and soil type were the primary and secondary factors, respectively, that significantly impacted the extent of DSL formation and/or development. Other more localized factors such as land use type were also of importance. However, under the different conditions of a significant large-scale factor (i.e., the climate condition that may be represented by different climatic regions), the influence of the local factors (i.e., land use, plant species and their growth ages) on DSL formation and development in each climatic region was unknown.

Therefore, in this study we have taken the entire Loess Plateau of China as the study area and divided it into three different climatic regions based on the annual precipitation. We concentrate on the objectives of: (1) comparing the characteristics of DSLs in the different climatic regions; (2) identifying the impacts of soil type, land use and plant species on DSLs in each climatic region; and (3) producing spatial distribution maps of DSL characteristics in different climatic regions. This information could be useful for policy making at the large scale and could enable the modeling of the regional water cycle and related eco-hydrological processes.

2. Materials and methods

2.1. Study area description

The study area was the entire Loess Plateau of China (34°–45°5′N, 101°–114°33′), which covers a total area of 620,000 km^2, with an elevation range of 200–3000 m (Fig. 1). The loess-paleosol deposits range from 30 to 80 m in thickness. The