Evolution of Vegetation System in Heihe River Basin in the last 2000 years

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Abstract: The response of vegetation system to the long-term changes in climate, hydrology, and social-economic conditions in river basin is critical for sustainable river basin management. This study aims to investigate the evolution of natural and crop vegetation systems in Heihe River Basin (HRB) over the past 2000 years. Archived Landsat images historical land use maps and hydrological records were introduced to derive the long term spatial distribution of natural and crop vegetation and the corresponding biomass levels. The major findings are: (1) both natural and crop vegetation experienced three development stages: Pre-development stage (before Republic of China), rapid development stage (Republic of China - 2000), and post-development stage (after 2000). Climate and hydrological conditions did not show significant impacts over crop vegetation while streamflow presented synchronous changes with natural vegetation in the first stage. For the second stage, warmer temperature and increasing streamflow were found to be important factors for the increase of both natural and crop vegetation in the middle reaches of HRB. For the third stage, positive climate and hydrological conditions, together with policy interventions, supported the overall vegetation increase in both middle and lower HRB; (2) there was a significantly faster increase of crop biomass than that of native vegetation since 1949 which could be exaplained by the technological development; and (3) the ratio of natural vegetation to crop vegetation decreased from 16 at Yuan Dynasty to about 2.2 since 2005. This ratio reflects the reaction of land and water development to a changing climate and an altering social-economic conditions at the river basin level, therefore, it could be used as an indicator for water and land management at river basins.

Key Words: Natural vegetation, crop vegetation, biomass, remote sensing, reconstruction, river basin

1. Introduction

Natural vegetation plays a key role in maintaining functions of catchment ecosystems including contributions to goods, services, and ecosystem biodiversity at arid and semiarid river basins (Ahlström *et al.*, 2015; Feng *et al.*, 2013; Kefi *et al.*, 2007). With the rapid population growth, an increasing amount of water has been allocated worldwide to support human activities, particularly for agricultural irrigation, whereas water for natural vegetation, wetland, and other catchment ecosystems might have been compromised. Consequently, natural vegetation systems in water-limited regions have been degraded, and salinization and desertification have been reported repeatedly (Huang *et al.*, 2015; Li *et al.*, 2007; Su *et al.*, 2007; Xue *et al.*, 2015). An understanding of the development of natural vegetation under different water availability conditions and its interactions with the human crop system, is vital for sustainable river basin management.

There is an overwhelming amount of studies on the impact of land use and land cover changes, driven by either human activities or climate changes, on the catchment hydrological regime and the water cycle (Esteban and Albiac, 2011; Ian and Reed, 2012; Leggett *et al.*, 2003; Xue *et al.*, 2015). However, few studies have investigated how the vegetation system evolved in response to the changes in water regimes at the basin scale. In the last decade, an increasing number of studies have contributed to the knowledge of allocating the limited water resources among different ecosystems in river basins to balance the economic development and environmental sustainability (Wang *et al.*, 2007). However, most of these studies were carried out within a short time range, either to identify the rationality of water allocation schemes reform (Cheng, 2002; Yang *et al.*, 2003) or to test the effectiveness of ecological restoration projects (Thevs *et al.*, 2015). Long-term changes study in vegetation systems in response to significant alternations in climate, hydrology, and social-economic conditions is lacking in current literature (Sivapalan *et al.*, 2012).

The knowledge gap identified above happened partly due to the unavailability of long-term instrumental data on vegetation and hydrological change at the basin scale. With the rapid development of remote sensing technique, images acquired from multiple satellite platforms provide an ideal method to track the landscape changes at river basins in the past five decades (Nian *et al.*, 2017; Beuchle *et al.*, 2015). Among a mass of the remote sensing based metrics to characterize vegetation system, spatial extent, normalized differential vegetation index (*NDVI*) and biomass are commonly recognized as the most effective indices which have been widely applied in spatial analysis of landscape ecosystems (Pettorellia *et al.*, 2005; Pinsky and Fogarty, 2012). For historical periods (previous years with no remotely sensed data), emerging approaches including dendrochronology, ice core analysis, and other empirical methods have been applied to reconstruct eco-hydrological elements and their long-term variations (Turner *et al.*, 2007; Lowry and Morrill, 2011). Several studies tried to reconstruct historical cultivated vegetation systems, but relatively little attention has been paid to natural vegetation distributions in historical periods (Hu and Li, 2014; Xie *et al.*, 2013; Ramankutty and Foley, 1999). Moreover, factors and mechanisms driving vegetation evolution have largely remained neglected.

The Heihe River Basin (HRB), located in arid North-western China, is an important part of the ancient Silk Road established in the Han Dynasty (206 BC - AD 220). It was also a trade center between China and western countries, which facilitated a cultural and economic exchange for approximately 1500 years. HRB is a typical inland river ecosystem, which includes natural vegetation, irrigated crop, desert and terminal lakes. The middle course of the basin has an agricultural history over more than 2000 years while the lower reaches are located at the alluvial fan - supporting local human civilization and ecosystem development (Fu *et al.*, 2014). Increasing agricultural development and changing climate and hydrology over the past 2000 years have significantly changed use of land and water resources and have modified the catchment vegetation system (Lu *et al.*, 2015, Yan *et al.*, 2016). More specifically, several decadal scale studies have provided quantitative descriptions of agricultural and natural vegetation changes responding to the water transfer project implemented since 2000, which effectively prevented further ecosystem degradation (Zhao *et al.*, 2016; Zhang *et al.*, 2015). Within a centurial scale, Nian (2017) found that the rapid expansion of cultivated land was the primary force causing serious ecological deterioration in the HRB. However, information about long term vegetation changes responding to the rise and fall of civilizations, as well as the changed climate and hydrology conditions, is currently lacking. Such information is crucial for an understanding of the ecosystem's health and for promoting sustainable management in the basin.

The present study aims to understand the vegetation evolution in HRB over the past 2000 years, for which both natural and crop vegetation are considered. The specific objectives of the present study are: (1) to determine the area and biomass of vegetation using remote sensing imagery for recent years (since 1987); (2) to reconstruct vegetation distribution and biomass levels for previous periods (before 1987) and (3) to determine potential factors for vegetation evolution. It is expected that the methods developed and the findings obtained from this study could assist in achieving an understanding of how current ecosystem problems emerged in the past and what their implications can be for future river basin management.

2. Material and Methods

2.1. Study area

HRB is the second largest inland river basin in China, which stretches between 38 °- 43 °N and 98 ° - 102 °E (Figure 1). The middle and lower course of HRB contain several types of landscape including river delta plain, terminal lakes, mobile dune and semi-mobile dunes, and low mountains and hills. The unused land such as the desert, Gobi and bare land accounts for more than 75% of the river basin while cropland only takes up 4% (according to land cover map of 2011, data available at WestDC database http://westdc.westgis.ac.cn/). The rest of the landscape are distributed with natural oasis. The main vegetation types in these regions are dry steppes and shelter forests.

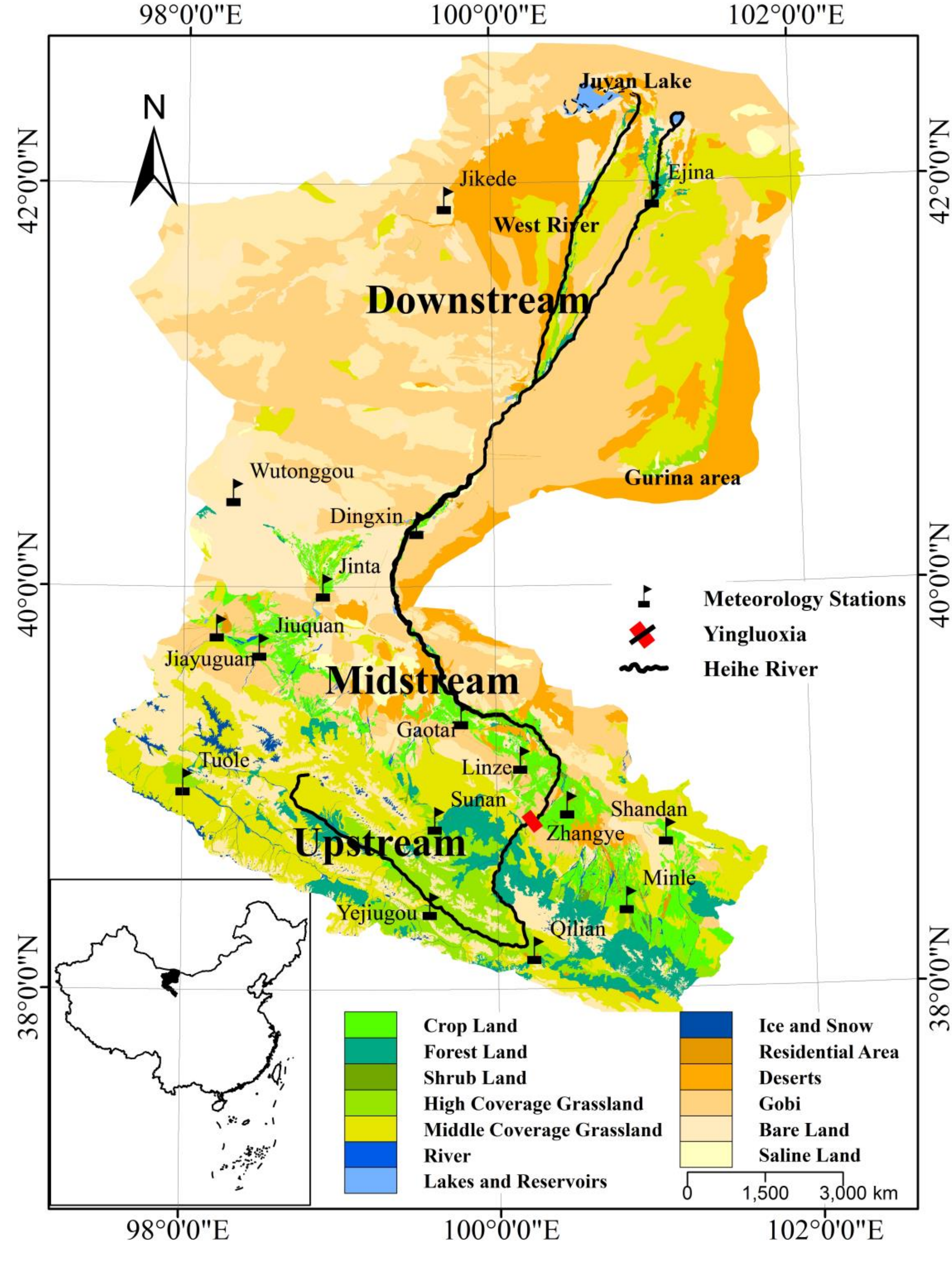

Figure 1: Location of the Heihe River Basin (HRB). Land cover data (2011) is available at WestDC database (http://westdc.westgis.ac.cn/)

The terrain in HRB gradually tilt from southwest to northeast. The altitude of the area ranges from about 820 to 1100 m. The region is occupied with a typical continental arid climate characterized by frequent wind, scarce rainfall, abundant sunshine and intensive evaporation. The average annual temperature in this area over the last three decades is 8.3 ^{o}C (with remarkable seasonal variations). Temperatures can decrease to -37.6 ^{o}C in winter months and reach up to 43.1 ^{o}C in summer months (the highest temperature normally occurs around July). The annual average pan evaporation in the

Ejina oasis is 3,749 to 4,132 mm/year, which is much higher than the mean annual precipitation (ranged from 7 to 101 mm/year) with substantial interannual variations over the past three decades.

River inflow from the North Qilian Mountain constitutes the primary water source for the river basin. It makes HRB an important grain production base and the region has experienced intensive agricultural activities to meet the grain demands of military events since the Han Dynasty (121 BC – 220 AD) (Xie *et al.*, 2013). Nowadays, the midstream is still one of the most important agricultural belts in Northwest China. However, the increasing water abstraction for irrigation, along with increasing usage for domestic purposes in middle reaches, has substantially consumed the available water supply for downstream systems over the past several decades. Consequently, the Juyan Lake shrank dramatically in the last 100 years, and dried-up in 1992 (east Juyan lake). Since the late 1990s, the Chinese government has implemented a series of policies to secure the required amount of water for sustaining the ecosystems in lower river courses and to avoid further degradations. In 2002, the Juyan Lake (east) started to retain water again which was taken as an important sign of ecosystem recovery (Nian *et al.*, 2017).

2.2. Study period

We selected the past 2000 years as our study period, which started from the Han Dynasty (206 BC – AD 220) (Table 1). This timescale covered several ancient dynasties of China, the Republic of China (RC), and the Peoples' Republic of China. The period has experienced dramatic changes in climate, land use, runoff, management policy, population, social and ecological developments. All these factors could contribute to changes in water cycles within the river basin and can, therefore, influence vegetation distributions.

Table 1: major dynasties during the selected study period (Lu, *et al.*, 2015).

Dynasty	**Period**	**Main production**
Han Dynasty	206 BC – AD 220	Agriculture
Wei-Jin Era	AD 220 – AD 420	Animal husbandry
Sui-Tang Dynasty	AD 581 – AD 907	Agriculture
Yuan Dynasty	AD 1271 – AD 1368	Animal husbandry
Ming Dynasty	AD 1368 – AD1644	Agriculture
Qing Dynasty	AD 1644 – AD 1912	Agriculture
Republic of China (RC)	AD 1912 – AD 1949	Agriculture
The Peoples' Republic of China (PRC)	Since AD 1949	Agriculture

2.3. Determining vegetation distribution and estimating vegetation biomass

2.3.1. Landsat image preprocessing

Landsat images were used to derive vegetation distribution and biomass since 1980s. Five Landsat scenes (path/row 133/31, 133/32, 133/33, 134/31, 134/32) for each year were required to cover the area. The collected images covered the timescale ranging from 1987 to 2015 except for 1989 and 1996 when there were no high-quality images. Most of these images were acquired from June to October to represent the growing season for crops and natural vegetation in the study area.

The Landsat datasets containing digital numbers (DN) were downloaded from the United States Geological Survey (USGS) Earthexplorer website (http://earthexplorer.usgs.gov/). The DN values were converted into top-of-atmosphere (TOA) reflectance using the radiometric gain and offset values associated with each Landsat images. Then a Quick Atmosphere Correction (QUAC) method was adopted to account for atmospheric scattering and to derive land surface reflectance. *NDVI* was then calculated using the red and near-infrared bands for each year.

As demonstrated with MODIS *NDVI* series (Figure 2), natural and crop vegetation presented significant phenology cycles. Since the collected annual, Landsat images were acquired at different dates (sometimes in different months) of a year, the above calculated *NDVI* values might have included these seasonal variations. To compensate this effect, we used the MODIS *NDVI* profile in 2013 to calibrate the Landsat *NDVIs* to annual maximum *NDVI* using a linear interpolation algorithm. Specifically, with the knowledge of acquisition date of Landsat image for a specific year, the ratio of MODIS *NDVI* for that date to the maximum MODIS *NDVI* was calculated and this ratio was applied to Landsat derived *NDVI* to calculate maximum *NDVI* for that year. The method could be presented with the following equation:

$$NDVI_{L-max} = NDVI_{Li} \times {}^{NDVI_{M-max}}\!/_{NDVI_{Mi}} \qquad (1)$$

where *L* stands for Landsat, *M* stands for MODIS, *i* stands for the date when Landsat *NDVI* need calibration. MODIS 250m NDVI product (i.e. MOD13Q1) was applied in this procedure. Only the data of 2013 was used with the consideration that annual vegetation growth would follow a similar phenology cycle. Thus, it is necessary to use the 2013 *NDVI* series to calibrate Landsat *NDVI* in extra years without causing significant uncertainties in the final results.

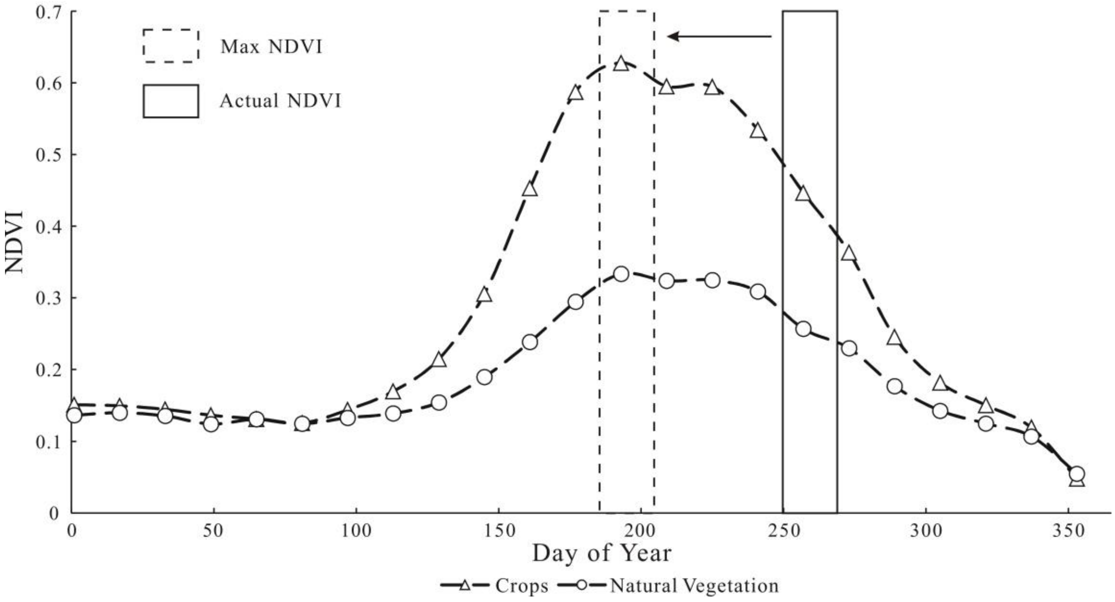

Figure 2: *NDVI* profile for natural vegetation and crops in 2013. The rectangles indicated the scheme of calibrate actual Landsat *NDVI* (solid rectangle) to annual maximum *NDVI* (dash rectangle).

2.3.2 Determining vegetation areas and biomass since the 1980s with satellite images

Two rounds of threshold analysis were applied to determine natural and crop vegetation distributions in HRB since the 1980s. Through an analysis of the *NDVI* histogram distribution characteristics, 0.12 was selected as the first threshold value to mask out non-vegetation landscapes, including water surfaces, deserts, residential areas and other bare surfaces. Then, the second round of threshold analysis was introduced to separate crop vegetation from natural vegetation according to their phenology differences (Figure 2). In short, we randomly sampled the vegetation maps and derived the average *NDVI* levels for natural and crop vegetation, respectively. Then, 0.35 was set as the second threshold to separate crop ($\geq$0.35) and natural ($<$0.35) vegetation. A most recent land cover map (i.e. 2011) created by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, was introduced to assist identifying vegetation types. The preliminary results were first overlaid with each year's Landsat images to check the accuracy. The threshold for the year was adjusted when it presented significant errors in the classification results. In addition, the results in 2000 and 2011 were verified with a set of land use maps (2000, 2011) obtained from the WestDC database (http://westdc.westgis.ac.cn/). A detailed scheme of inter-comparison of land cover maps between this study and existing results were detailed in Zhao (2016). Overall, the two datasets presented substantial consistency where kappa coefficients (k) were 0.7206 and 0.6731 for 2000 and 2011. Areas of natural and crop vegetation for each year were calculated by summing areas of every small patch of natural and crop vegetation respectively.

To study the vegetation development and water usage, biomass for natural and crop vegetation was calculated using NDVI. Regression models established by Zhao et al. (2007, 2010) for HRB were adopted. In Zhao's research, herbaceous biomass was measured by means of dry biological weighing methods and the field measured biomass for natural and crop vegetation showed high correlation with NDVI ($R > 85\%$ and $p < 0.01$). Therefore, the following equations were established for natural and crop vegetation respectively.

$$\text{Biomass}\ (\text{g/m}^2) = 327.4 \times \text{NDVI} + 102.29 \quad \text{for natural vegetation} \quad \text{(Zhao et al. 2007)} \tag{2}$$

$$\text{Biomass}\ (\text{g/m}^2) = 1{,}789 \times \text{NDVI} + 559.68 \quad \text{for crops} \quad \text{(Zhao et al. 2010)} \tag{3}$$

These two equations were applied to the $\text{NDVI}_{\text{L-max}}$ series created in section 2.3.1 to obtain the crop and natural vegetation biomass since 1980s in HRB.

2.3.3 **Historical vegetation distributions and biomass levels**

The crop and natural vegetation areas in previous dynasties (Table 1) were derived from Lu (2015)'s results. In Lu's study, historical cropland was reconstructed based on population, grain yield and ancient ruin distributions (Lu *et al.*, 2015). Natural vegetation distributions were estimated based on the assumption that people tended to select natural oases (grassland and forest) rather than desert for reclamation in historical periods because the former have better water and soil conditions in these arid regions, while the abandoned croplands desertified. Thus, natural vegetation for previous dynasties could be evaluated based on the changes in cropland between the previous and current dynasties (Lu *et al.*, 2015).

To estimate historical vegetation biomasses, we first established the relationship between biomass and several variables which have potential impact on vegetation development. The candidate variables include temperature (T), river flow from upstream (Q), river flow to Juyan Lake (Q_l), groundwater recharge (Q_g) and precipitation (P). T and P records were collected from the surrounding weather station (Figure 1). River flow to Juyan Lake was determined according to the records measured at Ejina station. Streamflow through Yingluoxia gauge station stands for the total upstream inflow to the study area (Q). Groundwater reserves data were obtained from the government statistics yearbook. The component of streamflow consumed for vegetation developments (ΔQ) was then determined by deducting Q_l and Q_g from Q. With this established database, a stepwise regression method was introduced to explore relationships between biomass (biomass for natural vegetation, biomass for crops and, the total biomass) and the selected hydrological and climatic metrics. As indicated by the regression model, the significant relationship between total biomass and T and water supply (ΔQ) was found as listed below ($R^2 = 0.612$).

$$Total\ Biomass = 39.246 * T + 9.312 * \Delta Q - 345.671 \quad (4)$$

$$\Delta Q = Q - Q_l - Q_g \qquad (5)$$

We then applied equation 4 to estimate historical total biomass levels using the corresponding (T, ΔQ) settings. Specifically, historical T was derived from paleoclimate records reported by Yang (2002). Q estimations by Sakai et al. (2012) based on glacier mass balance analysis were adopted. Since the spatial extent of the lake did not change considerably in historical periods, Q_l was assumed to be equal to evaporations from the lake surface which could be derived from public articles (Xiao and Xiao, 2008); Q_g was set to be 0 based on the assumption that groundwater level did not change over the historic periods when agricultural activities were relatively small.

Unlike crop biomass which was largely influenced by technological development, the biomass of natural vegetation was considerably less influenced by human activities. Therefore, we assumed that biomass density for natural vegetation in the region did not change over the study period. According to the Landsat-based results for the past 30 years, the average biomass density for natural vegetation was stable at about 190 g/m^2 and this value was applied to historical vegetation maps to get the corresponding biomass estimations for natural vegetation. Crop biomass was then estimated by deducting the component for natural vegetation from the total biomass estimations.

2.4 Determination of potential driving factors for vegetation developments

Hydrological variables including Q, ΔQ and climatic variables including P and T were related to spatial extents and biomass levels of natural and crop vegetation through multiple linear regression analysis to assess whether or not there were any significant relationships. The regression analysis was applied to the dataset covering the entire study period and the sub-dataset since 1980s (derived from Landsat) respectively to check the robustness of the relationship. The analysis was performed with the IBM SPSS Statistics software package (version 20.0).

3 Results

3.1 Spatial and temporal variations in vegetation distribution in the past 2000 years

The reconstructed natural (green) and crop (red) vegetation distributions spanning the past 2000 years are shown in Figure 3. Historic maps (before 1987) were derived from Lu's results (Lu *et al.*, 2015) and maps after that were interpreted from Landsat images. The spatial extent of crop vegetation in both midstream and downstream of HRB has changed significantly over the study period. Distribution of crops was focused within the Ejina and Jinta in Han dynasty. Since Tang dynasty, the major crop distribution shifted to the regions surrounding the current Zhangye City, while cropland in lower reaches largely decreased. Since the establishment of the PRC the crop vegetation had increased at a high rate, especially in the midstream. As for natural vegetation: prior to Yuan Dynasty, natural vegetation in downstream was primarily distributed along the East river channel. Vegetation distributions along the West River were observed since the Ming Dynasty. For modern China (after RC), natural vegetation presented an overall decrease from RC to 1980s and 1990s. A recovering trend was observed since the 2000s.There were few changes in natural vegetation distribution in the midstream regions in ancient dynasties (prior to Qing Dynasty). From 1949 to 2000, natural vegetation in the midstream basin has significantly increased with substantial inter-annual fluctuations. After 2000, vegetation distribution was relatively stable at a high level.

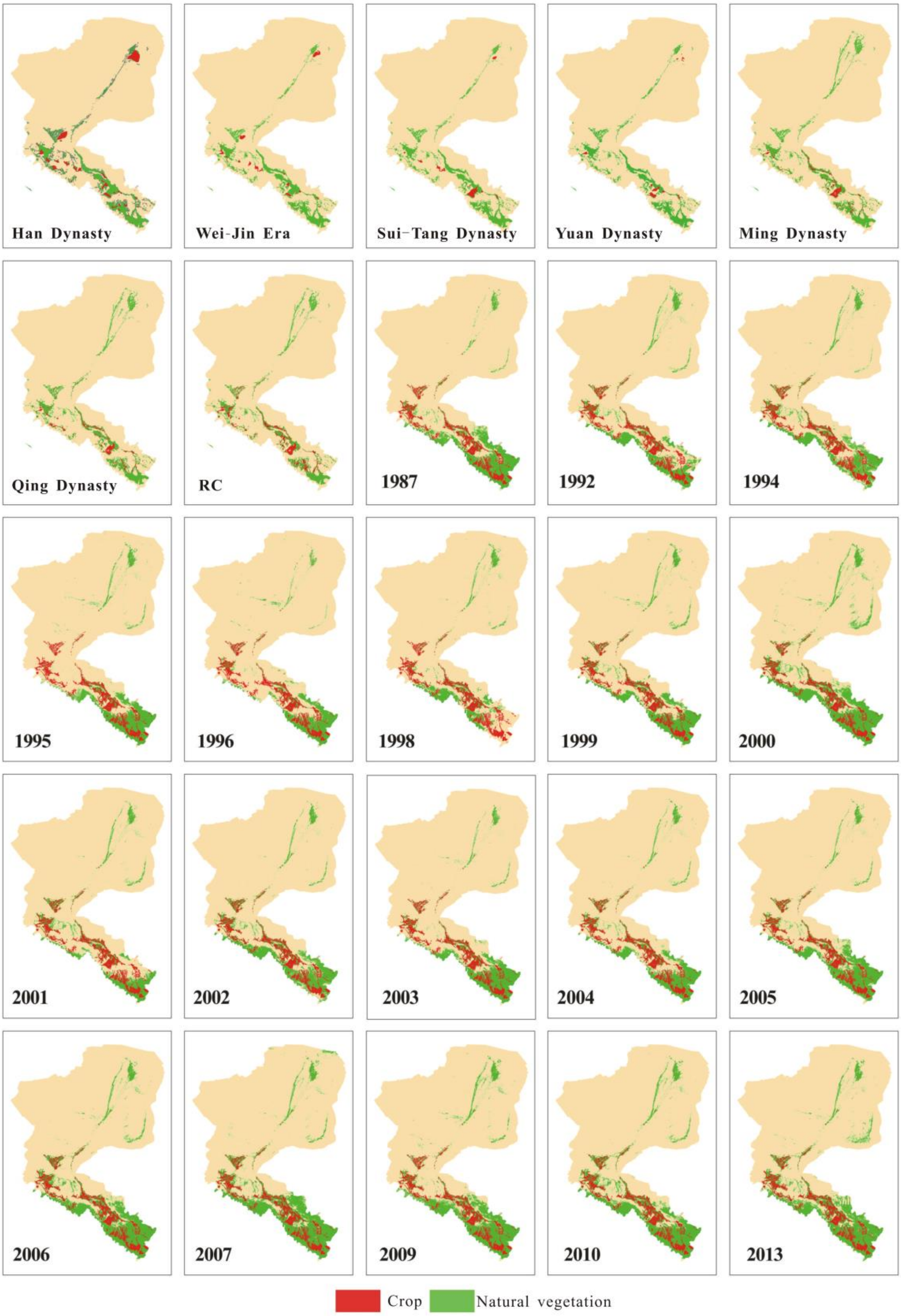

Figure 3: Reconstructed natural (green) and crop (red) vegetation distributions in the past 2000 years. Historic maps (before 1987) were derived from Lu's results (Lu *et al.*, 2015) and maps after that were interpreted from Landsat images.

The temporal variation of vegetation areas over the past 2000 years is presented in Figure 4. The total vegetation area increased by 8,732 km^2 during the studied period. Historically, total vegetation within HRB experienced a slight decrease, from about 8,122 km^2 in Han Dynasty to about 6,918 km^2 in the Republic of China. Natural vegetation for this period constantly decreased by 21% to only 5,000 km^2. Cropland for the same period presented more variations: it had a large spatial extent in Han Dynasty at about 1,755 km^2, and then gradually decreased to about 379 km^2 in Yuan Dynasty. From the Ming Dynasty onward, it started to increase again and reached a peak of 1,917 km^2 in the Republic of China. Situations were different in the period of modern China. Total vegetation area increased from about 6,918 km^2 to 11,362 km^2 in 1987 and to 13,863 km^2 in 2000 with an increasing rate of 2% per year, while the crops have substantially increased by about 150% to 4,939 km^2 in 2000. In the same period, natural vegetation has also substantially increased from about 6,559 in 1987 to about 8,924 km^2 in 2000. After 2000, the increasing rate of the crop area has decreased from 3% per year to 0.3% per year while the natural vegetation has substantially increased to about 11,691 km^2 in 2013, resulting in the total vegetation area steadily increased to 16,854 km^2 in 2013.

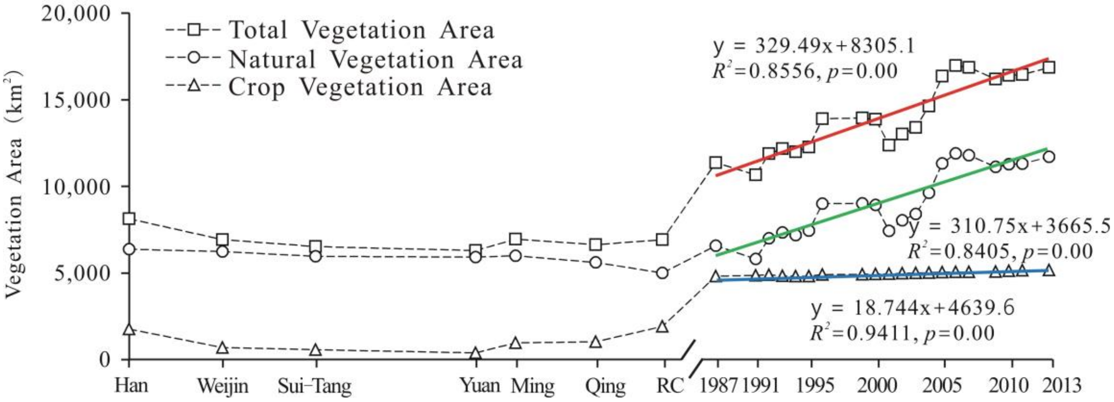

Figure 4: Temporal variations in total vegetation areas (square), natural vegetation (circle) and crops (triangle). It should be noted that data after 1987 reflect the results after applying a 3 years moving average to reduce the annual fluctuations.

The ratio of natural vegetation area to crop vegetation area varied over the past 2000 years (Figure 5). The ratio, to some extent, reflected the relationship and interactions between the two vegetation systems. As demonstrated in Figure 5, although small in scale, natural vegetation occupied a major portion of the vegetation in this area in Han Dynasty and it substantially increased until Ming Dynasty when the ratio peaked at 16. The increased ratio during this period could be attributed to the decreased amount of farming activities (Figure 3, Figure 4). As agriculture started to boom since Qing Dynasty, the ratio decreased significantly to about 1.4 in the Republic of China. Afterward, the ratio showed a constant increase with a rate of 0.06 per year (R^2 = 0.8063). Overall, the ratio of natural vegetation area to crop vegetation area during the modern China period was relatively stable compared to the great historic fluctuations and ithas stabilized at around 2.2 since 2005.

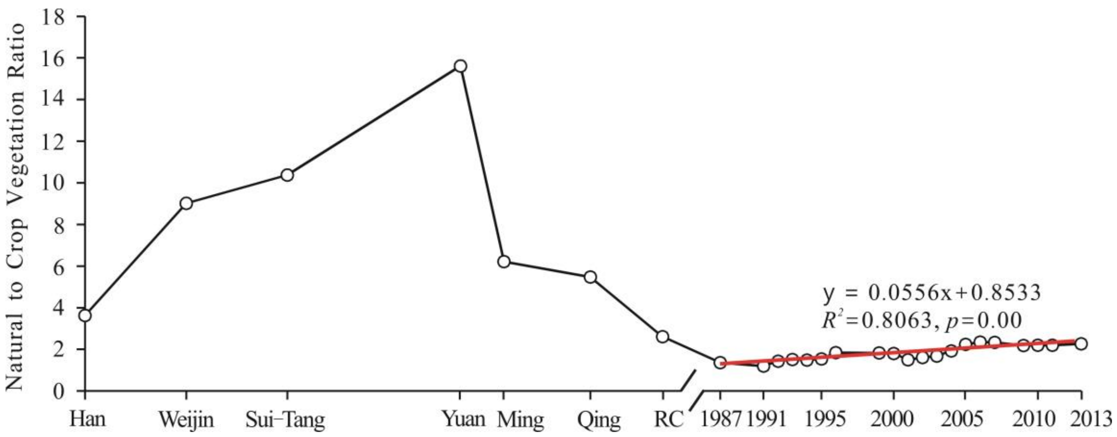

Figure 5: Changes in ratio between the areas of natural vegetation to crop vegetation in the past 2000 years

3.2 Changes in vegetation biomass over the past 2000 years.

Using the Landsat-derived biomass estimations and the corresponding hydrological and climatic records, we created the relationship between biomass and T and ΔQas demonstrated in equation 3. The relationship was applied to the long term T and streamflow records to derive historic biomass estimations. As showed in Figure 6, biomass in natural vegetation in historic periods (prior to the Republic of China) had experienced a decrease by 20% and the biomass of crop underwent a decrease before Tang Dynasty and increased after. Since the Republic of China, biomass in natural vegetation has shown a gradual increase from about 95 $\times 10^4$ t to 159 $\times 10^4$ t in 2000. After 2000, the upward trend continued with a higher increasing rate. For crops, the biomass presented a sharp increase by about 4 times from RC to 1980s. A slight increase trend in past 30 years was observed. The average biomass per unit area of natural vegetation was stable while the average biomass per unit area of crop increased by 2.2 times over the past 2000 years. The average biomass per unit area of crop increased by about 180% since PRC.

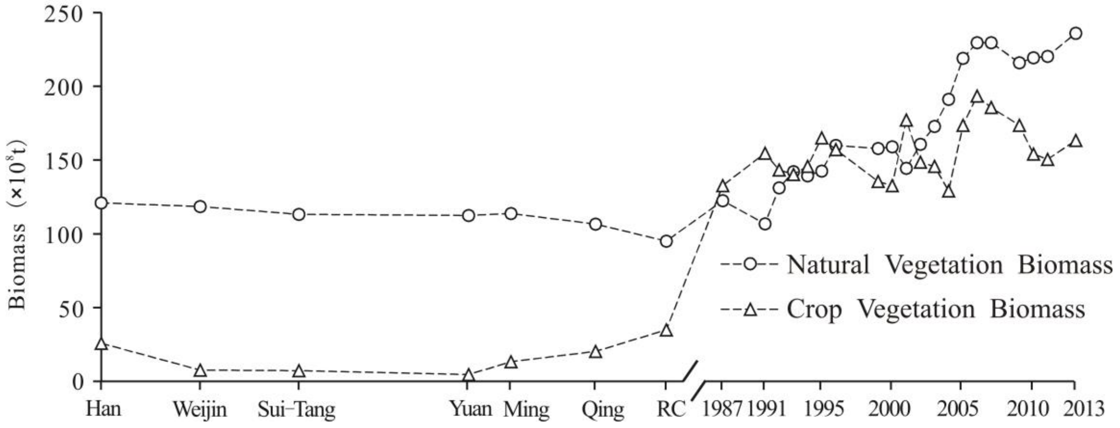

Figure 6: Temporal variations in biomass of natural vegetation (triangle) and crops (circle) over the past 2000 years

3.3 Impacts of hydrological and climatic variables over vegetation development in the past 2000 years

The regression analysis between vegetation development and hydrological and climatic variables show that both *T* and *ΔQ* present an overall positive effect on natural and crop vegetation distributions (Figure 7 a and b). From a holistic perspective, *T* showed a significant impact over natural vegetation expansion while its effects on crops were quite limited. Meanwhile, *ΔQ* exerted similar effects on both natural (R^2 = 0.6016, p = 0.00) and crop (R^2 = 0.9188, p = 0.00) vegetation development over the past 2000 years. It is also found that *T* showed significant positive impacts over both natural (R^2 = 0.7684, p = 0.00) and crop (R^2 = 0.6836, p = 0.00) vegetation during the past three decades with instrumental data (Figure7 c and d). Similar for *ΔQ*, it alone contributed about 77% and 60% of the area expansion since 1980s for natural (p = 0.00) and crop (p = 0.00) vegetation, respectively. A multiple factor regression analysis shows that increasing *T* and *ΔQ* could explain over 90% of the vegetation development (i.e. 96.0% for natural vegetation and 91.7% for crops). Although the development of vegetation did not show an evident relationship with precipitation, there were some years during which vegetation area was less than other years in last 30 years, for example, 1992 and 2001, which may be due to the inter annual variations of precipitation.

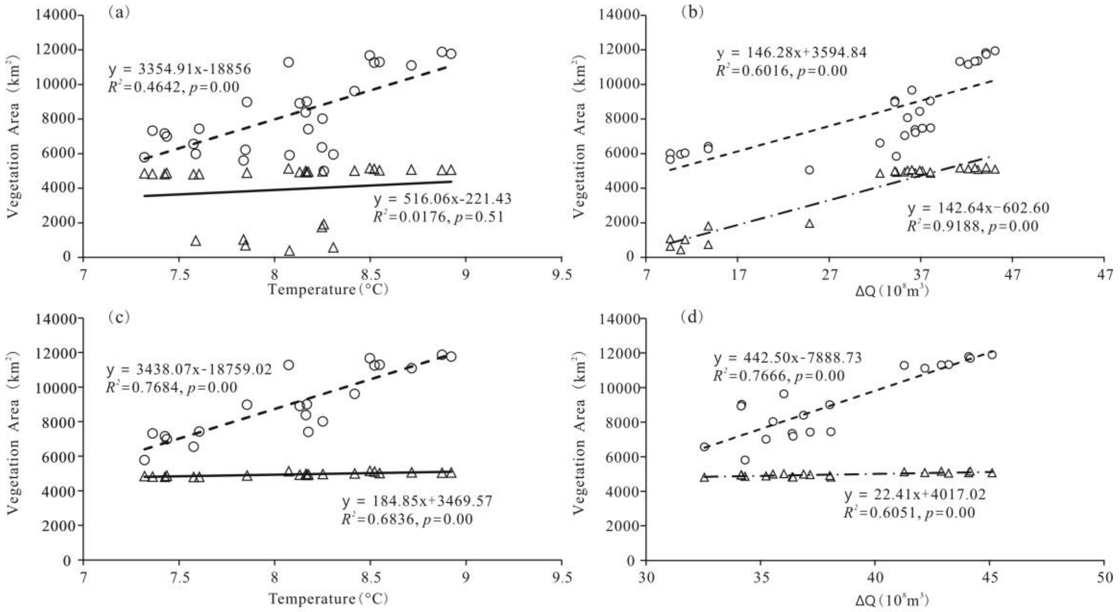

Figure 7: Correlation between vegetation (circle: natural vegetation, triangle: crops) and *T* (a, c) and *ΔQ* (b, d). (a) and (b) presented all reconstructed data for the past 2000 years, (c) and (d) only used Landsat-derived estimations.

4 Discussion and Conclusions

This paper presented an empirical study of the evolution of vegetation systems in the HRB over the past 2000 years. The vegetation system was categorized into natural vegetation and crop vegetation. The area and biomass of each vegetation system since the 1980s were estimated based on the remote sensing image data. For the historical periods, the area and biomass of each vegetation system were reconstructed based on the relationship between the area and biomass of the vegetation system and the climatic and hydrological variables in the last 30 years with the measured data. Some major research findings and their implications for future research and river basin management practice will be discussed below.

Both natural and crop vegetation development in HRB, based on the change in area and biomass in the past 2000 years (Figures 3, 4, 7), can be divided into 3 stages: (1) Pre-development stage (before RC), (2) rapid development stage (RC-2000), and (3) post-development stage (after 2000). In pre-development stage, agriculture was developed at a low level, resulting in a high natural to crop vegetation ratio. Water was not limiting agricultural activities. No significant contributions from climatic (T and P) and hydrological (Q) variables were observed in the regression analysis either. The small scale and decreasing crop vegetation distributions could be attributed to the small population size. Previous studies have reported that agricultural activities for these periods were primarily aimed to meet the political and military needs (Xie *et al.*, 2013). However, the slightly decreased streamflow (Sakai *et al.*, 2012) might be a key contributor to the overall decreased natural vegetation prior to the Ming Dynasty, as evidenced by the synchronous change between vegetation area and streamflow records (Figure 4, Figure 8) and the regression relationship between the two (Figure 7a). In the Ming Dynasty, temperature dropped while streamflow slightly recovered (Figure 8). The decreased evapotranspiration and increasing water availability might have stimulated vegetation growth along the river channel as demonstrated in Figure 3, especially for the natural vegetation distributions along the West River.

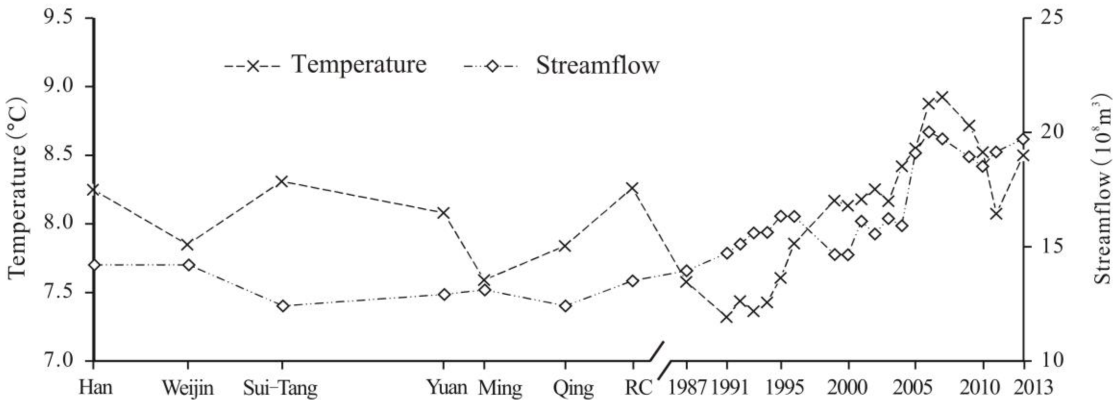

Figure 8: Temporal variations in temperature (°C) and streamflow (10^8 m^3)

After RC (the rapid development stage), crop area in HRB experienced rapid increase as food security had been the priority agricultural policy in China. The government encouraged farmers to reclaim unused land and promoted numerous irrigation projects (Zhang, *et al.*, 2015). In addition, the shelter forest system established after the 1980s not only protected the existing cropland but also made it possible to change the desert surrounding oasis into tillable lands. The consistently increasing streamflow due to the warm climate (more notably for the past two decades) and therefore increased precipitation and snow melting in upper reaches might have supported the expansion of crop vegetation. The increased streamflow might have supported the rapid natural vegetation growth in the middle reaches as well, either through direct watering of the river side vegetation system, or through water leakage from crop irrigation areas. However, vegetation in the lower reaches did not show synchronous development. Obviously, overuse of water in the middle reaches was the primary contributor which coheres with the existing literature (Nian *et al*., 2017; Zhao *et al*., 2016; Cheng 2002; Wang *et al*., 2007).

Since 2000 (the post-development stage), crop vegetation distribution has slightly increased but natural vegetation has experienced a relatively faster increase. This could be attributed to two major reasons. The first is the elevated temperature and increased streamflow provided sufficient water for both crop and natural vegetation development, this could be evidenced by their significant relationship with both natural and crop vegetation areas (Figure7 c, d). The second is owing to the implementation of the water reallocation policy which aimed to “secure water supply to the lower course of the basin to avoid ecosystem degradation”.

There was a much faster increase of crop biomass than that of natural vegetation since 1949 (Figure 6). The average biomass of crop per unit area increased by 180% while the biomass of natural vegetation did not change considerably. Lu et al (2015) also found that the agricultural water productivity increased by 6 times in the past 50 years in the middle reach of HRB. This is due to technological progress on agriculture and water application. After 1949, especially after reform and opening of the national economy in the late 1980s, there were great improvements in irrigation, crop varieties, chemical fertilizers and pesticides, and mechanization in HRB. Technological improvement influences the relationship between crop and natural vegetation. Advances in agricultural and water technologies enabled more crop biomass without the increase of crop area and facilitated the transfer of water from agriculture to downstream ecological purposes without compromise of the middle stream economic benefit.

The total vegetation area in HRB has been increased by 8,732 km^2 in the past 2000 years. Crop and natural vegetation presented different evolutionary patterns (Figure 3 and Figure 4) and the ratio of natural vegetation to crop vegetation ranged from 16 at Yuan Dynasty to at about 2.2 since 2005 (Figure 5). It was the result of the increase in: (1) human water demand from agriculture and urban development, (2) agricultural and water technological development for improving crop biomass, (3) water allocation for the environment (terminal lake) and (4) temperature and upstream runoff. Any changes in these factors will bring about change in the ratio of natural vegetation to crop vegetation. This ratio represents the land and water development at river basin scale at changing climate and social-economic conditions. Thus, it could be used as an indicator of water and land management for the better balance between the human and natural systems in river basins.

Finally, some limitations in our study need to be acknowledged. Seven ancient periods were studied to track the long term vegetation dynamics, where the short-lived Sui Dynasty (AD 581 - 617) was combined with the Tang Dynasty. However, some periods documented with human activities were not included in the current study due to a lack of data. For instance, Xixia Dynasty ruled the area for more than 150 years (AD 1038 - 1227) and prosperous human activities were recorded which might cause substantial changes to both crop and natural vegetation. Existing literature reported crop distribution in the lower reaches of HRB in Xixia using archaeological methods (Hu and Li, 2014), but data for crop and natural vegetation covering the entire basin is lacking in both literature and historical documents. Meanwhile, there was also an inconsistency between the reconstructed historic vegetation distribution and remote sensing-based extractions. For reconstruction periods, the priority was given to the river side regions while vegetation in remote areas were less discussed; whereas for modern periods, remotely sensed images captured comprehensive vegetation distribution in all regions. Moreover, more research is needed to develop an understanding of the mechanism of dynamic interaction between natural vegetation and crop vegetation.

Acknowledgement:

This project is supported by the National Natural Science Foundation of China (No: 41301036, 41501464, 91625103), Natural Science Foundation of Jiangsu Province, China (BK20130996) and the Australian Research Council (Project No: FT130100274).

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