Vegetation changes in recent large-scale ecological restoration projects and subsequent impact on water resources in China's Loess Plateau

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HIGHLIGHTS

- Satellite-derived vegetation index experienced significantly increasing trend.
- More evapotranspiration from restored vegetation is the primary reason for the reduced runoff index.
- Ecological restoration projects produce both positive and negative effects on the overall ecosystem services.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:

Received 7 April 2016

Received in revised form 14 June 2016

Accepted 17 June 2016

Available online 4 July 2016

Editor: D. Barcelo

Keywords:

Loess Plateau

Runoff

Vegetation change

Ecosystem services

ABSTRACT

Recently, relationship between vegetation activity and temperature variability has received much attention in China. However, vegetation-induced changes in water resources through changing land surface energy balance (e.g. albedo), has not been well documented. This study investigates the underlying causes of vegetation change and subsequent impacts on runoff for the Northern Shaanxi Loess Plateau. Results show that satellite-derived vegetation index has experienced a significantly increasing trend during the past three decades, especially during 2000–2012. Large-scale ecological restorations, i.e., the Natural Forest Conservation project and the Grain for Green project, are found to be the primary driving factors for vegetation increase. The increased vegetation coverage induces decrease in surface albedo and results in an increase in temperature. This positive effect can be counteracted by higher evapotranspiration and the net effect is a decrease in daytime land surface temperature. A higher evapotranspiration rate from restored vegetation is the primary reason for the reduced runoff coefficient. Other factors including less heavy precipitation, increased water consumption from town, industry and agriculture also appear to be the important causes for the reduction of runoff. These two ecological restoration projects produce both positive and negative effects on the overall ecosystem services. Thus, long-term continuous monitoring is needed.

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1. Introduction

Arid and semiarid regions cover 41% of the Earth's land surface and contain 38% of the human population. These regions are more ecologically vulnerable, and sensitive to climate change and human activities, the health of which is a critical challenge (Reynolds et al., 2007; Liang et al., 2015; Yang et al., 2014, 2016). In order to address the serious environmental and ecological issues, a series of large-scale ecological restoration projects were carried out throughout the world (Allana et al., 2013), and China has also taken efforts in such actions since the 1950s (Huang et al., 2009). Recently, two large-scale ecological restoration projects, i.e., the Natural Forest Conservation (NFC) project and the Grain for Green (GFG) project, have been launched to improve vegetation coverage in the Loess Plateau of North China (Feng et al., 2013; Liu et al., 2008). Undoubtedly, changes in vegetation directly or indirectly modify biosphere–atmosphere interactions, including the hydrological cycle (Liang et al., 2015) and energy budgets (McVicar et al., 2007; Chapin et al., 2005). A recent research has shown that vegetation growth cools local land surface temperature (Peng et al., 2014; Shen et al., 2015). However, the increased vegetation coverage result in changes in water resources, which is a dominant factor for fragile ecological regions, through inducing changes in land surface energy components, has not been well documented.

The Loess Plateau accounts for 6.6% of the entire land area of China and sustains 8.5% of the Chinese population (Fu et al., 2011). However, due to adverse environmental conditions (e.g., sparse vegetation coverage, periodic high intensity rainstorms) and intensified human activities (e.g., over grazing and coal mining) (Liang et al., 2013; Zhang et al., 2008), this region suffers from severe soil erosion and the average annual soil erosion rate of 2000–2008 is $3180 \text{ t km}^{-2} \text{ yr}^{-1}$ under soil erosion control service (Fu et al., 2011). The Northern Shaanxi Loess Plateau (NSLP), located in the middle of the Loess Plateau, is characterized by typical loess hills and gullies. Average sediment modulus in this region of 1960–1999 is $9370 \text{ t km}^{-2} \text{ yr}^{-1}$ (i.e., 3.8 times and 73 times higher than that in the Yellow River basin and average of continents over the world, respectively) (Mu et al., 2010). Severe soil erosion significantly affects environmental quality and social economy (Fu et al., 2011). To address this problem, large number of ecological restoration projects has been implemented for 30 years since the 1980s. But these costly efforts have yield little success during the first 20 years (Liang et al., 2015). Until the recent 10 years, vegetation restoration began to achieve certain effect and vegetation coverage in the NSLP increased from 29.7% in 1998 to 42.2% in 2005 (Cao et al., 2009). Consequently, it is essential to investigate these underlying causes of vegetation change.

Numerous studies have attempted to evaluate hydrological effects of vegetation dynamics using different methods such as observation experiments and statistic-based model. Huang et al. (2003) assessed runoff responses to afforestation in a watershed (1.15 km^2) on the Loess Plateau using paired watershed approach. However, traditional field experiments are generally constrained to field scale and site level studies may be sensitive to the specific climatic and soil condition (Guo and Shen, 2015). Zhang et al. (2015) establishes a relationship between the change in landscape parameter and vegetation change in a Budyko equation, and quantify the impact of vegetation change on the regional hydrological. However, in the Loess Plateau, there are many non-vegetation measures (e.g. check-dams) and the combined effect of vegetation and non-vegetation makes it a challenge to figure out the impact of vegetation coverage on runoff. Remote sensing products, which have the advantages of broad spatial coverage and high temporal resolution, have been widely used in analyzing the impacts of vegetation coverage change on biophysical properties of land surface (e.g. albedo) (Lü et al., 2015; Xiao, 2014) and thus on water resources changes. Nevertheless, large uncertainties can be involved due to limited scenes of quality images (Kalma et al., 2008; Long and Singh, 2012; Yang and Shang, 2013; Yang et al., 2015). Therefore, combining ground-based observation with remote sensing method is considered as an appropriate

approach to evaluate the effects of ecological restoration. Jia et al. (2014) quantified the benefits and equilibrium of the GFG project in NSLP in terms of soil conservation, water yield, evapotranspiration and net primary productivity (NPP) at the grid-cell level, which is not benefit for catchment management. On the other hand, detailed information about spatiotemporal changes in ecological restoration is not readily available, which precludes a comprehensive understanding of its effect.

Our objectives of this study were to: (i) analyze changes in vegetation variable (i.e. normalized difference vegetation index [NDVI]) and hydro-meteorological variables (i.e., runoff, precipitation and temperature) over 1982–2012; (ii) examine the spatiotemporal pattern of ecological restoration changes during 1999–2010; (iii) investigate possible reasons for changes in runoff coefficient (defined as the ratio between runoff depth and precipitation) during 2000–2012 in the China's Loess Plateau.

2. Methods

2.1. Study region

The Northern Shaanxi Loess Plateau ($35^{\circ}21' - 39^{\circ}34' \text{ N}$, $107^{\circ}28' - 111^{\circ}15' \text{ E}$), is located in the middle of the Loess Plateau with an area of $83,990 \text{ km}^2$ (see Supplementary Fig. S1), which is characterized by typical loess hills and gullies, and dominated by a semi-arid continental monsoon climate (Jia et al., 2014). Annual average temperature in this region varies from 6.5° C in the north to 12.5° C in the south and annual average precipitation increases from 250 mm in the north to 450 mm in the south, 60–70% of which occurs from July to September in the form of high intensity rainstorms (Fu et al., 1999). The soil is mainly derived from loess with fine silt to silt in texture which is vulnerable to erosion (Jia et al., 2014). The land-use types are primarily cropland, grassland and forest (Fig. S1b).

2.2. Data sources

Evapotranspiration (ET) data used in this study were obtained from Numerical Terra Dynamic Simulation Group (2000–2012) (<http://www.ntsg.umd.edu>) and a machine-learning algorithm using flux-tower ET measurements (2000–2011) (<https://www.bgc-jena.mpg.de/geodb/projects/Data.php>). Other MODIS products (i.e., NDVI, albedo, daytime land surface temperature [DLST]) of 2000–2012 were obtained from National Aeronautics and Space Administration (NASA) Earth Observing System (<http://reverb.echo.nasa.gov>). Global Inventory Modelling and Mapping Studies (GIMMS)-3g NDVI data with a spatial resolution of 8 km derived from the National Oceanic and Atmospheric Administration (NOAA), and Advanced Very High Resolution Radiometer (AVHRR)-NDVI of 1982–2012 were used in this study. MODIS NDVI have been used for two reasons: (1) AVHRR products cannot provide such energy variables; and (2) Both vegetation variable (MODIS NDVI) and energy variables (albedo, DLST) have the same data source, thus reducing the uncertainty from remote sensing data. The general information of these data products are listed in supplementary Table S1.

Meteorological data including annual mean temperature, annual and daily precipitation from 1982 to 2012 were obtained from the National Climatic Centre (NCC) of the China Meteorological Administration (CMA). Annual runoff data from 1982 to 2012 at 12 hydrological stations were acquired from the Yellow River Conservancy Commission (YRCC). The ecological restoration data of each county including returning cropland to forest, afforestation of barren land, and mountain closure (e.g. prohibition of fuelwood collection and grazing) from 1999 to 2010 were collected from the Forestry Department of Shaanxi Province.

Fig. 1. Annual changes in NDVI, runoff coefficient (R_c), precipitation and temperature during 1982–2012. For NDVI, black dots represent AVHRR NDVI and green dots represent MODIS NDVI. The stepped red straight lines represent the mean annual values of each period.

2.3. Data analysis

The annual NDVI series of each catchment was generated by averaging each pixel for each year. Similarly, the regional mean time series were also generated for albedo, DLST and ET. Meteorological data including precipitation and temperature were spatially averaged across the study area by the Co-Kriging interpolation algorithm using ArcGIS 10.1, which takes a digital elevation model (DEM) as a third independent variable. Runoff coefficient (R_c) for individual catchment was derived by runoff dividing corresponding precipitation. Linear regression method was used to estimate the trends in these variables (at annual scale). To investigate the relationship

among these variables, Pearson's correlation analyses were performed.

3. Results

3.1. Changes in NDVI, runoff, precipitation and temperature

We detected changes in annual NDVI using two different satellite-derived NDVI datasets: AVHRR (1982–2012) and MODIS (2000–2012). The AVHRR NDVI data showed a significantly positive trend during the entire period 1982–2012 ($P < 0.001$), with an annual increase of 0.002 yr^{-1} (Fig. 1a). However, this increasing trend was not unanimous

Fig. 2. (a) Areas of afforestation of barren land, returning cropland to forest/grassland and mountain closure in each country in 2010; and (b) Cumulative amount of land during 1999–2010.

before and after 2000. It was shown that the AVHRR NDVI over the NSLP slightly increased during the period 1982–1999 (Fig. 1a). In contrast, during their period of overlap in the 2000s, the two NDVI datasets exhibited similar mean trends, and both showed a significant ($P < 0.001$) increase in the annual NDVI during 2000–2012 in the region (6.4 times for AVHRR and 8.3 times for MODIS higher than that in the former period, respectively). Similarly, R_c showed relatively stable change during the former period, while a significantly decreasing trend was observed during the recent decade, with a decrease rate of 0.0017 yr^{-1} (Fig. 1b). However, precipitation has no statistically significant trends and changed very little (only increased by 2.6%) in the two periods

and air temperature even presents a slightly decreasing trend in recent decade (Fig. 1c and d).

3.2. Temporal and spatial pattern of ecological restoration

Fig. 2 showed the ecological restoration area about afforestation of barren land, returning cropland to forest/grassland and mountain closure. Generally, it could be found that cumulative area of land was gradually increased during the period 1999–2010, with large increase for 2002 and 2003 (Fig. 2a). After 2005, this region began to focus on natural rehabilitation (i.e., mountain closure), while the other two measures

Fig. 3. Time series of R_c (black triangles) and AVHRR (black dots)/MODIS (green dots) NDVI in 12 catchments of the NSLP. The blue and red dash lines represent the mean annual NDVI and R_c during different periods, respectively.

remained stable. By the end of 2010, the NSLP have afforested 6.32×10^5 ha of barren land, converted 5.5×10^5 ha of cropland into forest/grassland and have mountain closure area of 0.25×10^5 ha, respectively. Additionally, there is an obviously spatial difference in the implementation of these measures (Fig. 2b). Ecological restoration measures mainly focus on afforestation in the northwestern parts of the region where soil is sandy, whereas the portion of afforestation and returning cropland to forest/grassland were found almost equal in middle parts (Supplementary Fig. S1b).

3.3. Possible reasons for changes in runoff

Fig. 3 shows the inter-annual variation in two dataset NDVI and R_c at catchment scale. Similar to the change of whole NSLP, R_c generally decreased with the increase in NDVI, especially during the period 2000–2012 (Fig. 3). Meanwhile, R_c showed relatively lower value at the southern catchments than that in the northern ones. To further explore the potential causes of changes in R_c after 2000, a correlation analysis between R_c and MODIS NDVI, albedo, DLST and ET at regional scale was applied (Fig. 4). Results showed that annual R_c was negatively correlated with NDVI and ET across the NSLP ($R = -0.35$ and $R = -0.39$, respectively). On the contrary, the relationship between annual R_c , albedo and DLST were detected to be positive ($R = 0.58$ and $R = 0.30$, respectively). Both negative and positive relationship passed the significant test at 0.001 significance level.

At catchment scale, the relationship between MODIS NDVI, albedo, DLST and ET was also investigated. As expected, it was found that annual NDVI in all catchments were significantly negative correlated with albedo and DLST (Fig. 5). The average correlation coefficients were -0.76 and -0.73 over the 12 catchments, respectively. In contrast, NDVI and ET showed a positively correlated relationship (eight of them were statistically significant at 0.05 significance level) with average R of 0.59. In addition, these positive correlation relationship between NDVI and ET estimated in the machine-learning algorithm using flux-tower measurements [<https://www.bgc-jena.mpg.de/geodb/projects/Data.php>], were more robust (average correlation coefficient is above 0.85) with all catchments being statistically significant ($P < 0.001$) (Fig. S2).

4. Discussion

4.1. Driving factors of vegetation change

A great deal of large-scale vegetation restoration projects (such as the Three Norths Shelter Forest System Project, TNSFSP) as well as

Fig. 4. Relationships between R_c and NDVI, albedo, DLST and ET during 2000–2012. *** indicates the 0.001 significance levels.

many local projects, have been launched by the Chinese government during the past three decades (Liu et al., 2008). These projects not only cost plenty of labor and material, but also much financial support. For example, from 1978 to 2000, 7.27 billion yuan had been invested in the TNSFSP (Zhang and Song, 2003). Nevertheless, these costly efforts have yield little success in improving vegetation coverage (Fig. 1a). This can be interpreted as vegetation restoration is largely controlled by soil water availability in arid and semi-arid regions (Porporato et al., 2002; Chen et al., 2010), and artificial trees can consume more water than natural native species (Wang et al., 2008). During rainy seasons, precipitation is not sufficient to replenish the soil water storage (Chen et al., 2010), and finally resulting in artificial forest and grassland degradation during drought years. Statistics show that the overall survival rate of trees planted during afforestation projects has been only 15% across arid and semiarid northern China since 1949 (Tong et al., 2004). On the other hand, the fact is that the Chinese State Forestry Administration has been enthusiastic about tree planting and regeneration, but not necessarily so with restoring grass coverage or natural re-vegetation.

In reality, natural ecosystems that are not damaged too badly have a self-repair ability through natural processes (Aide and Grau, 2004; Yang et al., 2014). Therefore, the recent ecological restoration projects such as the NFC project and GFG project put more emphasis on natural rehabilitation (Fig. 2). In addition, the warming climate extends the length of the growing season and may intensify maximum rates of productivity (Shen et al., 2015). As a result, the satellite-derived vegetation index (NDVI) observed a significantly increasing trend in the most recent decade (Fig. 1a). However, precipitation and temperature, which are key climatic factors determining vegetation growth, changed slightly during the same period (Fig. 1c and d). Therefore, we speculate that recent large-scale ecological restoration, especially the NFC project and GFG project, is the primary driving factor for vegetation coverage increase. Similar result were also reported by Zhang et al. (2013) and Xiao (2014) who state that vegetation coverage on the Loess Plateau exhibited overall increases after the implementation of the GFG project.

4.2. Runoff response to vegetation change

Vegetation change may affect greatly on precipitation distribution ratio between actual evapotranspiration and runoff (Liang et al., 2015; Donohue et al., 2007; Li et al., 2013). NDVI in all catchments presented an obvious increasing trend while R_c presented an opposite trend of 2000–2012 (Fig. 3). The positive correlation between NDVI and ET (Fig. 5) can be the possible reason for runoff reduction. The soil type in the NSLP is the loessial soil, namely the soil has a light color (i.e., yellow) and vegetation albedo is relatively darker, which may result in the decrease of albedo and a positive effect on temperature. Moreover, when the net shortwave radiation (the difference between the incoming shortwave radiation and the shortwave radiation reflected by the surface) increases, there will be an increase in the longwave radiation emitted from the surface into the atmosphere. However, this extra energy, which results from lower albedo, can be dissipated as enhanced vegetation transpiration and soil evaporation.

Afforestation and grass-planting can intercept precipitation, improve the soil structure and increase infiltration (Miao et al., 2010; Xu, 2011). In addition, bark crack and leaf litter can result in the relatively higher soil surface roughness (Xu, 2012), all of which will greatly reduce runoff. Sun et al. (2006) shows that forestation practices may reduce water yield up to 50% especially in the temperate zones of northern China such as the Loess Plateau, which is also supported by Feng et al. (2012) who find that water yield have decreased at an annual rate of 1–48 mm in 38% part of the Loess Plateau.

4.3. Other factors' effects on runoff

Vegetation restoration is one of the major causes for the decreased R_c in recent years, but there are other factors that may be accelerate

Fig. 5. Relationships between NDVI and albedo, DLST and ET at 12 catchments during 2000–2012. *, **, and *** indicate the 0.05, 0.01, and 0.001 significance levels, respectively.

runoff decrease. For example, in order to meet the demands of the development of city, agriculture (i.e., irrigation) and industry, the withdrawal water of region between Toudaoguai and Longmen station (almost covers the study area) from the Yellow River increases from 1.04 billion m³ in 2000 to 1.92 billion m³ in 2012, having nearly doubled in the past ten years (YRCC, 2000; YRCC, 2012). The number of reservoir and check-dam increased rapidly over the past few decades. A recent study by Xu et al. (2010) shows that the total storage capacity of all registered reservoirs was to be 72 km³, which is much higher than the basin's 2000–2010 mean annual runoff (i.e., 23.6 km³). In addition, in our study area, especially in the northern part of the region such as Kuye River catchment (see Fig. S1, catchment 3), there are many of coal mines. The amount of coal mining in this catchment slowly increased from 1987 to 1997 (on average $<2 \times 10^4$ ton), while it increased rapidly after that and reached 13.2×10^4 ton in 2006 (Liang et al., 2013). Obviously, the intensive mining activities would have a negative impact on the groundwater system, and indirectly lead to a reduction in runoff. Precipitation type changes may be also an important driver of variability in the water balance. In the Loess Plateau, heavy precipitation is the major source of surface runoff. However, over the NSLP region, both the number of precipitation days (NPD) and precipitation intensity (PI) of heavy precipitation (>25 mm per day) have been decreasing for the past 30 years (Fig. S3 and Table S2). Compared with the period 1982–1989, NPD and PI during the recent 13 years (2000–2012) decreased by 18.6% and 23.3%, respectively (Table S2). The similar result can be also found in 12 catchments, particular in Xinshihe (Fig. S4).

4.4. Implications

Mountain closure takes full use of the ability of natural ecosystem recovery and accelerates the growth of vegetation, which is considered a fast, cheap and lenient method for the rehabilitation of degraded lands (Mengistu et al., 2005). Nevertheless, Cheng et al. (2014) states that long-term grazing exclusion has a negative impact on species generation and ecosystem stability, indicating that, to avoid degradation, management of the natural resources in the enclosures has to keep the balance between growth and harvest. With the recovery of native and cultivated plant species during 15 years for implementation of the NFC and GFG project (Wang et al., 2013), it is suggested that the recovery grassland can be used for mowing once every two years and light grazing (two sheep/ha) (Cheng et al., 2014). In addition, latest report states that further expanding the implementation of GFG project will reduce the available farmland and thus lead to local deficits of food supplies (Chen et al., 2015). By contrast, our results showed that the DLST presented a significantly decreasing trend, which can be related to the increase of vegetation coverage (Fig. 5). It is strongly consistent with other similar studies in the Tibetan Plateau (Shen et al., 2015). This indicates that vapor released from the plant foliage may benefit the residents by climate regulation in terms of improving temperature and moisture (Jia et al., 2014; Foley et al., 2003). In addition, the large-scale ecological restoration enhances soil conservation through reducing water amount and velocity as well as consequent sediment loads. However, it is still not clear whether the effects of these large-scale ecological restorations on the whole ecosystem services are positive at long time scale and long-term continuous monitoring is needed.

Acknowledgments

This work was funded by the National Natural Science Foundation of China (41571130083), the National Special Program on Basic Science and Technology Research of China (2014FY210100) and the Fundamental Research Funds for the Central Universities (GK201603072).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2016.06.141>.

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