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Evaluating the coupling effects of climate aridity and vegetation restoration on soil erosion over the Loess Plateau in China

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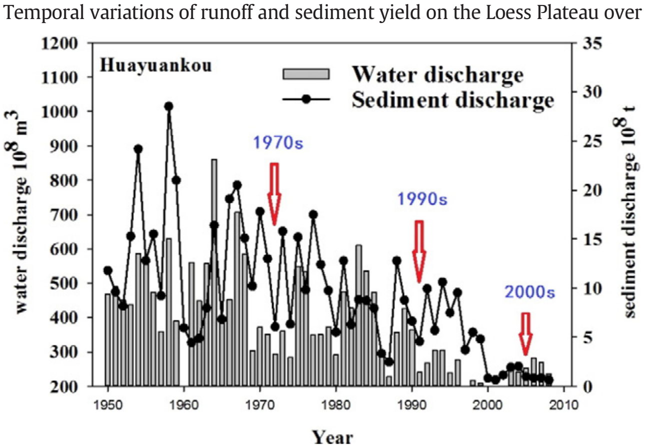
HIGHLIGHTS

- The drought variation trends of the Loess Plateau are identified by two drought indices.
- The impact of climate aridity on runoff and sediment yield is examined and evaluated.
- Changes in vegetation cover with the impacts of "Grain for Green" project are characterized.
- The responses of vegetation cover to drought and how this has effected soil erosion are discussed.
- Climate aridity and vegetation restoration led to a third extensive decrease in sediment yield.

GRAPHICAL ABSTRACT

Temporal variations of runoff and sediment yield on the Loess Plateau over the past six decades.



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ABSTRACT

In this study, the coupling effects of climate aridity and vegetation restoration on runoff and sediment yield over the Loess Plateau were examined and characterized. To take into consideration the complexity of drought, as well as the varied strengths and weaknesses of different drought measures, two drought indices are selected to identify and evaluate drought variability. The Normalized Difference Vegetation Index (NDVI) data were obtained to monitor and express spatiotemporal variations in vegetation cover. The results show that most regions of the Loess Plateau experienced increasingly severe droughts over the past 40 years, and these regions comprise the major source of the Yellow River sediment. Climatic drying initially occurred in the 1990s, and became statistically significant in 2000s. The increasingly severe droughts could negatively impact surface and groundwater supplies as well as soil water storage, but may also minimize surface runoff yield, which is one of the major causes of soil erosion on the Loess Plateau. Vegetation cover on the Loess Plateau was significantly improved after the implementation of "Grain for Green" project, which were helpful for controlling severe soil erosion. With the impacts of the construction of check dams, terraces and large reservoirs, runoff and sediment yield over the Loess Plateau initially exhibited downward trends between 1970 and 1990. After 1990, with the effects of the climate warming and drying, a second sharp reduction in runoff and sediment yield occurred. The coupling effects

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of climate aridity and vegetation restoration have led to a third significant decrease in runoff and sediment yield over the Loess Plateau after 2000.

1. Introduction

The Loess Plateau in China is well-known for suffering from among the highest levels of water shortage and soil erosion in the world (Yang et al., 2015; Wang et al., 2015). The region has a mean annual precipitation of approximately 420 mm, with roughly70% of the rain falling during the summer months, usually in the form of heavy storms (Zhang et al., 2012). This uneven rainfall distribution and the intensity of individual storms across the year have been recognized as the most important trigger for severe drought and soil erosion (Su and Fu, 2013; Li et al., 2014; Hou et al., 2014). Frequent droughts cause the Loess Plateau to have a sparse vegetation cover. Additionally, strong rainstorms, highly erodible loess soil layers, fragmented landscapes, and agriculture practiced on steep slopes have led to the destruction of the area's ecological system and exacerbated water scarcity and soil erosion (Zhang et al., 2013; Gao et al., 2014).

The Chinese government has paid special attention to the Loess Plateau over the past 30 years, particularly with respect to soil erosion and its environmental effects on the Yellow River. In order to improve vegetation cover and control soil and water losses, the government has invested considerable manpower, materials, and financial resources in this region. Notably, in 1999, a large-scale project (designated "Grain-For-Green") was initiated to control soil erosion and improve vegetation coverage on the Loess Plateau by returning sloped farmland (more than 15°) to forest or grassland. However, the vegetation restoration project will inevitably increase the regional water consumption, which could further intensify the water shortage in this region (Cao et al., 2015).In addition, it is reported that the Loess Plateau has experienced substantial climate warming over the past half century, which could also affect the surface water balance, and then aggravate the drought condition (Li et al., 2012a; Wang et al., 2011; Zhang et al., 2013). As such, this region is expected to become increasingly vulnerable to drought as water demands rise from increased climatic warming and the implementation of the Grain-For-Green Program.

Drought can negatively affect surface and groundwater supplies, soil water content, vegetation growth, and then the soil erosion (Wu et al., 2011; Dai, 2013). The ecology of the Loess Plateau, including sparse vegetation cover, uneven rainfall distribution, surface and groundwater deficits, low soil water storage, fragility, and the presence of numerous climatic regions, make it an appropriate place to estimate the impact of climate aridity on soil and water losses because the distinct seasonal wet/dry periods may be influenced by the effects of climate change earlier than other ecosystems (Wang et al., 2011). However, drought is complex, natural hazard that, to a varying degree, affect some parts of the world every year (Hisdal and Tallaksen, 2003).Despite its omnipresent nature, our knowledge of the onset, development and recession of drought is deficient, which hampers our ability to predict its occurrence at seasonal and longer timescales (Sheffield and Wood, 2007).Therefore, drought is natural hazard, caused by large-scale climatic variability, and cannot be prevented by local water management (Van Loon and Van Lanen, 2013).According to Tallaksen and Van Lanen (2004),drought is often defined as a sustained and spatially extensive period of below-average natural water availability with natural causes, such as, the deficit of precipitation or streamflow deficit relative to average conditions(Hisdal and Tallaksen, 2003). But, drought is not fully determined by precipitation and streamflow. Other variables that effect atmospheric water demand such as air temperature, wind speed, solar radiation, and vapor pressure deficit, are also need to be taken into account in drought identification (Vicente-Serrano et al., 2011; McEvoy et al., 2012; Xu et al., 2012).There is no single universally accepted method for precisely quantifying and qualifying the effects of drought. This is largely attributed to drought is a relatively gradual phenomenon that slowly takes hold in an area and becomes more severe over time, and it is often unnoticed and has diverse and indirect consequences (Van Loon, 2015).

In order to identify drought and monitor its development, many indices have been developed and applied (Yuan and Quiring, 2014), which are used to objectively quantify and compare drought severity, duration, and extent across regions with varied climatic and hydrologic regimes (Stagge et al., 2015).Among them, the Standardized Precipitation Index (SPI), which is based on a surface water budget probabilistic approach, is widely accepted by climatologists and hydrologists (McKee et al., 1993).It is based solely on accumulated Precipitation (*P*),and was developed to take into consideration multiscalar properties. A multiscalar index allows the user to examine wet and dry periods over a range of time scales. The main limitation of the SPI is that it is based entirely on *P* and ignores other variables that effect atmospheric water demand. In an effort to improve the SPI, the Standardized Precipitation Evapotranspiration Index (SPEI) was developed by Vicente-Serrano et al. (2010) to incorporate potential evapotranspiration (*PE*) as the estimation of water demand. By taking the atmospheric water demand into account, the SPEI may be able to better characterize drought for regions that experienced significant climatic warming, such as the Loess Plateau (Vicente-Serrano et al., 2010, 2012; Potop et al., 2012).

Recent research has suggested that vegetation cover on the Loess Plateau, which is very sensitive to droughts and moisture availability, will play an important role in controlling the impacts of global climate change on soil erosion (Wang et al., 2011; Zhao et al., 2015). Given the sensitivity of vegetation to drought, and the importance of maintaining vegetative cover to mitigate soil erosion, there is an urgent need to know more about both how the Grain for Green project has effected spatiotemporal variations of vegetation cover and how vegetation cover has responded to drought is needed for the development of future vegetation restoration programs (Xu et al., 2013a, b). Further, it is important to understand the coupling effects of climate aridity and changes in vegetation cover on runoff and sediment yield over the Loess Plateau.

The aims of this study are as follows: (1) to identify how drought has varied on the Loess Plateau; (2) to compare and characterize spatiotemporal changes in vegetation cover as impacted by the " Grain for Green" project; (3) to gain a better understanding of vegetation cover response to drought and how this has effected soil erosion; and (4) to analyze the coupling effects of climate aridity and vegetation restoration on the runoff and sediment yield over the Loess Plateau. To give adequate consideration to the complexity of drought and strengths and weaknesses of different drought indices, two drought indices, including SPI and SPEI, were used in this study. The Normalized Difference Vegetation Index (NDVI) data were obtained to monitor and express the spatial and temporal variations of vegetation cover. Observed hydrometric records from five key gauge stations along the mainstream of the Yellow River were used to characterize changes in runoff and sediment yield over the Loess Plateau. The results presented herein is excepted to provide a better understanding of the coupling effects of climate aridity and shifts in vegetation cover on runoff and sediment yield, which can provide some new insights on formulating more effective environmental restoration systems over the Loess Plateau.

2. Study area

The Loess Plateau covers an area of approximately 6.4×10^5 km^2 (34°–41°N, 98°–114°E), traversed by the upper-middle reaches of China's Yellow River (Fig. 1).The region is in an arid and semi-arid climate zone and has a mean annual precipitation of approximately420 mm, with