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Afforestation and the impacts on soil and water conservation at decadal and regional scales in Northwest China

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ABSTRACT

Massive afforestation has been conducted in dryland regions of Northwest China since 1978. With the impending effects of climate change, it is necessary to reconsider the effects of artificial vegetation on soil and water conservation at decadal and regional scales. Using long-term official and synthesized data, the vegetation's impacts on reducing water loss and their ecological water requirement were studied in four provinces (e.g., Inner Mongolia, Gansu, Qinghai, and Xinjiang). Results showed that vegetation of the four provinces was dominated by grass, while artificial forest had taken up 13% of the total forest area. At the plot scale, vegetation could reduce runoff and sediment by 44% and 83%, respectively. At the regional scale, soil erosion areas showed a decreasing trend, especially after the year 2000. In Inner Mongolia and Gansu, both runoff coefficients and water resource amounts showed decreasing trends. As such, future large-scale afforestation might be ecologically unsustainable in these two provinces. However, the runoff coefficients and water resource amounts of Qinghai and Xinjiang showed increases, mainly linked to climate change. This study helps elucidate the paradox of vegetation restoration in arid regions, and gives some suggestions for ecological restoration in other drylands of the world.

1. Introduction

Drylands cover >40% of the earth's land area (Millennium Ecosystem Assessment, 2005). Sustainable development in drylands depends upon techniques such as soil and water conservation (Mortimore et al., 2009). However, this fragile ecosystem can readily result in land degradation and desertification when mismanaged. Designer ecosystem is a coupled natural-human system designed to optimize ecological services and to alleviate adverse conditions that support ecosystem functions, when environmental degradation is extreme and restoration of an ecosystem to the past state is impossible (Martínez and López-barrera, 2008). Applying designer ecosystem and vegetation management to control soil water erosion could achieve the highest ecological, social, and economic benefits (Palmer et al., 2004).

Forest-water interaction is the central topic for most researches on afforestation in dryland ecosystems. Conversion of marginal cropland to fruit forest could save >70% crop water demand in Uzbekistan of Central Asia (Djanibekov et al., 2012). Fog harvesting was demonstrated to provide additional water input for seedling establishment in southeast Spain (Vallejo et al., 2012). For Mediterranean ecosystems in North Africa and West Asia, afforestation could be successful occasionally even when the annual precipitation is < 200 mm, where the species introduced is appropriate (Le Houérou, 2000). Precipitation and evapotranspiration are important climate variables in modelling the impact of afforestation on water yield. Simulated results showed that a 10% increase in tree cover in the headwaters would reduce river flows by 17% in the 7.5×10^4 km^2 Macquarie River catchment of Australia (Herron et al., 2002). However, on the 0.64 million km^2 Loess Plateau of China, it is estimated that the vegetation restoration from 1999 to 2007 had resulted in water yield decreased in 37% and increased in 35% of the study area (Feng et al., 2012).

Areas of Northwest China could be considered the perfect natural laboratory to study the impact of vegetation restoration on regional hydrological processes in earth surface systems. Most parts of Northwest China are drylands (arid and semi-arid regions) and are suffering serious environmental and ecological problems. In order to achieve multiple environmental objectives such as

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combating desertification, restoring groundwater sources, and eliminating dust storm hazards (e.g. haboobs), long term ecological studies are needed. The Three Norths Shelter Forest System Project, a massive afforestation project, has been conducted in Northwest China since 1978 (Cao et al., 2011; UNCCD and World Bank, 2013). Immediately after the beginning of China's Grand Western Development Program in 1999, other great ecological engineering plans (e.g., the Grain for Green Project) were launched.

However, inadvertent negative effects might arise when planting trees in drylands without carefully considering the prevailing ecosystem. On the Loess Plateau, vegetation restoration could exacerbate environmental degradation and soil desiccation caused by ignoring climate, pedological, hydrological, and landscape factors in large-scale afforestation (Cao et al., 2011; Jiao et al., 2012). In fact, local climate conditions (e.g., mean annual precipitation) and plant species should be major considerations in artificial forestation (Jin et al., 2011; Jian et al., 2015). Most previous research on the impact of vegetation restoration in dryland ecosystems of China was located in the semi-arid Loess Plateau, with little attention paid to truly arid regions. Zhou et al. (2015) noted that land cover changes (e.g., afforestation) in non-humid regions can lead to greater hydrological responses than that in humid regions. With deference to climate change, urgent consideration is needed concerning the trade-off between vegetation restoration and soil and water conservation in arid regions (Cao et al., 2010; Yang et al., 2010).

Given the lack of available research on afforestation in truly arid regions of China, the objectives of this study were to: (1) explore the current condition of vegetation restoration in Northwest China, (2) understand the effects of vegetation on soil and water conservation at both plot and regional scales, and (3) discuss the impact of long-term vegetation restoration on water resources in Northwest China.

2. Material and methods

2.1. Study area

Four provinces located in Northwest China (e.g., Inner Mongolia, Gansu, Qinghai, Xinjiang) were chosen for this study (Fig. 1). About 70.5% of the four provinces contributes to the inland rivers watershed (Chen et al., 2004), which is spatially larger than the arid region of China (Li et al., 2013). Furthermore, most part of the four provinces could be classified as drylands (State Forestry Administration of China, 2014). The main geomorphological units in the study area are mountains, plateaus, and basins. Climate of the region is dry with mean annual precipitation <400 mm. Dominant soils of the region include Orthic Aridosols and Gelic Cambosols, as classified by *Chinese Soil Taxonomy* (Gong et al., 2014). The forest types are dominated by shrub, coniferous forest and broad-leaved forest (State Forestry Administration of China, 2014) while the grassland ecosystem is dominated by tempered desert, tempered steppe, and alpine meadow (Meng, 1994). The total soil erosion area of the four provinces is 1.88 × 10^6 km^2, including 1.57 × 10^6 km^2 wind erosion area and 0.309 × 10^6 km^2 water erosion area. Only soil water erosion is considered in this study, since water eroded region should be given a priority to overcome the erosion problem in dryland ecosystems (Zhang et al., 2015). Finally, population densities of Inner Mongolia, Gansu, Qinghai, and Xinjiang are 21.1, 60.6, 8.0, and 13.6 people per km^2, respectively; areas of prime importance for animal husbandry of sheep, beef cattle, and horses.

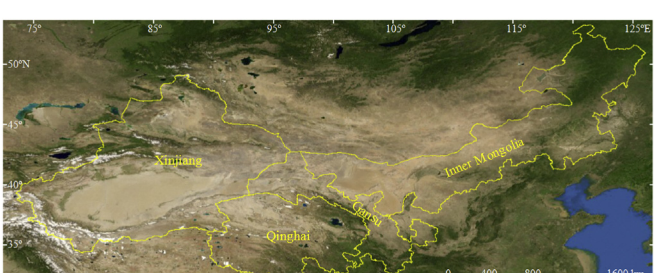

Fig. 1. Sketch map of four studied provinces in Northwest China.

2.2. Data sources, calculation and statistical methods

It is difficult to obtain long-term, large-scale data through field experiments. Thus, the vegetation data compiled in this study were derived from official authorities in China. For example, the forest resources area of China is regularly surveyed every five years. The forest area (including shrub area), artificial forest area, and forest coverage fraction data from 1988 to 2013 were all synthesized from forest survey results (State Forestry Administration of China, 2014; Zhang, 2015). Grassland area data for each province was derived from the Grassland Resources Survey of China (Meng, 1994; National Bureau of Statistics of China, 2011–2014), with the grass coverage fraction calculated thereafter. There was no continuous planting grass area data available. Subsequently, only data from 1990 (Meng, 1994), 1997 (Meng and Liu, 2000), 2000 to 2003 (Liu, 2002, 2003), and 2010 to 2013 (National Bureau of Statistics of China, 2011–2014) were collected.

Field plot approach for studying the impact of vegetation on soil and water conservation is time and labor intensive. Hence, only eight relevant case studies were collected from previous publications. Each plot was constructed with a cement ridge of 30 cm above ground around the borders. A marked H-flume and two volumetric tanks were built at the outlet of each plot for surface runoff and sediments collection (Wei et al., 2007). Plots used by Gao et al. (2007), Wei et al. (2007), and Chen et al. (2010) were 10 m × 10 m and 10 m × 5 m, while plots used by Zhang et al. (2004) and Xu et al. (2007) were 20 m × 5 m. The soil loss rate of two cases was measured using a ^{137}Cs approach (i.e., Zhang et al., 1994; Wu and Tiessen, 2002). Following the formula to calculate a C-factor, an index used to quantitatively express the effect of vegetation on preventing soil erosion in the universal soil loss equation (USLE) (Wischmeier and Smith, 1978), the runoff reduction factor (C_r), and sediment reduction factor (C_s) were calculated as Eq. (1) and (2).

$$C_r = V_r/B_r \quad (1)$$

$$C_s = V_s/B_s \quad (2)$$

where, C_r and C_s are the runoff reduction and sediment reduction factors, V_r and V_s are the amounts of runoff and sediment lost from a vegetated plot, and B_r and B_s are the amounts of runoff and sediment lost from a corresponding barren land plot. All the landscape conditions such as soil, climate and terrain of the vegetated plots are the same with the corresponding barren land plot for each case study. A comparison of different types of vegetation (e.g., forest, shrub, and grass) on reducing runoff and sediment was performed using one-way analysis of variance (ANOVA).

Data of soil water erosion area from 1985 to 2011 were collected from Li (2010) and the Ministry of Water Resources of China (2013), which were obtained by combining field survey and quantitative remote sensing assessment. Remote sensing images used in these four national soil erosion surveys were different, i.e., multispectral scanning system (MSS) image with a spatial resolution of 60 m was used in 1985, thematic mapper (TM) imagery with a spatial resolution of 30 m was used in 1995 and 2000, while satellite for earth