Ecological Indicators 95 (2018) 320–330

Contents lists available at ScienceDirect

Ecological Indicators

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

Spatial and temporal variations in surface soil moisture and vegetation cover in the Loess Plateau from 2000 to 2015

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ARTICLE INFO

Keywords:
Loess Plateau
Soil moisture
Vegetation cover
Spatial distribution
Temporal variation

ABSTRACT

The “Grain for Green” project utilizes large-scale revegetation to improve the local environment in the Loess Plateau. Understanding the trends in the variations in soil moisture content (SMC) and vegetation after the implementation of this project is necessary. This study examined the spatial and temporal variations in SMC and vegetation cover in the Loess Plateau after 1999. Furthermore, interactions between SMC and vegetation cover (e.g., spatial distribution and temporal variation) were assessed. The results of this study showed that (1) the SMC and vegetation cover increased in most of the Loess Plateau from 2000 to 2015; (2) both SMC and vegetation cover are predicted to decrease after 2015; (3) the increase in precipitation promoted SMC in the northwestern region, but the impact on vegetation cover was not significant; (4) the spatial variation in SMC exhibited a positive correlation with the spatial variation in vegetation cover, however, the difference in their cycle of change indicated that the interaction between SMC and vegetation cover varied over time. The most important results indicated that SMC and vegetation cover have begun to decrease since 2015.

1. Introduction

The Loess Plateau is famous throughout the world for its water scarcity and serious soil erosion (Liu and Diamond, 2005; Yang et al., 2015; Wang et al., 2015). In the 20th century, overgrazing, intensive cultivation, population growth and economic development exacerbated the soil and water losses on the plateau, leading to fragmentation and degradation of the environment (Fu et al., 2000; Wei, et al., 2006; Zhou et al., 2006; Su et al., 2011). The Chinese government implemented the “Grain for Green” project (GGP) to control soil erosion and prevent the further reduction of the ecological environment in the Loess Plateau. With the implementation of the project, vegetation cover and the soil environment have gradually improved (Xin et al., 2008).

However, whether vegetation reconstruction had a positive or negative effect on soil moisture since the implementation of the GGP remains unclear. Some study results have indicated that vegetation is beneficial for the improvement of soil moisture content (SMC); for instance, plant canopy shadows were found to reduce land surface temperature and soil evaporation and, thereafter, to increase SMC (Wang et al., 2009). Yang et al. (2002) believed that reasonable vegetation construction can lead to the accumulation of soil moisture. Li et al. (2008) found that, after analysing remote sensing observation data, water retention in forest and shrub areas was better than that in cropland and rangeland in relatively wet conditions. In contrast, other studies have shown that afforestation has negative effects on the soil moisture environment. Several past studies have shown that newly introduced plantation vegetation usually consumes more soil moisture than native plants (Cao et al., 2011; Yang et al., 2012). Zhang et al. (2009) and Zhou et al. (2009) both suggested that afforestation consumed a lot of soil moisture, causing grasslands and other species to survive. More importantly, excessive reforestation has resulted in the deterioration of soil ecosystems and decreased vegetation cover and has exacerbated water shortages (Jiao et al., 2007; Cao et al., 2011; Wang et al., 2011; Cao et al., 2015). These studies conducted at a small spatial scale, such as on slopes and small watersheds, have had difficulties explaining the response of soil moisture to vegetation restoration after GGP over the Loess Plateau. In addition, previous studies have focused on spatial changes in soil moisture and vegetation, but the limitations of these studies are that it is difficult to detect temporal changes in soil moisture vegetation over longer time series (Chen et al., 2005; Wang et al., 2013; Yang et al., 2014; Jiao et al., 2014, 2016; Yang et al., 2017). Therefore, previous studies were limited by the temporal or spatial scales of the experiments, which may lead to the controversy about relationship between SMC and vegetation.

In the above studies, there is still a lack of explanation for the variation in soil moisture in both time and space on the Loess Plateau.

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https://doi.org/10.1016/j.ecolind.2018.07.058
Received 2 May 2018; Received in revised form 23 July 2018; Accepted 27 July 2018

Since the implementation of GGP, whether the effects of vegetation on soil moisture are negative is still controversial, which is bound to affect the ecological restoration of the Loess Plateau. Therefore, it is necessary to study the relation between soil moisture and vegetation at regional spatial and temporal scales in the Loess Plateau. The goals of this study were to (1) analyse the spatial and temporal variations in soil moisture and vegetation over the period of 2000–2015; (2) detect the interactions between soil moisture and vegetation; and (3) explore the effects of precipitation variation on soil moisture and vegetation. We assume that observed interaction of soil moisture and vegetation may be affected by the scale of time and space. These results could help us further interpret the current soil moisture and vegetation stages and developments, evaluate the effects of the GGP on soil moisture at a regional scale, and provide scientific and reasonable references for future restoration of vegetation ecosystems by plantation forests in the Loess Plateau.

2. Materials and methods

2.1. Study area

The Loess Plateau covers an area of approximately 620,000 km^2 and is situated in the middle reaches of the Yellow River in northern China (from 100°54′E to 114°33′E and 33°43′N to 41°16′N). Most areas of the region are dominated by subhumid and semi-arid climates, and the climatic characteristics, especially the mean annual precipitation and temperature, are highly spatially heterogeneous. The mean annual precipitation increases from 135.2 mm in the northwest to 873.6 mm in the southeast (Fig. 1), and the annual average temperature ranges from 4.3 °C in the northwest to 14.3 °C in the southeast (Guo et al., 2011). Most precipitation is concentrated as intensive storms from June to September. The annual average evaporation is much higher than the amount of precipitation, ranging from 820 mm to 1650 mm. The landform of the plateau is dominated by mountains, hills, plains and broad valleys, and the terrain slopes from the northwest to the southeast, thus forming a complex geomorphology. The main vegetation types of the region are a patchwork of agricultural vegetation, forest plantations, orchards, herbaceous crops, and natural vegetation (i.e., grasslands and shrublands). However, the vegetation cover is low. The average thickness of the loess layer at the surface is 100 m, and this layer is prone to erosion. Due to the frequent heavy rainfall, steeply sloping landscapes, low vegetation cover, and highly erodible soils, the Loess Plateau has experienced some of the most serious soil erosion in the world (Gao et al., 2015). Approximately 90% of the sediment in the Yellow River is caused by soil erosion on the Loess Plateau. With social development and population growth, human activities, such as land reclamation and deforestation, have become the main factors impacting soil erosion. Therefore, the Chinese government has adopted a series of vegetation restoration measures, such as the GGP which is gradually transforming degraded farmland into forests and or grassland, to counteract soil erosion and ecosystem degradation in the Loess Plateau. Such 298,000 km^2 of farmland have been transformed into forests and grassland through the GGP from 1999 to 2017. These measures have improved the vegetation cover and changed the land use patterns to achieve the best ecological benefits.

Table 1
Grades of SMC and vegetation coverage.

Grades	SMC(cm^3*cm^{-3})	Vegetation coverage
Low (L)	< 0.15	< 0.3
Medium-low (ML)	0.15–0.20	0.30–0.45
Medium-high (MH)	0.20–0.25	0.45–0.60
High (H)	> 0.25	> 0.60

2.2. Data collection

2.2.1. Soil moisture data

The SMC data were derived from the Essential Climate Variable Soil Moisture (ECV SM) dataset (https://www.ncdc.noaa.gov), including the “active product”, “passive product”, and “combined product”. The former two data sets were created by fusing scatterometric and radiometric soil moisture products, respectively; the last data set is a blended product based on the former two data sets. The data used in this study were from the “combined product”.

As described above, the “combined product” merges the “active and passive products”, which makes up for the lack of data between the “active - passive products” that means the data is better, and improves the quality the data. The merged dataset presents surface SMC (0–5 cm) with global coverage, a spatial resolution of 0.25°, and a temporal resolution of 1 day with a reference time at 0:00 UTC. The SMC data for the “combined product” are provided in volumetric units [m^3 * m^{-3}]. The dataset spans 37 years covering the period from November 1978 to December 2015. In this study, SMC data from 2000 to 2015 were

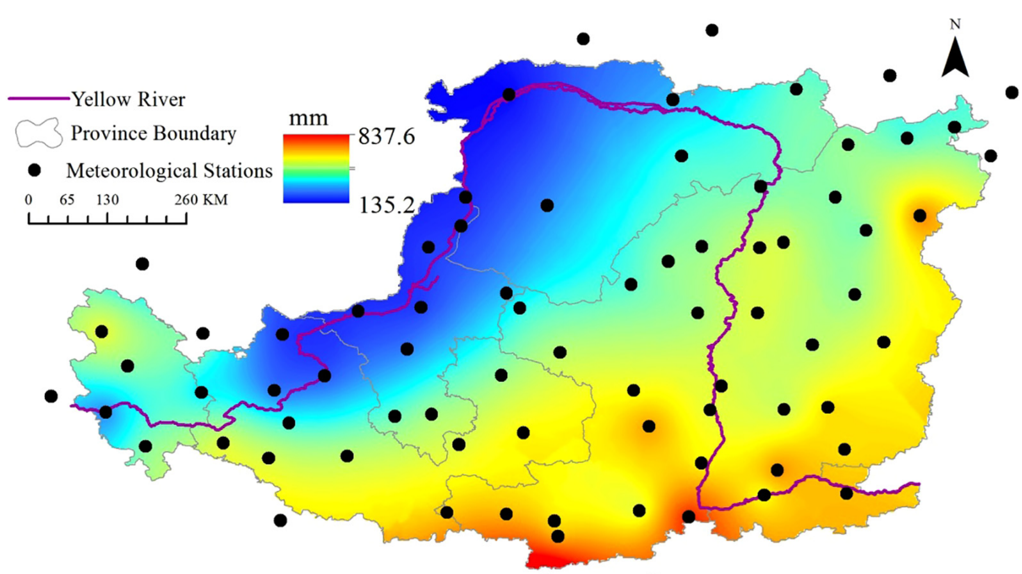

Fig. 1. Spatial distribution of annual precipitation over the Loess Plateau. The gradient colour is the mean value (mm) of annual precipitation from 2000 to 2015.