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Regional development boundary of China's Loess Plateau: Water limit and land shortage

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A B S T R A C T

The planetary boundary concept aims to define the environmental limits within which humanity can safely operate in the global scale. Identification of the regional development boundary and solutions for problems therein is the basis of the local and global earth system sustainable operation. The Loess Plateau in China is an ideal area for studying the regional development boundary concept. After reviewing the main natural and anthropogenic changes on the Loess Plateau and their hydrological and social-economic effects during recent decades, we identified the water limit for large scale revegetation and the land shortage caused by the Grain for Green project as the most important determinants of the regional development boundary. Therefore, it is necessary to readjust the existing revegetation strategy according to the water capacity, including identifying the suitable priority zones and the corresponding species, density and management for keeping the planted ecosystem healthy. In addition, as an integrative mode of land management, gully reclamation can not only create cropland and conserve soil and water, but also strengthen the construction of agricultural infrastructure, foster large-scale agricultural operations and promote the development of rural economy.

1. Introduction

The planetary boundary (PB) concept, introduced by Rockstrom et al. (2009a, 2009b) in 2009, aimed to define the environmental limits within which humanity can safely operate in the global scale. This is a new paradigm that can successfully integrate the continued development of human societies and the maintenance of the biophysical earth system in a resilient and accommodating state. The PB concept is mainly based on the intrinsic biophysical processes that regulate the stability of the Earth system and defines the planetary boundary as a human-determined acceptable level of a key global variable (Steffen et al., 2015). For example, nine boundaries representing specific thresholds of climate change, ocean acidification, stratospheric ozone, global nitrogen and phosphorus cycles, atmospheric aerosol loading, freshwater use, land-use change, biodiversity loss, and chemical pollution have been proposed and quantified. This concept of PB and the idea that there is an identifiable set of boundaries beyond which anthropogenic change will put the natural earth system outside a safe operating space for humanity, has already attracted great interest in the scientific community and gained some support among environmental policy makers (Mace et al., 2014).

Planetary boundary processes inevitably operate across scales as do ecosystem processes, from sub-region scale to the level of the Earth system as a whole (Hughes et al., 2013; Steffen et al., 2015). Hence, Steffen et al. (2015) argued it is necessary to link global and regional scales because changes in control variables at the sub-global level can influence functioning at the whole global Earth system level. This interdependence indicates the need to define sub-global boundaries that are compatible with the global-level boundary definition. In addition, the control variables for many processes are spatially heterogeneous (Hughes et al., 2013). Therefore, we need to focus attention on some special and important regions to identify and quantify regional development boundaries.

The Loess Plateau in China, which covers an area of 640,000 km^2 and is home to more than 50 million people, is widely acknowledged as the region with the highest soil erodibility in the world

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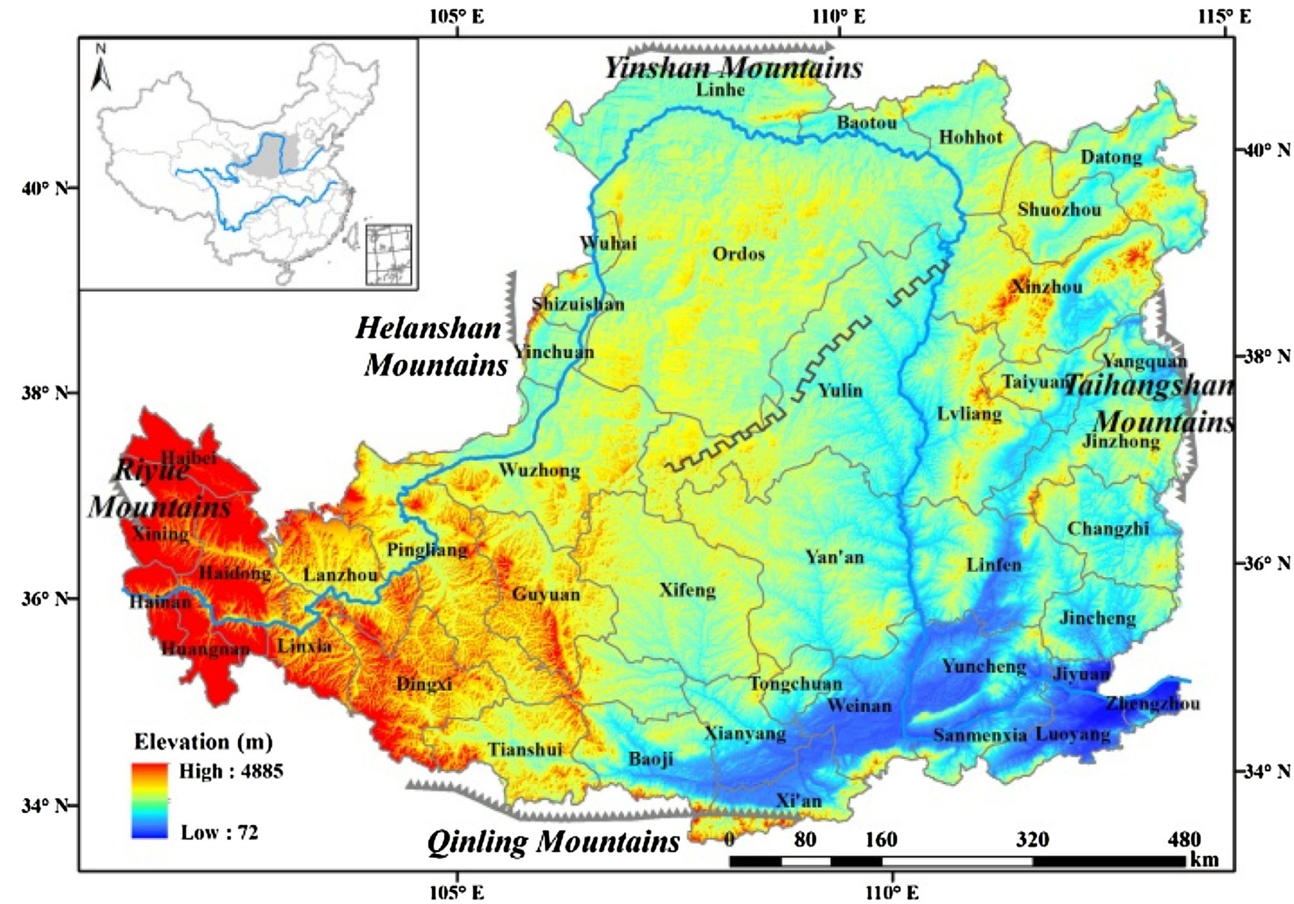

Fig. 1. Location of the Loess Plateau.

(Fig. 1). Nearly 90% of the sediment load of the Yellow River comes from the Loess Plateau. For a long time, this region was notorious for severe drought, erosion, sparse vegetation, high population pressure, low agricultural productivity and local farmer's poverty. Currently, the region is also of significance for China's entire ecological security and natural resources (e.g., coal, oil and gas, etc.) provision (Zhao et al., 2013). The Chinese government has recognized the serious situation in the Loess Plateau for many decades (Lü et al., 2012). Huge efforts and measures have been implemented to repair the deteriorated environments. Since the end of last century, many projects such as "Grain for Green" (GGP) and "Natural Forest Protection" were implemented (Feng et al., 2005, 2013). Large areas of sloping farmland were returned to forestlands and grasslands as a result of these projects (Wang et al., 2013). On the other hand, recent decades have also showed accelerated climate change trends in this region (Sun et al., 2015; Wang et al., 2012a,2012b).

Therefore, the Loess Plateau of China has experienced significant changes in earth surface processes and ecosystem structure and functions in these decades. The Loess Plateau has been the most effective zone for ecological restoration in China since 1999. Large-scale restoration measures and drought have led to a significant reduction of both runoff and sediment losses on the Loess Plateau, which have both advantages and disadvantages for the lower Yellow River (Huang and Zhang, 2004). Some local soil erosion has been successfully controlled, but the whole region remains very fragile ecologically. Thus, it is necessary to identify the regional development boundary of this ecologically vulnerable and climate change-sensitive area and propose some suitable solutions to the problems that exist within the boundary.

Some discussions exist on the synergy and trade-off relationships among the ecosystem services in the Loess Plateau. These discussions have been supported by quantitative assessment of ecological benefits of GGP and changes of major ecosystem services using a combination of remote sensing, model simulation and multivariate statistical analysis (Jia et al., 2014; Lu et al., 2014). Hu et al. (2014) developed a spatially explicit assessment and optimization tool for regional ecosystem services (SAORES), including a database, model base, scenario analysis module, tradeoff analysis module and integrated optimization module. Lü et al. (2012) revealed the spatial-temporal dynamic characteristics of ecosystem services, including water retention, soil retention, carbon sequestration and food production, in the Loess Plateau. However, few of these studies are related to the threshold of these ecosystem services for the socio-ecological system sustainable development in the Loess Plateau.

In this study, we applied the conceptual interpretation of a circular multistep knowledge development process for social-ecological systems research (Fig. 2), which includes system, target, and transformative knowledge (Partelow and Winkler, 2016). We reviewed the main natural and anthropogenic changes on the Loess Plateau during recent decades to identify the main development boundary of this region and propose some solutions for problems therein.

2. Materials and methods

Land cover data of the Loess Plateau were extracted from LANDSAT images with some additional images from the HJ 1A/B satellite (Fu et al., 2011; Zhang et al., 2014) to reveal the land cover changes from 1975 to 2010. In detail, land cover of 1975,

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