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The relationships between grasslands and soil moisture on the Loess Plateau of China: A review

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ABSTRACT

Drylands are important ecosystems that are facing severe challenges under a changing climate. The relationships between soil moisture and vegetation have garnered international interest because of their significant impact on ecosystem restoration in semi-arid and arid regions. Grasslands are among the largest ecosystems in the world and are very important to dryland ecosystems. The Loess Plateau in China is an important example of drylands, and grasslands occupy more than 1/3 of its area. Water is the primary limiting factor of vegetation restoration, so understanding the relationship between grasslands and soil moisture on the Loess Plateau is imperative. The processes of precipitation, soil surface infiltration and evaporation, root water uptake and leaf transpiration are important for the relationship between grasslands and soil moisture. This paper found the following research topics that were related to the Loess Plateau based on 283 references of local studies from CNKI, ScienceDirect and Springer: (1) the effects of grasslands on soil moisture, including the influence of precipitation, geography, grassland type, grass age and growth stage on soil moisture and soil moisture determination methods; (2) the influence of soil moisture on grasslands, including the influence of soil moisture stress on grass growth and the methods for determining the physiological and ecological characteristics of grass; and (3) models of the relationships between grasslands and soil moisture. International references were used to explain certain processes and were compared with studies on Loess Plateau. Existing studies on the Loess Plateau paid more attention to these phenomena compared to water transport processes. Additional process-based studies with greater accuracy, longer time series, and larger spatial scales are needed to achieve ecosystem sustainability on the Loess Plateau. This summary of studies on the Loess Plateau may provide examples for research on arid and semi-arid areas in other countries.

Contents

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1. Introduction

Drylands are an important ecosystem occupying over 40% of the Earth's land surface (D'Odorico and Porporato, 2006; Franz et al., 2012). The Intergovernmental Panel on Climate Change (IPCC) first working group's fifth assessment report suggests that mean precipitation will decrease in dry areas in the mid-latitudes in the future (Stocker et al., 2013). Extreme precipitation events will become more violent and frequent, and these changes will feature increasingly larger uncertainties (Qin et al., 2014; Shen and Wang, 2013). Under these conditions, global drylands will face severe challenges because these environments are sensitive to climate change and because their vegetation supports pastoral livestock production (D'Odorico et al., 2007; Franz et al., 2012; Manzoni et al., 2013a). The relationships between soil moisture and vegetation have garnered international interest because of their significant impact on ecosystem restoration in semi-arid and arid regions, such as the savannahs in Africa, the North American Monsoon Region and the Loess Plateau in China (Caylor et al., 2006; Lin et al., 2011; Liu et al., 2013b; Vivoni et al., 2007; Vivoni et al., 2009; Wang et al., 2008b; Wang et al., 2009a; Wang et al., 2013b).

Grasslands are among the largest ecosystems in the world, and woody savannahs, savannahs and non-woody grasslands occupy 22.1% of the global land area (excluding Greenland and Antarctica) (Suttie et al., 2005; White et al., 2000). Grassland areas are large, and their position is important because most grasslands are located adjacent to barren land, according to land cover data from the MOD12Q1 database developed by the University of Maryland land cover classification system (Dixon et al., 2014; Zhao and Running, 2010). At the frontier of international ecohydrology research, the existing studies on the coupled effects of scale on vegetation and soil moisture have mainly focused on forests or shrublands in humid regions (Méndez-Barroso and Vivoni, 2010; Muneepeerakul et al., 2008; Rodriguez-Iturbe et al., 2007) and tropical and subtropical arid regions (Kumagai and Porporato, 2012; Legates et al., 2011; Rodríguez-Iturbe and Porporato, 2004; Tromp-van Meerveld and McDonnell, 2006; Zhu and Shao et al., 2008). However, the amount of quantitative studies that examine the relationships between grasslands and soil moisture in temperate arid and semi-arid regions at a medium scale is far from adequate (Dobriyal et al., 2012; Foley et al., 2005; Fu et al., 2003; Montenegro and Ragab, 2012; Schymanski et al., 2009; Wang et al., 2008a). Water controls the dynamics of the grassland ecosystem directly and grass modulates several hydrological processes as well as the rate of the water cycle (D'Odorico et al., 2010). In addition, relationships between the soil moisture and the grassland ecosystem control the quality and quantity of pasturage and food supplies; thus, these relationships are directly coupled to human livelihoods in water-limited regions (D'Odorico et al., 2010; D'Odorico and Porporato, 2006; Franz et al., 2012; Lu et al., 2014).

The Loess Plateau in China is an important part of the world's drylands because it is a typical loess area with a monsoon climate in the mid-latitudes (Lü et al., 2012; Qin et al., 2002). Because the groundwater is deep and the soil moisture originating as precipitation is the only source of water for plants, it is a suitable place to study the relationships between vegetation and soil moisture (Yao et al., 2012). Grasslands are widely distributed on the Loess Plateau and occupy nearly 1/3 of its total area, even before the *Grain for Green Project*, according to geobotanical charts (Zhang, 2007). The soil moisture deficit is the main ecological factor limiting vegetation growth, due to the lack of precipitation and the great temporal and spatial variations in this arid region (Chen et al., 2008b; Wang et al., 2015; Yang et al., 2012b). Existing international research has shown that soil moisture losses occur via evapotranspiration, deep infiltration, and surface runoff (Milly, 1993; Porporato et al., 2004; Rodriguez-Iturbe et al., 1999; Stavi et al., 2009). In a typical semi-arid region of the Loess Plateau in China, vegetation growth can change the redistribution of precipitation because root growth can accelerate the infiltration rate. At the same time, transpiration and root water uptake decrease the soil moisture (Chapman and Reiss, 1999). The groundwater level in the Loess Plateau is deep and cannot be accessed by roots. Furthermore, precipitation and infiltration barely reach the deep layers, and soil water is the main water source for roots in deep layers. Consequently, unsuitable vegetation establishment may cause soil desiccation (Qiu et al., 2000), and the lack of water in the root zone may constantly limit the growth of grasslands (Xie and Wang, 2007). Over the past several decades, many projects have been designed by the Chinese government to conserve soil and water and to control desertification on the Loess Plateau (Liu et al., 2008; Wang et al., 2004, 2007, 2010). The Chinese government established the *Three – North Shelterbelt Development Program* in 1978, with the principal goal of combating desertification and controlling dust storms (Wang et al., 2004, 2007, 2010). In 1999, the Chinese government also established the *Conversion of Cropland to Forest & Grassland Program*. These programs had a positive and dramatic influence on the local environment, and the area of grassland in 2008 reached 271,400 km^2 (Liu et al., 2008; Lü et al., 2012). The vegetated area has increased, and some artificial grasslands, which feature species such as *Medicago sativa* L., now support the animal husbandry industry on the Loess Plateau. Nevertheless, these projects have recently had problems, the most serious being soil drying caused by the artificial vegetation (Huang et al., 2005). The resource exploitation and soil desiccation caused by the growth of unsuitable vegetation cannot be recovered from a short period (Jia et al., 2006, 2009). Unreasonable vegetation restoration may contribute to vegetation degeneration (Wang et al., 2011b). A better understanding of the relationships between grasslands and soil moisture is needed to avoid these problems, which should serve as a reminder to policymakers and scientists that the sustainability of these ecosystems is threatened (Fang and Zhao, 2013; Liu and Zhao, 2013).

Summarizing the existing studies will not only provide guidance concerning the speed and amount of vegetation restoration that has occurred on the Loess Plateau but will also provide examples for research on this topic in other arid and semi-arid regions around the world. The objectives of this study were to (1) examine recent research on the relationships between grasslands and soil moisture on the Loess Plateau and (2) provide a summary of the problems and gaps that exist in current studies compared to international studies based on 283 references from CNKI (the National Knowledge Infrastructure), ScienceDirect and Springer.

2. Study area and methods

The Loess Plateau of China is located along the upper and middle reaches of the Yellow River (33°43′–41°16′N and 100°54′–114°33′E) and has a typical semi-arid monsoon climate with an extremely fragmented hilly loess landscape (Fig. 1). The Loess Plateau encompasses 640,000 km^2 and belongs to a transition zone from semi-arid and semi-humid areas to arid desert areas. It is also characterized by poverty because cropland yields cannot satisfy the primary demands of the population in this region (Wang et al., 2008a). The ecosystem here is fragile, and the soil is loose and erodible. The groundwater level of the region is deep, and the annual rainfall is low, ranging from 300 to 650 mm, whereas the average annual potential evaporation is as high as 1669 mm (Chen et al., 2008b; Liu et al., 2008; Yang et al., 2012b). The limited precipitation mainly occurs as high-intensity, short-duration rainfall between June and September. Under these conditions, agricultural productivity is primarily limited by water, and this region experiences the most serious soil erosion both in China and in the world (Zhang, 2008). In addition to the natural environmental factors, inappropriate land use aggravates the detrimental effects of drought, such as grassland degradation, water loss and accelerated erosion (Liu et al., 2013b).

Articles from the period of 1988–2015 in scientific databases such as CNKI, ScienceDirect and Springer were searched by their abstracts. The keywords *soil moisture*, *grass* and *Loess Plateau* were used. Review articles and repetitive articles were removed, leaving 283 articles to be