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Exploring the role of land restoration in the spatial patterns of deep soil water at watershed scales

Yali Zhao[a,c,d], Yunqiang Wang[a,b,c,*], Li Wang[c,d], Xiaoyan Zhang[a], Yunlong Yu[a,c], Zhao Jin[a], Henry Lin[a,e], Yiping Chen[a,c], Weijian Zhou[a,b,c], Zhisheng An[a,b,c]

[a] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710061, China
[b] Interdisciplinary Research Center of Earth Science Frontier, Beijing Normal University, Beijing 100875, China
[c] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[d] 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
[e] Department of Ecosystem Science and Management, Penn State Univ., University Park, PA, USA

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ABSTRACT

Soil water is a key variable for re-vegetation and environmental restoration in water-limited terrestrial ecosystems such as the Chinese Loess Plateau. Large land restoration projects (e.g., the "Grain for Green" launched in 1999 and the "Gully Land Consolidation" launched in 2011) had substantial impacts on the storage, distribution, and spatial patterns of soil water, and these factors remain poorly understood across watershed scales. We measured the amount of water stored in soil layers from the surface down to 5 m depth and characterized the vertical distribution of gravimetric soil water content (SWC) among four land uses (cropland, shrubland, forestland, and orchard), two slope aspects (shady vs. sunny), and two landforms (slope vs. gully) in three watersheds on the Chinese Loess Plateau. All three of the watersheds were affected by Grain for Green project, two were affected by the Gully Land Consolidation project (named NG and GT-T watersheds) and one was unaffected by restoration efforts (named GT-U watershed). In the three watersheds, the slope and gully SWCs varied from 2.4 to 24.2% and from 4.8 to 46.6%, respectively, during the sampling period in October 2015 (end of the rainy season). The amount and vertical distribution of slope SWC differed significantly among the land uses and between shady and sunny slopes in the three watersheds ($p < 0.05$). The mean gully SWC (20.4%) was significantly higher than the mean slope SWC (8.7%) for each of the three watersheds ($p < 0.01$). Gullies filled by the Gully Land Consolidation project had a large capacity to store soil water by increasing the infiltration of precipitation, which accounted for 14.7% and 11.3% of the total annual rainfall in the NG and GT-T watersheds, respectively. Filled gullies can serve as large reservoirs of soil water to relieve the problem of water shortage and can also increase the amount of land available for cultivation to ease deficits in food production. A combination of the Grain for Green project on slopes for soil conservation and the Gully Land Consolidation project in gullies for storing more soil water and increasing farmland area is an effective land restoration strategy on the Chinese Loess Plateau and is helpful for managing water cycles in regions around the world with deep soils.

1. Introduction

The Chinese Loess Plateau covers an area of ~620,000 km^2. It is a typical fragile terrestrial ecosystem; ~1.6 billion tonnes of sediments have been eroded into the Yellow River in past decades (Chen et al., 2007b; Zhang and Liu, 2005). The unique geomorphology creates specific conditions that prompt of soil deposition, but ecological service functions are weak making governmental strategies for long-term sustainable development on the Chinese Loess Plateau difficult to formulate (Dang et al., 2013; Y.Q. Wang et al., 2015b). The Grain for Green project and the Gully Land Consolidation project are two well-known initiatives implemented by the Chinese government to restore vegetation and create farmland for cultivation, respectively (Li et al., 2016; Liu et al., 2013; Uchida et al., 2005). The scales of both projects were unprecedented, with budgets of ~337 billion RMB ($51.8 billion) and ~30 billion RMB ($4.6 billion), respectively (Jin, 2013; J.Y. Wang

* Corresponding author at: State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710061, China.
E-mail address: wangyunq04@163.com (Y. Wang).

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et al., 2013).

The Chinese Loess Plateau is a predominantly water-limited area. Soil water content (SWC) is the main factor limiting re-vegetation and environmental restoration efforts in this region. The SWC also plays a key role in both Grain for Green project and Gully Land Consolidation project by controlling plant growth and land engineering, respectively. Therefore, determining the impacts of these projects on storage, vertical distribution, and spatial patterns of soil water are essential. This is especially important for water stored in deep soils which can be extracted and used by perennial plants (widely planted in Grain for Green project) and can be sequestered and stored by land-filled gullies (results from Gully Land Consolidation project).

The landscape on the Chinese Loess Plateau has changed tremendously since the implementation of Grain for Green (Miao et al., 2012; Piao et al., 2005; B.Q. Zhang et al., 2013). Vegetation coverage nearly doubled between 1999 and 2013 (Chen et al., 2015). Wang et al. (2015a) reported that a large afforestation project was the largest contributor to a reduction in soil erosion since the 1990s; this was determined using an attribution approach to analyze 60 years of runoff and sediment load observations along the course of the Yellow River over the Chinese Loess Plateau. Grain for Green has achieved great success in environmental improvement and the control of soil erosion, but it has introduced a few new problems. For example, large-scale conversion of farmland to forests and/or grasslands has led to a deficit of available farmland and to some extent, has threatened food security of this region (Bennett, 2008; Chen et al., 2015; Liu et al., 2015). The excessive expansion of vegetation cover can also aggravate water resource limitations which produce dried soil layers in the deep soil profile. Such occurrences can adversely impact plant growth and lead to the degradation or death of the restored vegetation (Li et al., 2008; Y.Q. Wang et al., 2010; Wang et al., 2009). Measures must be taken to achieve sustainable development.

Gully Land Consolidation was implemented in 2011 in Yan'an city which is located in the middle of the Chinese Loess Plateau. The goal was to address the problem of the reduction in farmland which resulted from the wide implementation of Grain for Green. Gully Land Consolidation aims to create farmland by (1) consolidating gullies with soil removed from the surrounding hills, (2) compacting the soil to make it less susceptible to tunneling and subsidence and (3) leveling the land surface to create flat or gentle sloping fields (Liu et al., 2013). This project plans to create 4.0 million ha of farmland from 2011 to 2020 for planting crops in what were originally gully channels. Liu et al. (2015) reported that Gully Land Consolidation can help to reduce soil transport by nearly 10% and create more terraces or land. However, the effect of Gully Land Consolidation project on SWC redistribution at the watershed scale, and the amount of water that can be stored in new lands of the gully, remains unclear.

Considering that SWC plays a critical role in a series of eco-hydrological processes and may determine the transport of material and energy, the absorption and utilization of water by plants, and is related to biogeochemical processes (Bryan, 2000; Laio et al., 2001; Rodriguez-Iturbe, 2000; Vereecken et al., 2014; Western et al., 2002; Xia and Shao, 2008), some researchers have investigated the heterogeneity of SWC in space and time, and found that SWC can be affected by dozens of environmental factors including land use/vegetation, topographic factors, and soil properties (Fu et al., 2003; Qiu et al., 2001; Qiu et al., 2003). However, the impacts of intensively-managed projects such as Grain for Green and Gully Land Consolidation on the spatial patterns of deep SWCs at watershed scales are largely unknown, and this information is needed to improve hydrological modeling and water resources management.

Watersheds on the Chinese Loess Plateau can generally be divided into two parts: uplands which are usually hill slopes and top slopes, referred to as "slope SWC", and gullies, referred to as "gully SWC". The soil water regimes of slopes and gullies need to be studied to determine the effect of Grain for Green and Gully Land Consolidation at a watershed scale which is essential for a better understanding of the effects of land restoration projects on hydrological processes. Evaluating the effect of Gully Land Consolidation on SWC redistribution can further provide useful information to policy makers who are tasked with making strategic decisions that will impact the long-term sustainability of the environment. Therefore, the objectives of this study were: (1) to investigate the overall amount and vertical distribution of SWC on slopes and in gullies within three watersheds, and determine if there are relationships between slope SWC and land use, and slope SWC and slope aspect, after 16 years of Grain for Green, and (2) to determine the status of SWC in gullies in the three watersheds, and evaluate the effect of Gully Land Consolidation on soil water storage at the watershed scale.

2. Materials and methods

2.1. Description of the study area

We chose three representative watersheds to evaluate the effect of Grain for Green and Gully Land Consolidation on soil water regimes. All three watersheds have been a part of the Grain for Green project since 1999, and the vegetation coverage on the slopes has greatly increased since the initiation of Grain for Green. The gullies of the two watersheds, Nangou (NG) and Gutun (GT-T), were filled with soil in 2013 as part of Gully Land Consolidation. The third watershed, Gutun (GT-U), was used as a control for Gully Land Consolidation effects. The areas of the NG, GT-T and GT-U watersheds were 0.36, 0.45, and 0.43 km^2, respectively (Fig. 1), and the areas of the gully land filled in NG and GT-T were 44,110 and 50,941 m^2, respectively.

All three watersheds are near the city of Yan'an in the middle of the Chinese Loess Plateau (Fig. 1). This region has a typical continental monsoon climate with an annual mean precipitation of 541 mm (Fig. 2) according to the Yan'an weather station data collected from 1956 to 2015. A majority of the precipitation (70%) falls between June and September, and a relatively high pan evaporation of 1000 mm (Li et al., 2008). The mean annual temperature is approximately 9.8 °C (Fig. 2). The three watersheds are in a typical hilly-gully region and range in elevation from 966 to 1267 m. The study area contains mainly loessial soil with 4.1–7.1% clay, 63.3–70.5% silt, and 25.4–29.7% sand (Table S1). The soil has low fertility that is vulnerable to erosion. The predominant types of land use are rain-fed farmland (in gullies), shrubland, forest, and native grassland (on slopes). The most common types of vegetation are locust (*Robinia pseudoacacia* L.), korshinsk pea shrub (*Caragana korshinskii* Kom.), sea buckthorn (*Hippophae rhamnoides* L.), and bunge needle grass (*Stipabungeana* Trin.). The trees (locust) and shrubs (sea buckthorn) on the slopes of the three watersheds were planted in 1999 when the Chinese government launched "Grain for Green", while grassland was naturally grown on the land after farmlands were abandoned. Several (usually five years) years following the implication of Grain for Green, the branches of locust trees were thinned once a year, the shrubs were kept without thinning, and while grazing is officially prohibited on the grasslands, it can occasionally be found as local farmers may secretly allow their sheep or cattle onto the grassland. The current land use types of the three watersheds had been established about 16 years prior to when the soil samples were collected. In contrast, the rain-fed agriculture in the gullies was established in 2013 when the Gully Land Consolidation project created the farmland.

2.2. Soil sampling and laboratory analyses

We super imposed 80 m × 80 m grids on Google maps of the NG, GT-T and GT-U watersheds (Fig. 1), ensuring that the sampling sites were uniformly distributed in the watersheds and represented all land uses in each watershed. In each grid cell, we selected one representative site where the dominant species appeared to collect soil samples on the