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Does Vegetation Restoration Change Regional Ecohydrological Condition at the Loess Plateau in China?

Xiongwen Chen[1] & Jianzhi Niu[2]

[1] Department of Biological and Environmental Sciences, Alabama A&M University, Normal, AL 35762 USA

[2] College of Soil and Water Conservation, Beijing Forestry University, Beijing, P.R. China

Correspondence: Xiongwen Chen, Department of Biological and Environmental Sciences, Alabama A&M University, Normal, AL 35762 USA. Tel: 256-372-4231. E-mail: xiongwen.chen@aamu.edu

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Abstract

The Loess Plateau is a severely eroded and very venerable area in the northwestern China. Large scale vegetation restoration has been conducted in this region during the recent decades, its effect on the regional ecohydrology is under concern. In this study, long term satellite and derived data were used to analyze regional hydrological condition at the major part of the Loess Plateau (35°-37°N and 105°-110° E). The results indicate that there was an increase in the regional normalized difference vegetation index, evapotranspiration, rainfall intensity, soil water storage (surface 1m layer) and runoff. It was also observed that the total annual precipitation did not change significantly.The possible mechanisms may be related to the complicated processes of vegetation on ecohydrology. Our results and approach may be useful to evaluate the benefits of ecological restoration and further vegetation restoration at the Loess Plateau and other regions.

Keywords: evapotranspiration, satellite data, vegetation, water

1. Introduction

The Loess Plateau is located in the northwestern China with an area of 620,000 km^2 (about 6.6% of the entire land of China) including the provinces of Shanxi, Ningxia, Shaanxi, Gansu, Qinghai, and Nei Monggol Autonomous Region. The semi-arid climate results in sparse vegetation coverage with periodic intense rainstorms. Due to the combined effects of heavy rainfalls during summer, steep topography, low vegetation cover, and highly erodible loess soil, the Loess Plateau is one of the most severely eroded areas in the world (Zhang & Liu, 2005). With large scale overgrazing, agricultural practice and coal mining, the soil erosion rate reached 9,370 t km^{-2}yr^{-1} during 1966-1999. Even under soil erosion control, the soil erosion rate was still 3,180 t km^{-2}yr^{-1} during 2000-2008 (Fu et al., 2011).Soil erosion can remove topsoil and subsequently lower the fertility of farmland which affect crop yield and long-term soil productivity as well as water quality (Boers, 1996; Verstraeten et al., 2002). In order to control soil erosion and improve local environmental quality in this region, the Chinese government has dedicated much effort to conduct several large ecological restoration projects since 1980s, such as Natural Forest Conservation Project and Green for Grain Project. The vegetation coverage increased from 29.7% in 1998 to 42.3% in 2005 and 59.6% in 2013 (Cao et al., 2009; Chen et al., 2015).

Since vegetation can change the distribution of energy and water, numerous studies have evaluated hydrological effects of vegetation dynamics at different spatial and temporal scales using varied methods such as observation experiments, satellite image comparison and statistic-based models. The benefits from vegetation recovery in terms of soil conservation, water yield, evapotranspiration and net primary productivity was quantified at a small area (Jia et al. 2014). An equation with a relationship between the changes of the landscape parameter and quantified hydrological response to vegetation change at catchments was analyzed (Zhang et al. 2015). However, the combined effect of vegetation and non-vegetation landscape makes it hard to evaluate impact of vegetation coverage on runoff at a regional scale. The impact of vegetation restoration on regional water resource in this region was evaluated and a conclusion was made that the increased vegetation coverage resulted in increased evapotranspiration, which is the main contribution factor for the reduced runoff coefficient although water consumption from other activities (e.g., industry and resident) might also increase (Li et al. 2016). Chen et al. (2015) also proposed the same concern that the evapotranspiration in the recovered natural vegetation might decrease runoff. The benefits of vegetation restoration on ecohydrological condition is under concern.

However, the complexity of hydrological processes were ignored, especially the feedback of vegetation. A new hypothesis was developed recently to explain how forests attract moist air (Makarieva et al., 2006). This hypothesis suggested that forest cover plays a much greater role in determining rainfall than previously recognized. The hypothesis agrees with local people at forested regions that forests "attract" rain. Makarieva et al. (2009) and Sheil and Murdiyarso (2009) argue that broad expanse of forest (presumably significantly greater than 2 km^2) leads to increased precipitation. Chen (2016) found that a forest has approximately 20% more precipitation and runoff than a nearby city through remote sensing data. Analysis of underlying ecohydrological processes is needed for vegetation restoration at such a large scale. The goal of this study is to test whether the ecohydrological condition was changed at the Loess Plateau due to large scale vegetation restoration. The specific objectives include (i) whether the land surface temperature decreased at the entire region; (ii) whether the evapotranspiration increased with vegetation restoration; (iii) whether the soil stored more water, and (iv) whether the precipitation increased or rainfall intensity changed, and runoff decreased. The results will be useful to understand the regional ecohydrological processes and to make further decision on vegetation restoration projects in this region.

2. Material and Methods

2.1 Study Area

The study area is located at 35°-37°N and 105°-110° E and covers the major area of the Loess Plateau (Figure.1), which is characterized by loess hills and gullies. The soil is loess with fine silt texture which is vulnerable to erosion. The region has a semi-arid climate. The annual average temperature varies from 4.3°C to 14.3°C and average annual precipitation ranges from 200 mm to 750 mm (Sun et al., 2014). The natural vegetation includes forests, grassland, and desert-steppe (Zhang & Liu, 2005).

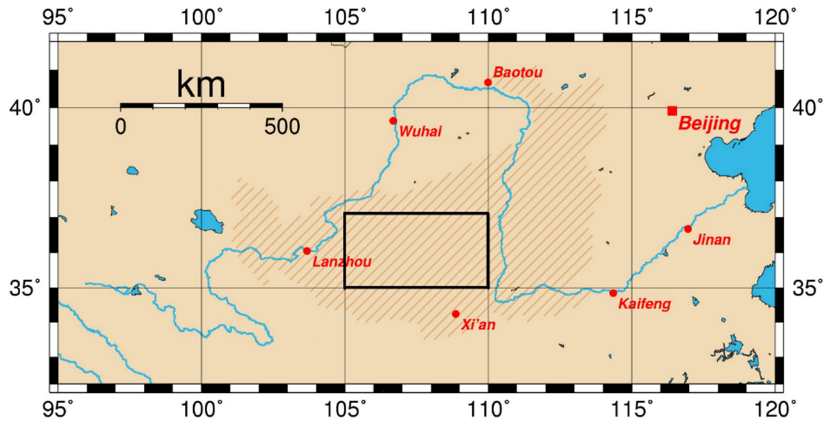

Figure 1. The location of study area (as marked by solid and bold line in the center)

2.2 Methods

Satellites can provide quantitative, spatially explicit, and (in some cases) physically based estimates of a number of biophysical parameters at different scales. Although not all ecosystem properties are amenable to direct detection by satellites, many more can be indirectly used if combined with ground observations or through modeling. Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the Terra and Aqua platforms are uniquely designed to monitor earth change. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths (e.g., Salomonson et al.,1989). Based on the satellite observation, a series of land surface state and flux products from 2000 to 2013 have been generated by the Global Land Data Assimilation System at varied scales. More detailed information can be found at http://airs.nasa.gov and http://modis.gsfc.nasa.gov.

The aridity index (AI) is estimated as:

$$AI = (evapotranspiration - precipitation) / evapotranspiration$$

The runoff coefficient is calculated as $Runoff \ / \ precipitation$.

The commonly used statistical analysis methods, such as REG of SAS was used for data regression with the significance at p <0.05.

3. Results

3.1 Vegetation

The Normalized difference vegetation index (NDVI) reached the maximum values during summer time (June to August) each year (Figure 2). The annual maximum NDVI increased about 30% during summer time, which is significantly from 2000 to 2013 ($y = 0.0103x - 20.237$, R^2=0.8079, p<0.01). The minimum NDVI (winter) also increased about 20%, which mean winter vegetation (e.g., coniferous trees) also increased.

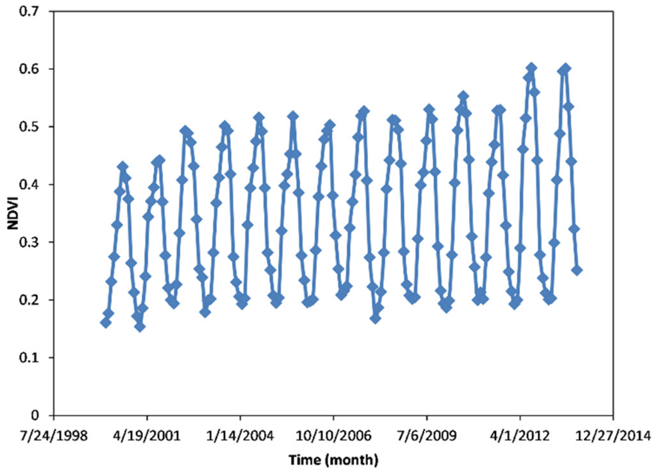

Figure 2. The dynamics of NDVI

3.2 Land Surface Temperature

The land surface temperature at both day and night decreased slightly at the entire region (Figure 3), but was not statistically significant ($p > 0.05$).

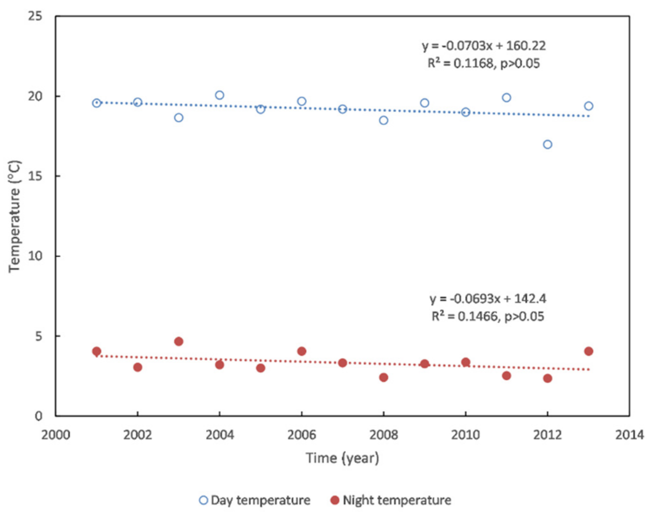

Figure 3. The dynamics of land surface temperature

3.3 Evapotranspiration

The monthly evapotranspiration reached the maximum value during June or July each year (Figure 4a). There was a trend of decreasing evapotranspiration from 1998 to 2008, but a trend of increasing evapotranspiration from 2009 to 2013. The aridity index increased, but a linear relationship is not statistically significant (R^2= 0.0446, p>0.05) (Figure 4b). There was a high correlation between NDVI and evapotranspiration (R^2= 0.7715, $p < 0.05$) (Figure 4c).

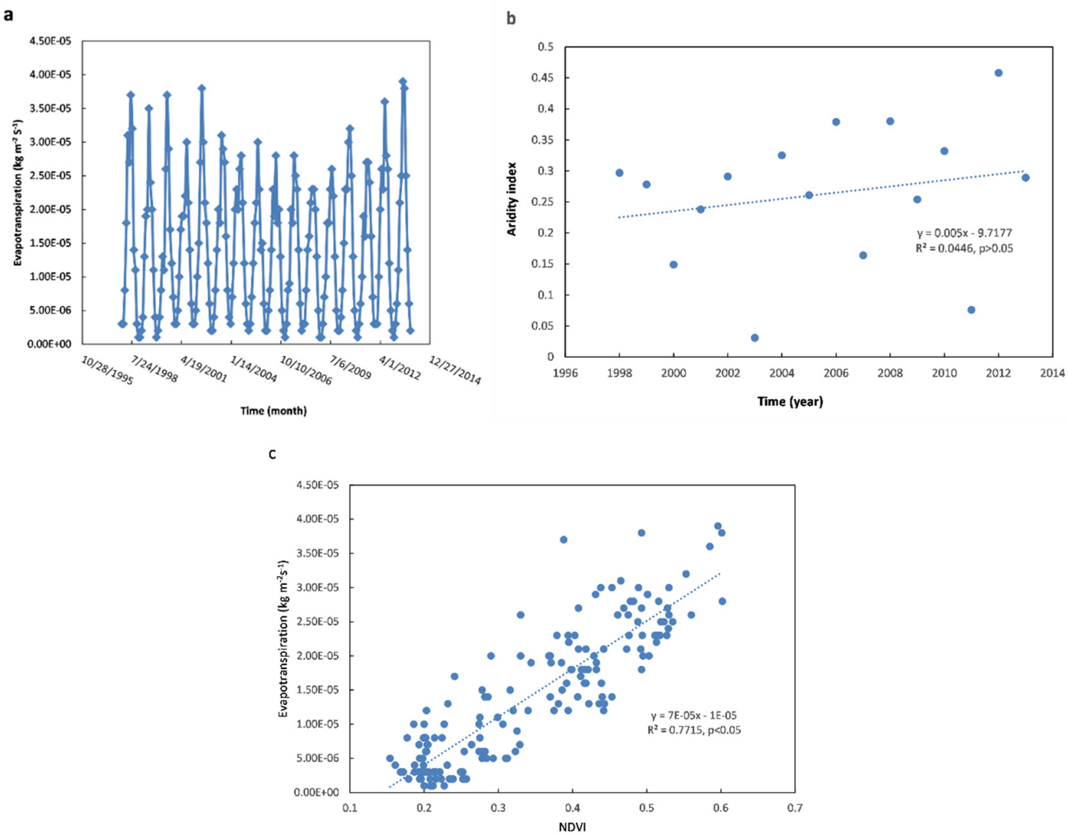

Figure 4. The dynamics of evapotranspiration (a), aridity index (b) and the correlation between NDVI and evapotranspiration (c)

3.4 Precipitation and Rainfall Intensity

The average monthly precipitation was decreased first slightly and then increased from 1979 to 2013 (Figure 5a). There was approximately 55% precipitation falling in summer (June - August) (Figure 5b).

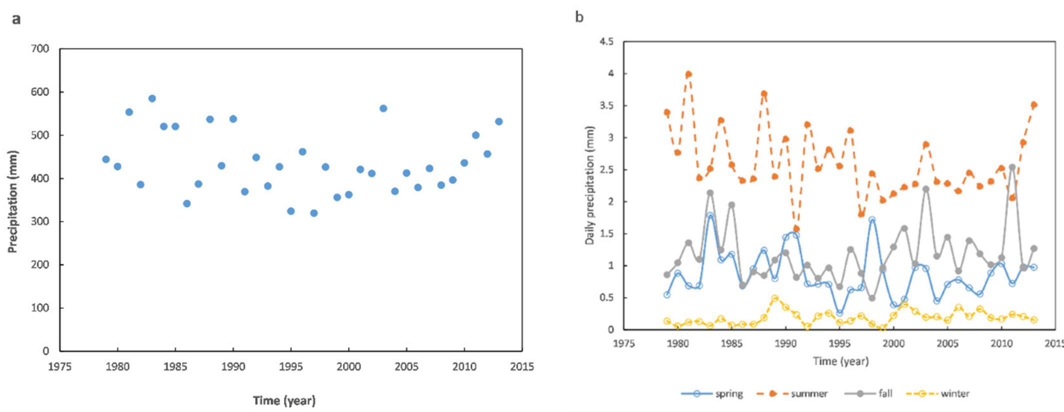

Figure 5. The dynamics of monthly precipitation (a) and seasonal patterns (b)

There was a trend of increasing rainfall intensity (Figure 6a) and the rainfall intensity reached the highest in 2013. The higher rainfall intensity also occurred in summer time (June to August) (Figure 6b). There was a good correlation between monthly rainfall intensity and monthly evapotranspiration ($R^2 = 0.7994$, $p < 0.05$) (Figure 6c).

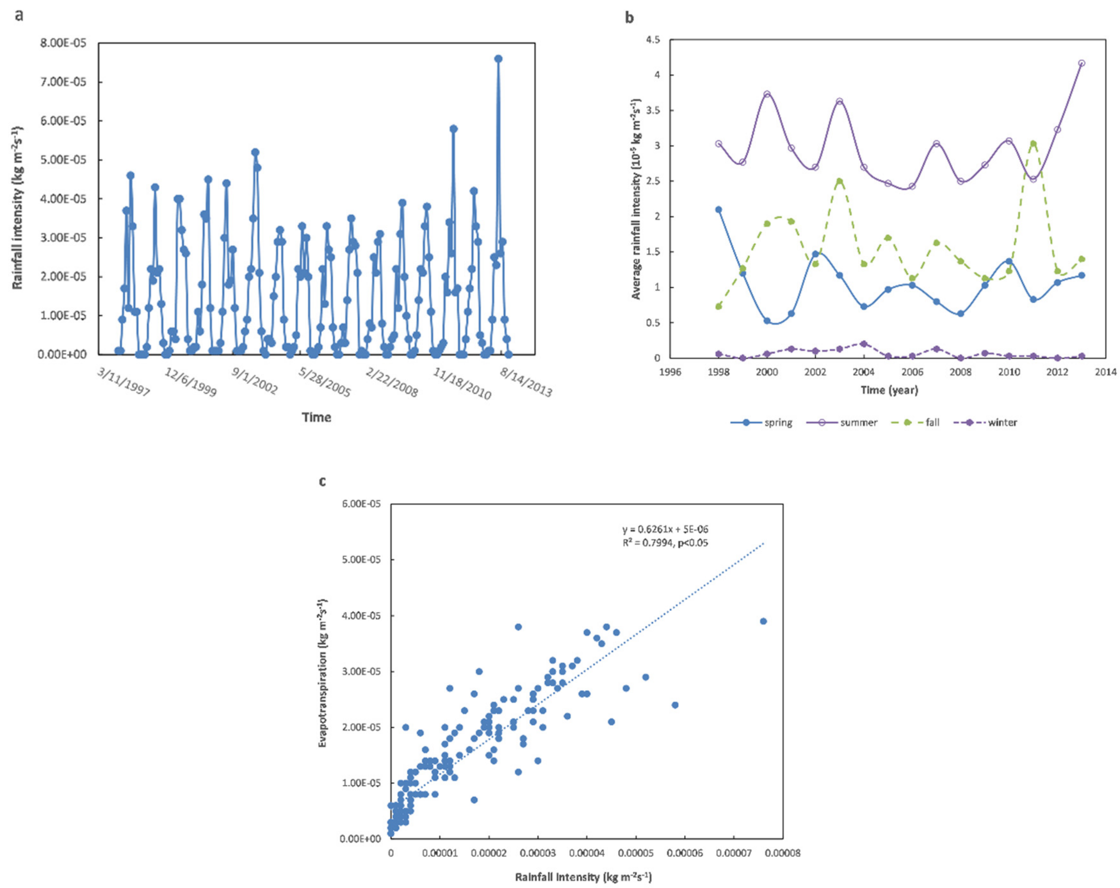

Figure 6. The dynamics of monthly rainfall intensity (a), seasonal patterns (b), and the correlation between evapotranspiration and rainfall intensity (c)

3.5 Runoff

There was a general trend of increasing surface runoff across the region (Figure 7a). The surface runoff is about 4 fold of the surface runoff in 1998. A positive correlation existed between NDVI and surface runoff although it is not statistically significant (R^2= 0.3767, p>0.05) (Figure 7b). The subsurface runoff also generally increased (Figure 7c), but there was high subsurface runoff in 2004. The surface runoff coefficient was relatively stable (Figure 7d), but there were high fluctuations in the subsurface runoff coefficient.

3.6 Water Storage

The soil water content within surface 1 m of soil layer changed dramatically. There were relatively higher soil water content in 2002 and 2004 (Figure 8a), but lower in 2009, after then it increased. The soil water content usually reached the highest in winter and the lowest in summer. The soil water content in winter also increased recently. The total water storage at vegetation canopy also changed (Figure 8b). The water storage at vegetation canopy was positively correlated with NDVI (R^2= 0.615, p < 0.05) (Figure 8c).

3.7 Near Surface Air Specific Humidity

The monthly near surface air specific humidity decreased slightly from 1998 to 2013 (Figure 9a). There was a good correlation between NDVI and monthly air specific humidity (R^2 =0.7796, p < 0.05) (Figure 9b).

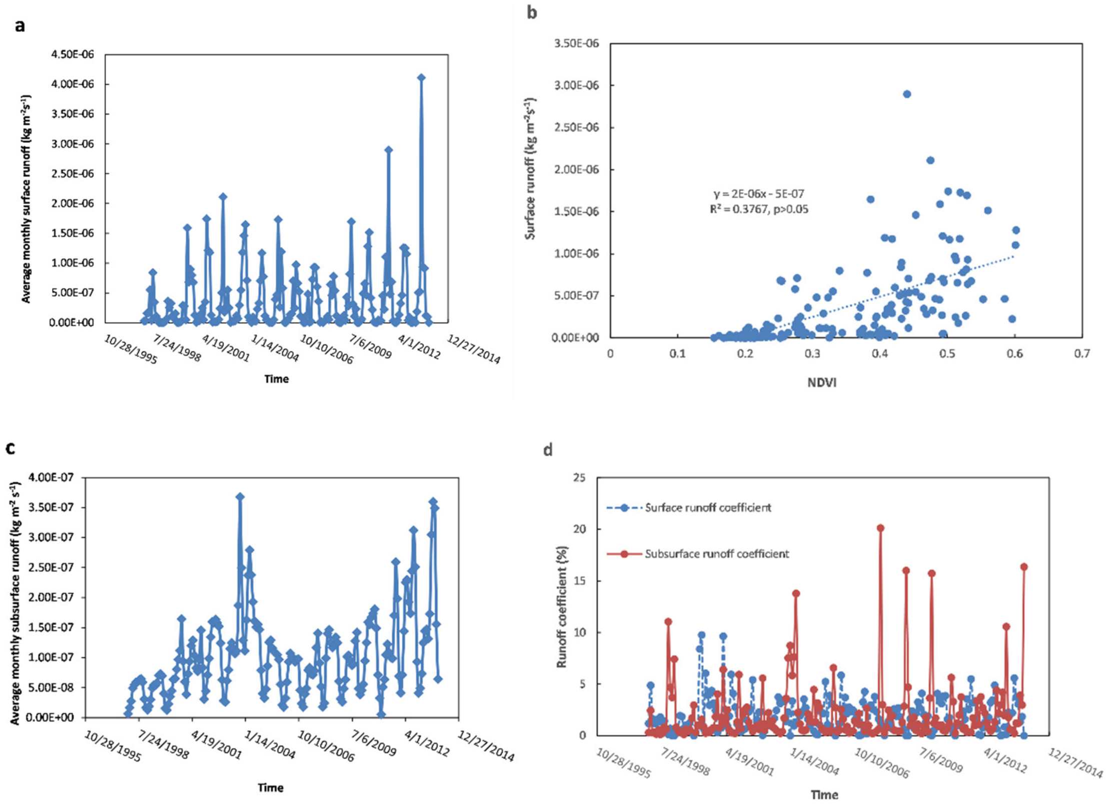

Figure 7. The dynamics of monthly average surface runoff (a) and its correlation with NDVI (b); the dynamics of monthly average subsurface runoff (c) and runoff coefficient (d)

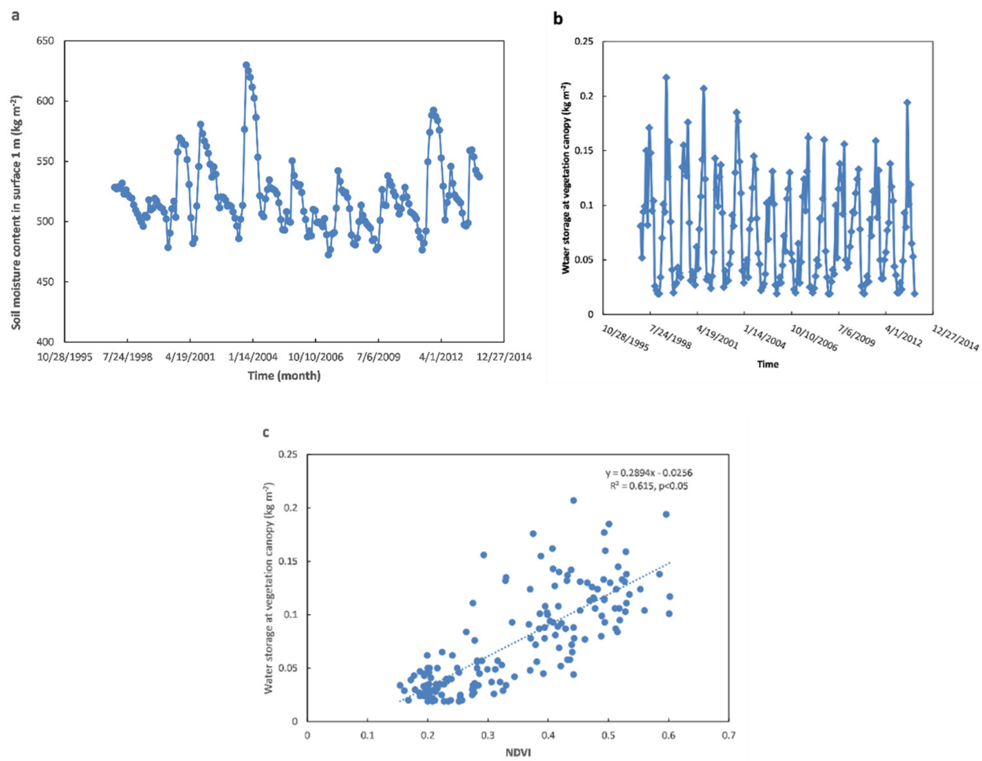

Figure 8. The dynamics of soil water content within surface 1 m layer (a) and seasonal patterns (b); the water storage at vegetation canopy (c) and the correlation between NDVI and water storage at vegetation canopy (d)

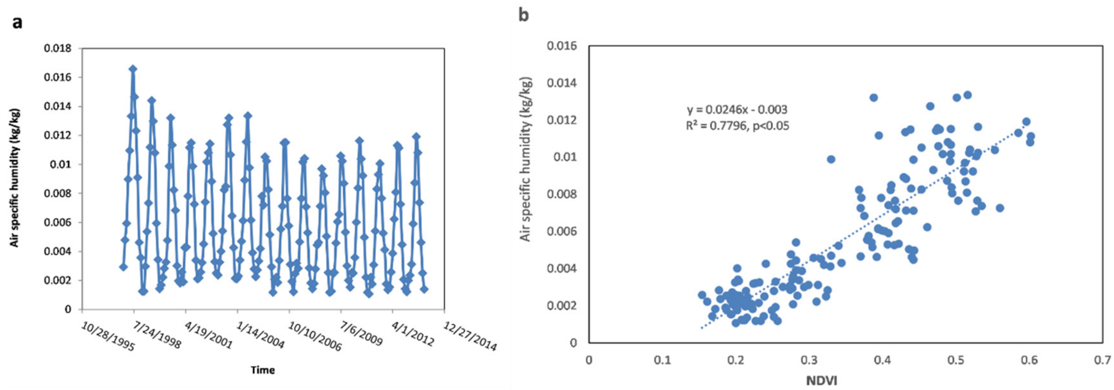

Figure 9. The dynamics of monthly surface air specific humidity (a) and the correlation between NDVI and air specific humidity (b)

4. Discussion

The vegetation restoration at the Loess Plateau in China through several projects (e.g., Natural Forest Preservation and Grain for Green Project) increased regional NDVI and evapotranspiration. Due to increased evapotranspiration, the land surface temperature both during day and night time decreased. Thus, the vegetation restoration not only changed local social and economic status, it also did impact regional hydroclimate. This general trend of temperature change is similar with Li et al. (2016).

The increased vegetation coverage did not increase annual precipitation significantly or effect its seasonal pattern, but it did change for important regional water allocation. Evapotranspiration and the water intercepted by vegetation canopy increased, but the land surface air specific humidity did not increased significantly although there is a positive correlation between NDVI and air specific humidity. The soil water storage (within surface 1 m depth of soil layer) was greatly increased, especially for water storage in winter during recent years. This result was not reported in the previous research. Chen et al. (2010) indicated that the precipitation during rainy seasons is not sufficient to replenish the soil water storage and finally results in vegetation degradation during drought years. Others suspected the benefit of the costly vegetation restoration due to increased evapotranspiration. The increased soil water will be important to satisfy agricultural and local social needs. Also, the runoff at both surface and subsurface was found to have an increase in this study. In the previous research, the decreased runoff was found or assumed (Chen et al., 2013; Li et al., 2016), but the water consumption from urbanization and other use may decrease the soil water storage. The vegetation restoration has already produced positive ecological service although the processes may be complicated, such as increased soil water storage in winter, and also increased evapotranspiration might be partially from the increased canopy interception. The increased soil organic matter and improved soil structure through vegetation restoration (Deng et al., 2016) might also increase infiltration and water holding. Again, the increased soil water will increase plant growth (Bever, 2003). Vegetation may provide complicated and dynamic eco-hydrological behavior on existing soil system. The concept of water balance at a small scale (e.g., catchment) may not be proper to understand hydrological processes at a regional scale. In addition, the low survival rate (e.g., 15%) of planted trees during reforestation projects (Tong et al., 2004) might be partially related to poor management practices. In this study, the runoff at unit land surface was used, which should be much accurate than the original runoff based on stream or catchment.

Most precipitation occurred in the summer time, same as the rainfall intensity. There was a trend of increasing rainfall intensity in the region. The increase in rainfall intensity could cause soil erosion, which is a critical problem in this region. However, with the increase of vegetation coverage, the damage from soil erosion may be decreased because of the increased threshold of rainfall intensity to cause soil erosion at vegetation covered land surface. Different vegetation types have different thresholds in rainfall intensity to produce soil erosion (Zhou et al., 2016). The spatial distributed vegetation patch could minimize soil erosion and its distribution (Puigdefábregas et al., 1999; Bautista et al., 2007). Fu et al. (2012) suggested that the mixed forest trees and shrubs would be optimal for inhibiting soil erosion. Vegetation also was positively correlated with air specific humidity.

5. Conclusion

In conclusion, after studying the long term remote sensing data, it was discovered that the vegetation restoration at the Loess Plateau in China has slightly improved the regional hydroclimatic condition, such as decreased land surface temperature, increased soil water storage. The changed hydroclimate may benefit the agriculture and society in this region. This overall change may not be observed at a small scale due to spatial heterogeneity. The spatial and temporal complexity in eco-hydrological processes related to vegetation restoration at a large scale may provide underlying mechanisms. However, further vegetation restoration or management in this region will depend on the tradeoff between economic, social and environmental interactions. Local native plants (e.g., fruit trees, coniferous and shrubs) should be selected to form communities of mixed trees and shrubs with low water consumption for ecological restoration. Also, social and economic factors (gain or lose) need to be included.

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