As the editor and the referees all mentioned the spelling and grammar in our manuscript, a native English-speaking expert have edited it to improve the English expressions of the whole manuscript. Follows are some specific changes based on the editor and referees' comments.

Edit based on the editor's comments:

P1L14-17: Changed the sentence to "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."

P1L22-24: Changed the last sentence of Abstract to "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."

P2L10: Changed "water conditions" to "water availability conditions"

P2L14-16: Changed the sentence to "However, few studies have investigated how the vegetation system evolved in response to the changes in water regimes at the basin scale."

P2L23: Changed "missed" to "lacking"

P2L28: Changed "provides" to "provide"

P2L32: Changed "to reflect the status of the vegetation and widely" to "which have been widely"

P2L35: Changed "enabled the possibilities of reconstructions of" to "been applied to reconstruct"

P3L2: Changed "the way of" to "use of"

P3L18: Changed "of" to "in"

P3L21: Changed "such as Gobi desert" to "such as the desert, Gobi..."

P3L22: Changed "is" to "are"

P4L8: Changed "could" to "can"

P4L9: Changed "fetch up" to "reach up"

P4L13: Changed the sentence to "River inflow from the North Qilian Mountain constituted the primary water source for the river basin."

P5L3: Changed "elevated" to "increasing"

P7L20-21: Added the units of biomass to the equations

P7L32: Edited the paragraph to "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)."

Edit based on referees' comments:

Referee 1

2) P2, Lines22, there were some references about the historical landscape changes about this research area, and please cite these literatures, for example, "Nian, Y. Y., X. Li, and J. Zhou. 2017.'Landscape changes of the Ejin Delta in the Heihe River Basin in Northwest China from 1930 to 2010.' International Journal of Remote Sensing 38 (2): 537-57. doi:

10.1080/01431161.2016.1268732".

We add "To a centurial scale, Nian (2017) found that the rapid expansion of cultivated land was the primary force causing serious ecological deterioration in the HRB." to the Introduction Section.

4) P3, Line20, the moving and semi moving dunes should be revised as the words of the mobile dune and semi-mobile dune.

We correct the "moving and semi moving dunes" to "mobile dunes and semi-mobile dunes" as suggested.

5) P3, Line21-22, when did these percent happen? please give more descriptions.

We add "according to land cover map of 2011, data available at WestDC database http://westdc.westgis.ac.cn/" to the sentence.

6) P4, Figures1, please mark the name of the meteorological stations.
10) Yingluoxia Station is a key point to divide the upstream, midstream and downstream, but it is hard to identify the position of this station. Please change the symbol and color in the Figrue1. Furthermore, Heihe River Basin is your study area, so I would suggest to draw out the upstream area in figure 1 as well.

We updated Figure 1 with: adding meteorological stations labelled with station names; adding upstream area of the Heihe River Basin; changing the symbol and color of Yingluoxia Station.

7) P5, Line8, the Juyan Lake started to retain water again in 2002, please make sure this is correct or maybe you shall cite other reference about the lake restore.

We added the references "(Nian *et al.*, 2017)".

9) P5, Line25, please delete the words of "during late summer and early autumn", and retain the words of "from June to October".

We changed "during late summer and early autumn" to "from June to October"

11) Page 5, line 17. The study area has a long history and many human activities took place during different periods. The ancient study periods given in this manuscript is incomplete. First, historical documents support evidence that there are human activities in the Heihe River Basin in Sui Dynasty, and this should be included. Also, you can combine those two dynasties in Sui and Tang Dynasties. Second, there were prosperous human activities performed in the study area more than 150 years during Xixia Dynasty. I think the history of the Heihe River Basin should include the Xixia Dynasty. It is incomplete to ignore the above two important historical periods for HRB. Recommend to refer to some papers to get the information about the human activities developed in the downstream of the Heihe River Basin during the Xixia Dynasty. e.g., Hu and Li, 2014. Spatial distribution of ancient

agricultural oasis in Juyan, northwestern China).

We edited the “Tang dynasty” to “Sui-tang Dynasty” in the manuscript. And at the end of our manuscript, we add “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.” to describe our limitation in Xixia dynasty.

13) P 6, Figures 2, the equation in the figure should be separated from the figure.

The equation in the figure was separated from the figure.

17) P10, from your results and Figure3, how to interpret (forcing mechanism) the vegetation change in the west river of the lower reaches of the Heihe River from Yuan Dynasty to Ming Dynasty, also how to interpret the vegetation change in the Gurina area from RC to 1987.

We add “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).” to the Discussion Section.

19) I think the discussion will be more convincing if the authors can further discuss the relationships between the climate change and human activities and the evolution of vegetation system. For example, how the climate influence the trend of vegetation changes can be analyzed according to the meteorological data or the previous studies. There is enough space to improve the discussion in the manuscript.

We add “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”.” to the Discussion Section.

Referee 2

1) Page 3. Legends should be added to Figure 3.

We updated Figure 3 with legends.

2) Page 7. Need more explanation for the data you quoted.

We rewrite P7L26-34 to "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).".

3) Page 14. Figure 7 is not very clear to me.

We included more details in the caption to clearly provide information about the scatter diagram and increased the font size and resolution of the figure.

4) In general view, natural vegetation and crops compete of water resources. Can you explain why in your results the natural vegetation and crops increase or decrease synchronously?

We add "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)." to the Discussion Section.

A marked-up manuscript version on next page.

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~~y~~ 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 ~~were applied to derive vegetation spatial extent and biomass for 1987 to 2015.~~historical land use maps and hydrological records were introduced to derive the long term spatial distribution of natur~~e~~al and crop vegetation and the corresponding biomass levels.~~The area and biomass of the vegetation before 1987 were reconstructed based on former research results the derived relationship between the vegetation biomass and climatic and hydrological variables in the last 30 years with instrumental data~~. The ~~key~~ major findings are: (1) both natural and crop vegetation ~~have gone~~ experienced three development stages: Pre-development stage (before ~~1949~~Republic of China), rapid development stage (~~1949~~Republic of China - 2000), and post-development stage (after 2000). Climate and hydrolog~~y~~ical 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 ~~driven~~ factors for the increase of both natural and crop vegetation ~~increase~~ in the middle reaches of HRB. For the third stage, positive climate and hydrological~~y~~ conditions, together with policy interventions, supported the overall vegetation increase in both middle and lower HRB; (2) there was a ~~much~~ significantly faster increase of crop biomass than that of native vegetation since 1949 which could be exaplained by the technological~~y~~ dev~~l~~elopment~~,~~; and (3) the ratio of natural vegetation to crop vegetation decreased from 16 at Yuan Dynasty to ~~at~~ about 2.2 since 2005. This ratio ~~represents~~ reflects the ~~relationshipresponse~~reaction of land and water development ~~at river basin atreact~~ to a changing climate and an altering social-economic conditions~~y~~ at~~in~~ the river basin level, therefore, it could be used as an indicator for ~~to plan the objective or examine the outcome of~~ water and land management at river basins~~at river basin~~.

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 ~~growth of~~ population growth, an increasing amount of water ~~worldwide~~ 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). ~~To understand the~~ An understanding of the development of natural vegetation under different water availability conditions and its interactions with the human crop system, is vital for ~~the~~ sustainable river basin management.

There ~~are~~ 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 ~~been found to~~ investigated how the vegetation system evolved ~~to accommodate~~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~~at~~ a short time ~~scale~~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-econom~~y~~ic conditions is ~~missed~~ 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~~s~~ an ideal method to track the landscape changes at river basins in the past five decades (Nian~~, Y.~~ *et al.*, 2017~~,~~; Beuchle *et al*., 2015). Among a mass of the remote sensing based metrics to characterize vegetation system, spatial extent~~ or area~~, normalized differential vegetation index (*NDVI*) and biomass are commonly recognized as the most effective indices~~ to reflect the status of the vegetation and~~ which have been widely applied in spatial analysis of landscape ecosystems (Pettorellia *et al*., 2005; Pinsky and Fogarty, 2012). For ~~the~~ historical periods~~ earlier than five decades from now~~ (previous years with no remotely sensed data), emerging approaches including dendrochronology, ice core analysis, and other empirical methods have ~~enabled the possibilities of reconstructions of~~ 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, ~~However, few~~but relativelylittle attention~~s~~ has~~ve~~ been paid to ~~historical landscapes and most of the limited existing reconstructions focused on the cultivated area~~natural vegetation distributions in historical ~~records~~ periods (Hu and Li, 2014; Xie *et al*., 2013; Ramankutty and Foley, 1999). Moreover, factors and mechanisms driving vegetation evolution~~s~~

~~were largely unsolved~~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~~is~~ 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~~ the way of ~~ use of land and water resources ~~use ~~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.~~Therefore, HRB is an ideal study area for investigating the evolution of vegetation system at river basin for a long time frame.~~

~~This ~~The ~~paper ~~present study aims to understand the ~~evolution of vegetation system~~vegetation evolution in HRB over the past 2000 years~~ in which .~~,for which b~~B~~oth natural ~~vegetation ~~and crop vegetation ~~were ~~are considered. The specific objectives of the present study are: ~~In addition, this paperSpecifically, it includes three objectives: Specifically, it includes three objectives: ~~(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 ~~driving ~~factors for vegetation ~~developments~~evolution. It is expected that the methods developed and the findings obtained from this study could assist in achieving an understanding of~~ to understanding ~~ how current ecosystem problems ~~were created~~emerged in the past and what their implications can be for~~are their implications for~~ future river basin management.

2. Material and Methods

2.1. Study area

HRB is the second largest inland river basin ~~of ~~in China, which stretches between 38 °- 43 °N and 98 °- 102 °E (Figure 1). The middle and lower course of HRB ~~are occupied~~contain ~~with different~~ several types of landscape~~s~~ including river delta plain, terminal lakes, mobile dune and semi-mobile dunes~~moving and semi-moving 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~~ in which t~~. The main vegetation types in these regions are dry steppes and shelter forests.

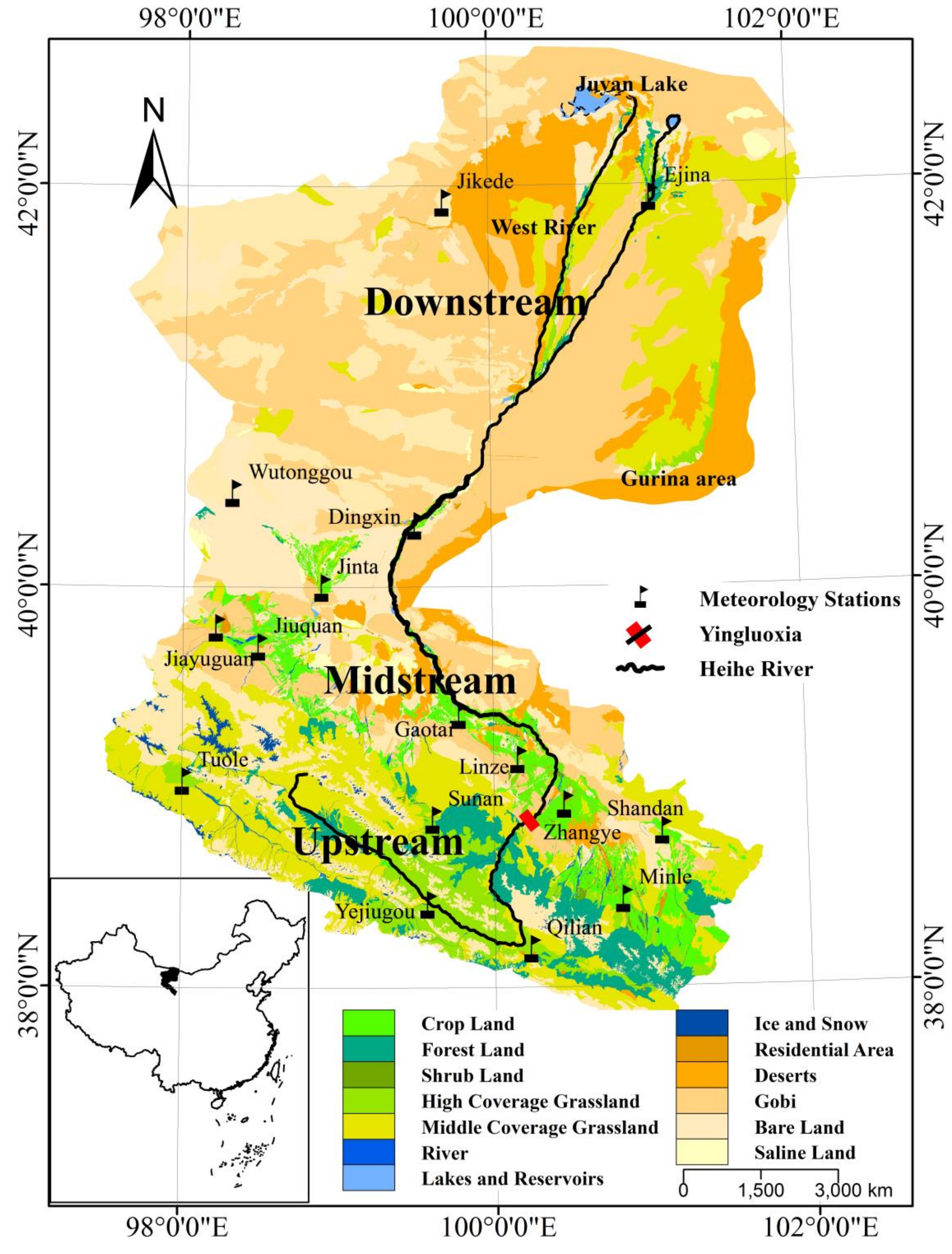

Figure 1: Location of the Heihe River Basin (HRB). Land cover data (2011) is available at WestDC database (http://westdc.westgis.ac.cn/)

The terrain in HRB ~~is a~~ gradually tilt from southwest to northeast. The altitude of the area ranges~~d~~ 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~~Annual average~~ temperature in this area over the last three decades is 8.3 ºC ~~during the last three decades~~ (with remarkable seasonal variations). Temperatures ~~could~~ can decrease to -37.6 ºC in winter months and reach up to 43.1 ºC in summer months (~~while~~ the highest temperature normally occurshappened aroundin July), which can reach ould fetch up to 43.1 °C. 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.

Benefiting from the Heihe River originated in the North of Qilian Mountains of Tibetan Plateau,River inflow from the North Qilian Mountain constitutesd the primary water source for the river basin. It makes HRB an important grain production base and the region HRB 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 irrigationng, along with elevated increasing usage for domestic purposes in middle reaches, has substantially consumed the available water supplywater 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 ensure secure that water delivered to lower course of the basin was enough water to the required amount of water for sustaining the ecosystems in lower river courses and to avoid any further degradations. In 2002, the Juyan Lake (east) started to retain water again which was taken as an important sign of ecosystem recovery and it is reported the degradation trend of the downstream of Heihe River has been changed by water transfer project (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.We used all available cloud-free Landsat images in HRB to derive vegetation dynamics for 1987 to 2015. 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 ~~during late summer and early autumn (~~from June to October~~)~~ to represent the growing season for crops and natural vegetation in the study area.

The ~~data products~~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~~ in order to ensure that the change detection analysis truly detected changes at the Earth's surface rather than solar illumination differences or potential differences in atmospheric conditions~~. ~~The normalized Differential Vegetation Index~~*NDVI* was then calculated using the red and near-infrared bands for each year.

As demonstrated ~~in~~ with MODIS *NDVI* series (Figure 2)~~ with phenology profile of~~, natural and crop vegetation ~~derived from Moderate Resolution Imaging Spectroradiometer. (MODIS), *NDVI*~~ presented significant ~~seasonal variations~~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 ~~would~~ might have included ~~this seasonal variations~~these seasonal variations ~~and not suitable for inter annual comparisons~~. To compensate this effect, we used the MODIS *NDVI* profile in 2013 to calibrate the Landsat *NDVIs* to annual maximum *NDVI*~~, which could effectively reflect the same growth stage of vegetation in multiple years,~~ 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 ~~estimate~~ 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~~in~~ 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.

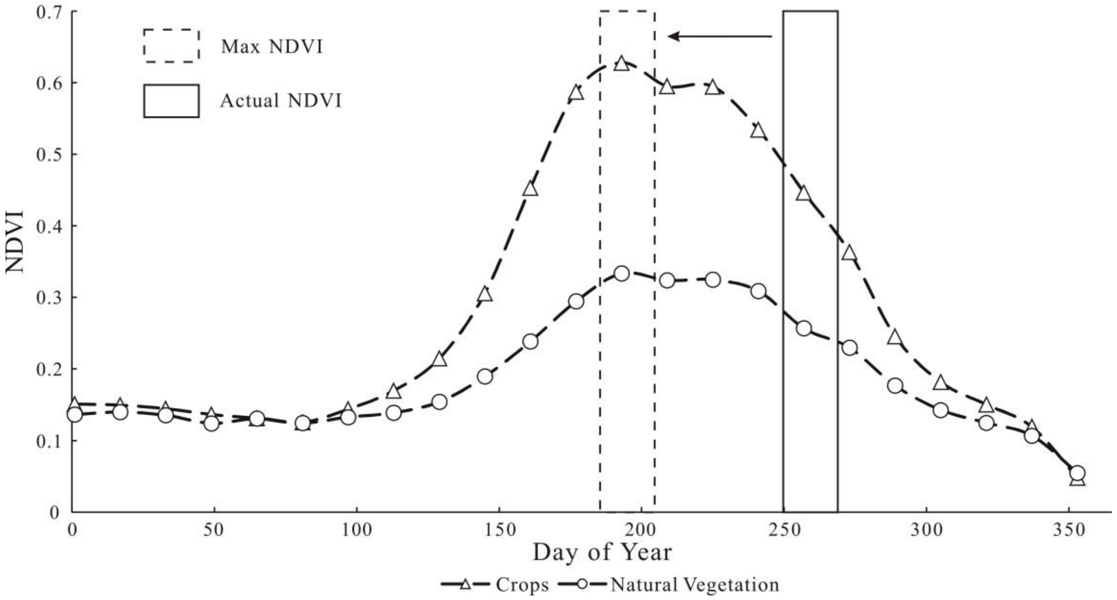

Figure 2: *NDVI* profile for natural vegetation and crops in 2013. The rectangles indicated the scheme of calibrate actual Landsat *NDVI* (solid rectangle) to annual maximum *NDVI* (dash rectangle).~~The equation in the figure indicated the scheme for calibrating the actual *NDVI* values (L stands for Landsat, M stands for MODIS, i stands for the date when actual *NDVI* need calibration)~~

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 ~~analyzing~~an analysis of the *NDVI* histogram distribution characteristics, 0.12 was selected as the first threshold value ~~Non-vegetation landscapes, including water surfaces, deserts, residential areas and other bare surfaces, were masked out through analyzing the *NDVI* histogram distribution characteristics,~~ to mask out non-vegetation landscapes, including water surfaces, deserts, residential areas and other bare surfaces~~selecting 0.12 as the first threshold value and making minor verify for each year~~. Then, the second round of threshold analysis was introduced to separate crop vegetation from natural vegetation according to their phenology differences (Figure 2). ~~Briefly~~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 (≥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 w~~as~~ere 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 ~~et al.,~~ (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.

~~In order~~ ~~T~~To study the vegetation development and water usage, ~~we calculated~~ biomass for natural and crop vegetation was~~ere~~ calculated using ~~based on~~ NDVI. Regression models established by Zhao et al. (~~2006~~2007, 2010) for HRB were adopted ~~to quantify biomass for both natural and crop vegetation~~. In ~~those~~ Zhao's research, ~~the~~ herbaceous biomass was measured by means of dry biological weighing methods and the field measured biomass for natural and crop vegetation ~~in this region~~ showed high correlation with NDVI ($R > 85\%$ and $p < 0.01$)~~.~~. ~~in the same area and t~~ Therefore, ~~t~~the following ~~formula~~ equations ~~was~~ were established for natural and crop vegetation respectively.

$$\text{Biomass}\ (\text{g/m}^2) = 327.4 \times \text{NDVI} + 102.29 \quad \text{for natural vegetation} \quad \text{(Zhao et al. 2007)} \quad (~~1~~2)$$

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

~~We used the equations above to calculate the biomass from 1980 pixel by pixel each year and use regional statistics method to acquire natural vegetation biomass and crops biomass of the study area.~~

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

2.3.3 ~~Reconstructing~~ Historical vegetation distributions and biomass levels ~~in historical periods~~

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 ruins~~s~~ 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).

~~Lu (2015) reconstructed vegetation distribution in past 2000 year in our study area to analyze the evolution of human–water relationships. In Lu's study, the historical cropland was reconstructed based on population, grain yield and ancient ruins distributions (Xie, 2013). The area of natural vegetation was estimated based on two assumptions: (1) people selected the regions with natural oases (grassland and forest) rather than desert for reclamation in the historical periods because the former have better water and soil conditions in these arid regions, and (2) once the reclaimed farmlands were abandoned and no vegetation was covered, they were subsequently decertified (Lu et al., 2015). The crop and natural vegetation area of each dynasty was calculated based on Lu's results.~~

~~The vegetation biomass in the historical periods was not available in the literature.~~ To estimate historical vegetation biomasses, we first established the relationship between biomass and ~~Using the satellite-based results since the 1980s, we reconstructed the vegetation biomass based on its relationship with~~ several variables which ~~could~~ have potential impact on ~~the~~ vegetation development. The ~~selected~~candidate ~~variables~~ variables ~~are~~ 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. ~~The significant correlation among total biomass, ΔQ and T were found (R^2 = 0.612).~~ As indicated by the regression model, the significant relationship between total biomass and ~~both energy~~ ~~(~~T~~)~~ and water supply (ΔQ) ~~present positive effects over vegetation productivity~~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 ~~much~~ 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 ~~much~~ considerably less influenced by human activities. Therefore, we ~~made an assumption~~assumed that biomass density for natural vegetation in the region ~~over the study period~~ 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. ~~Biomasses for historical natural and crop vegetation were further estimated.~~

2.4 Determination of potential driving factors for vegetation developments

~~Multiple linear regression analysis was adopted to investigate the potential driving factors causing changes in spatial extent of vegetation and its biomass levels.~~ 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 ~~find~~ assess whether or not~~if~~ there were any significant relationships. ~~These selected variables were also taken as independent variables to find the quantitative models between these variables and the vegetation spatial extents.~~ 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. ~~As the reconstruction data for the historical periods might incur great uncertainties in records and estimations, the regression analysis was conducted for the whole study period and the recent decades with instrumental data respectively.~~ 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 ~~in~~ 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. ~~Historic distribution~~ Distribution of crops was focused within the ~~relatively small regions with certain variations~~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 ~~were~~ largely decreased. ~~It was until~~Since the establishment of the PRC the crop vegetation ~~started to~~had increased at a high rate, especially in the midstream. ~~As clearly demonstrated in the maps, there were crop areas distributed in downstream regions around Juyan Lakes in historic periods, however, in the modern China, crops were distributed mainly in the middle basin of HRB.~~ 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~~ere~~ observed since the 2000s.~~there~~ 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 ~~substantially~~ significantly increased with ~~large~~ substantial inter-annual fluctuations. After 2000, vegetation distribution was relatively stable at a high level. ~~The downstream vegetation has experienced gradually increase corresponding to the crop area decreasing during these periods.~~

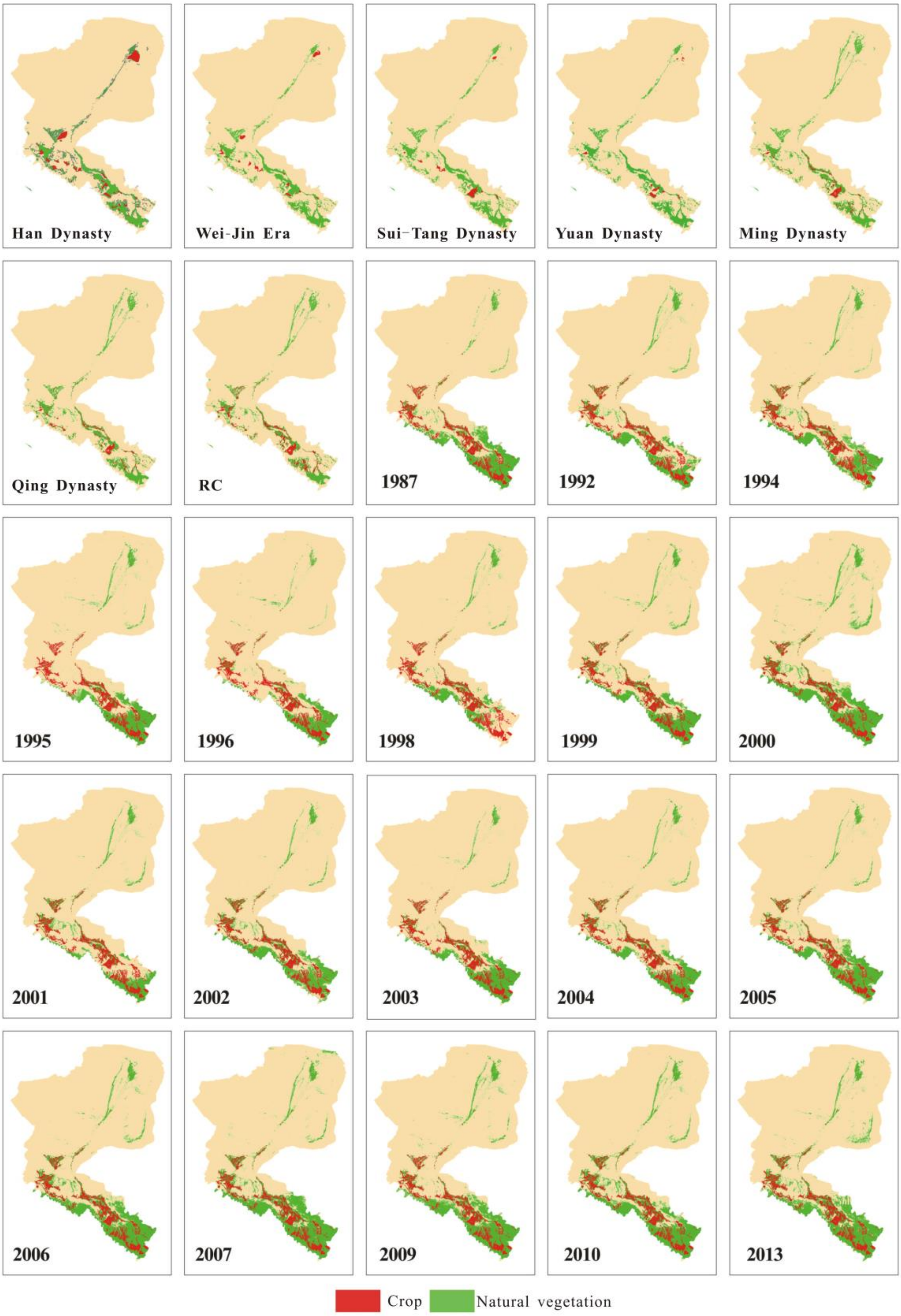

Figure 3: Reconstructed natural (green) and crop (red) vegetation distributions in the past 2000 years. Historic maps (before 1987) were derived from Lu's results (Lu *et al.*, 2015) and maps after that were interpreted from Landsat images.

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: i~~I~~t had a large spatial extent in~~at~~ 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 ~~keeping~~ steadily increased ~~steadily~~ to 16,854 km^2 in 2013.

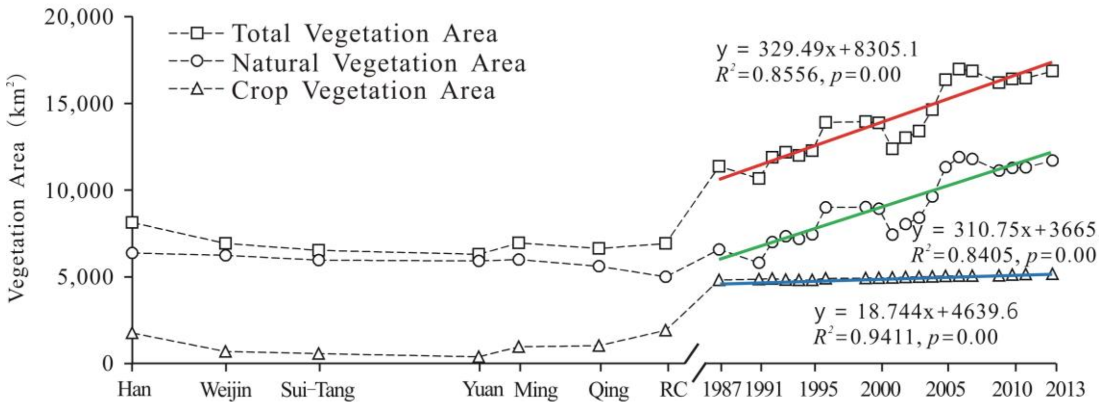

Figure 4: Temporal variations in total vegetation areas (~~triangle~~square), natural vegetation (~~square~~circle) and crops (~~circle~~triangle). It should be noted that data after 1987 ~~was~~ reflect the results after applying a 3 years moving average to reduce the annual fluctuations.

The ratio of natural vegetation area to crop vegetation area~~s~~ 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 ~~degraded~~ 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~~s~~ during the modern China period was relatively stable compared ~~with~~ to the great historic fluctuations and it ~~is~~has stabilized at around 2.2 since 2005.

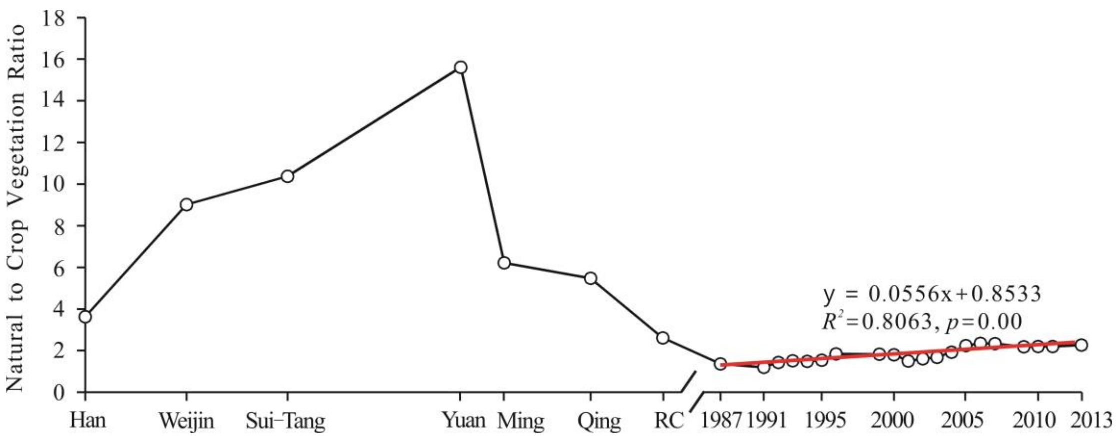

Figure 5: Changes in ratio between the areas of natural vegetation to crop vegetation in the past 2000 years

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 ~~produced~~ created the relationship between biomass and T and ΔQ~~streamflow~~ as 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 (~~Han Dynasty~~prior to the Republic of China) had experienced a ~~slight~~ 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~~ly~~ increase from about 95 ×~~*~~ 10^4 t to 159 ×~~*~~ 10^4 t in 2000. After 2000, the upward trend continued with a higher increasing rate~~ was observed~~. For crops, the ~~annual~~ biomass presented a sharp increase~~ trend since 1949~~ by about 4 times from RC to 1980s.~~ and s~~ A s~~S~~light increase trend in past 30 years was observed. The average ~~productivity~~ biomass per unit area of natural vegetation was stable while the average ~~productivity~~ biomass per unit area of crop increased by 2.2 times ~~in~~ over the past 2000 years. The average ~~productive~~ biomass per unit area of crop increased by about 180% since PRC.

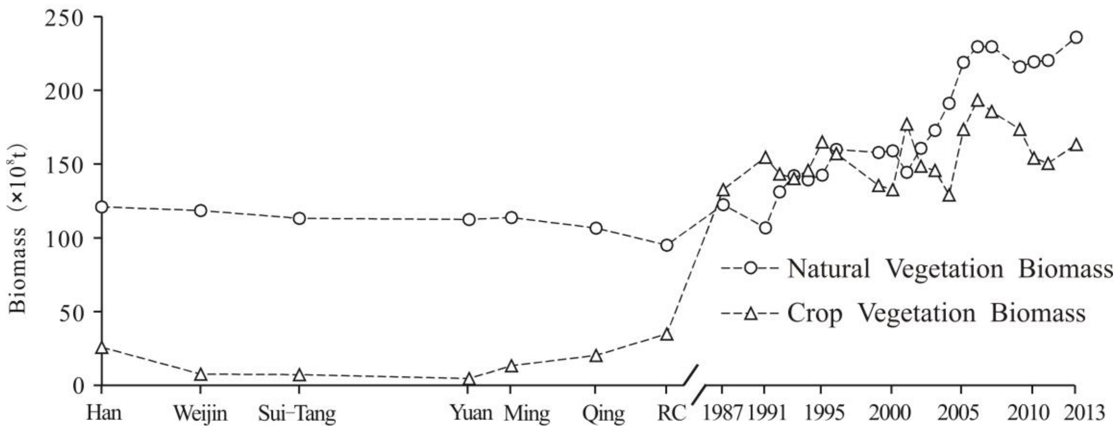

Figure 6: Temporal variations in biomass of natural vegetation (triangle) and crops (circle) over the past 2000 years

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

2000 years

The regression analysis~~ on the relationship~~ between vegetation development and hydrological and climatic variables ~~and vegetation development~~ show that both *T* and *ΔQ* present~~ed~~ 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~~ or~~ (i.e. 96.0% for natural vegetation and 91.7% for crops). Although the development of vegetation did not show an ~~obvious~~ evident relationship with precipitation, there were ~~few~~ some years ~~that~~ 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.

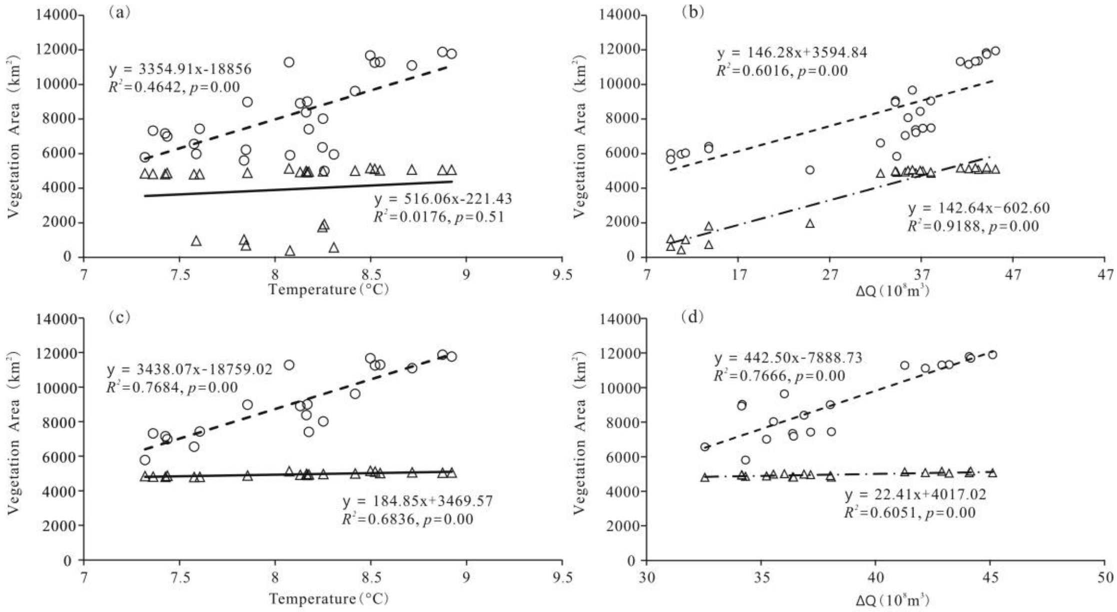

Figure 7: Correlation between vegetation (circle: natural vegetation, triangle: crops) and *T* (a, c) and *ΔQ* (b, d). (a) and (b) presented all reconstructed data for the past 2000 years, (c) and (d) only used Landsat-derived estimations.

4 Discussion~~s~~ and Conclusions

This ~~study~~ paper presented an empirical study of ~~investigating~~ 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 ~~are discussed as follows:~~will be discussed below.

Both natural and crop vegetation development in ~~Heihe River Basin~~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 ~~1949~~RC), (2) ~~R~~rapid development stage (~~1949~~RC-2000), and (3) p~~P~~ost-development stage (after 2000). In pre-development stage, agriculture was developed at a low level~~er~~, 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 ~~as well~~either. The small scale and decreasing crop vegetation distributions could be attributed to the small population size. Previous ~~scholars~~studies have reported that agricultural activities for these periods were primarily aimed to ~~level only for~~ meet the political and military needs (Xie *et al*., 2013). However, the slightly decreased streamflow (Sakai *et al*., 2012) might be ~~the~~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. ~~During this period, the temperature fluctuated marginally and the terminal lake area did not change much (Yang, et al., 2002; Lu, et al., 2015). The natural vegetation showed a slight decrease trend as the runoff from upstream decreased from 14.2 × 10^8 m^3 to 13.5 × 10^8 m^3. The natural vegetation/crop ratio came to the highest point in the Yuan Dynasty in Fig.5.~~

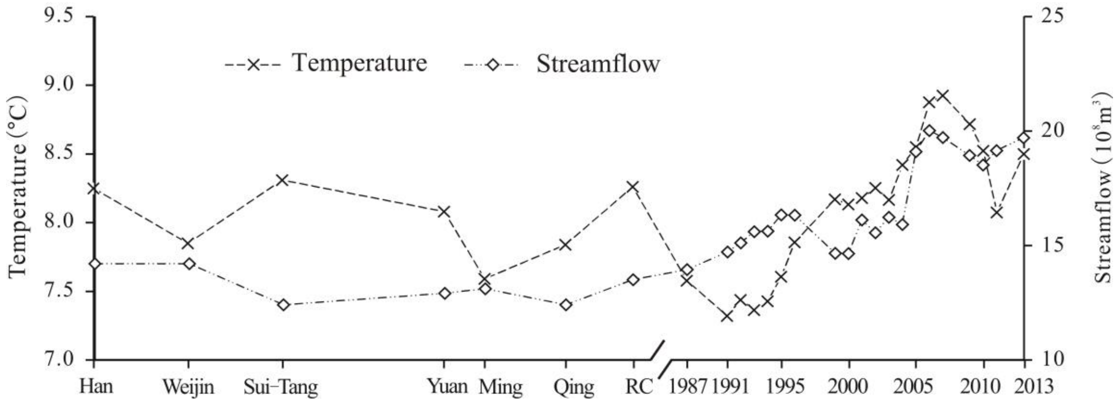

Figure 8: Temporal variations in temperature (^oC) and streamflow (10^8 m^3)

After ~~1949~~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 ~~lots of~~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 ~~farm~~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 ~~Natural vegetation during this period also experienced rapid~~

increase, temperature increase by 0.5 - 1° C and upper stream runoff increase from 13.5 × 10^8 m^3 to 15 × 10^8 m^3 could explain it. And water leakage from crop irrigation areas may also contribute to natural vegetation development.. However, vegetation in the lower reaches did not show synchronous development. Obviously, overuse of water in the middle reaches was the primary contributor which agreed well coheres with with the existing literatures (Nian *et al.*, 2017; Zhao *et al.*, 2016; Cheng 2002; Wang *et al.*, 2007). As a consequence of the rapid development of agriculture, the terminal lake (Juyan Lake) of about 900 km^2 was dried up and groundwater was over-pumped for irrigation.

After 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 kept relatively stable as a result of the implementation of the policy "secure water supply to the lower course of the basin to avoid ecosystem degradation". Natural vegetation keeps increasing during this period because the temperature and runoff continue to increase. These stage developments were the result of changes in agricultural and water policies and changes in climatic and hydrologic variables.

There was a much faster increase of crop biomass than that of native natural vegetation since 1949 (Figure 6). The average biomass of crop per unit area increased by 180% and while the biomass of natural vegetation did not change muchconsiderably. 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 Heihe RiverHRB. This is the result ofdue 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 is was the result of the increase in: (1) –human water demand from agriculture and urban development, (2) increase in agricultural and water technological development for improving crop biomass, increase in(3) water allocation for the environment (terminal lake) and increases in(4) temperature and upstream runoff. Any changes in these factors will bring about the change of 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-economy economic conditions. Thus, it could be used as an indicator to of plan the objective or examine the outcome of water and land management at river basin. More research is needed in future to develop an understanding of the mechanism of dynamic interaction between natural vegetation and crop vegetation. With the knowledge of this interaction, water and land would be better managed 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. Exsisting 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, ~~M~~more research is needed ~~in future~~ to develop an understanding of the mechanism of dynamic interaction between natural vegetation and crop vegetation.

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