Spatio-temporal dynamics of NDVI and its response to climate factors in the Heihe River Basin, China

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Abstract. Ecosystem in the Heihe River Basin (HRB) is very vulnerable and sensitive to variations in the climatic conditions and human activities. In this study, The SPOT and MODIS NDVI time series data from 1998 to 2012 were used to analyze NDVI variation characteristics and its response to climatic factors in the HRB based on Mann–Kendall test, relative Sen’s slope, linear regression and partial correlation analysis. The results indicate that: (1) There is an obvious decreasing trend during 1998-2001 and a significantly increasing trend from 2001 to 2012. The vegetation in the HRB was improved by 1.5% of annual average level from 1998 to 2012, and rate of change is greatest in the lower reaches. (2) During 1998-2001, the rainfall is proved to be the most significant factor influencing NDVI for each reaches, and temperature and radiation are also related significantly with NDVI in the middle and lower reaches respectively. However, during 2001-2012, all climatic factors are not significantly related with NDVI for each reaches, excepting rainfall in the middle reaches. This demonstrates that the climatic variation cannot totally explain the significant improvement of vegetation during 2001-2012 in the HRB, whereas ecological restoration projects implemented in this period might be a reasonable factor for the improvement of ecological environment in the HRB.

1. Introduction

Vegetation is an important component of global ecosystems, and plays important roles in the interception of rainfall, alleviation of runoff, prevention of desertification, and conservation of soil and water for terrestrial ecosystems, especially for arid and semi-arid zones [1-3]. Vegetation cover and density are commonly considered as the sensitive indicators for ecological environment change [4-7]. Numerous studies have been reported that vegetation cover dynamics and its driving factors, including climatic change, land use transformation, and the fertilization effect of CO₂, in various ecosystems in China [8-12].

In the past two decades, with the development of earth observation system and the long-term remote sensing data accumulation, most previous studies have employed time series of indicator derived from remote sensing data exhibiting vegetation coverage, primarily the Normalized Difference Vegetation Index (NDVI), and meteorological data measured from ground stations to analyze the vegetation response to climate change and human activities [13]. The understanding of spatio-temporal characteristics of vegetation variation induced by climate change and human activities at
region scale is very helpful for local decision makers to make more scientific and effective eco-management planning.

Vegetation dynamics in arid and semi-arid areas have been proved to be more sensitive to climate change when compared with those in other regions [12, 13]. The vulnerable terrestrial ecosystems are generally thought to be highly susceptible to degradation and desertification with climatic fluctuations. In addition, vegetation deterioration and inappropriate land use practices by humans can also lead to severe land degradation and other serious problems to the ecology and environment. The response of arid ecosystems to water supply variation, climate change and human activities has been widely concerned because of the economic, hydrological and ecologic significance of most arid and semi-arid areas around the world.

The Heihe River Basin (HRB) located in northwestern China is the second largest inland river basin, and is characterized by an arid and semi-arid climate. Glacier/snow meltwater from the Qilian Mountain in the upper reaches and precipitation can provide water resources for the Heihe River, and spatial distribution pattern of vegetation types in the HRB is totally affected by the site-specific climatic conditions. The HRB has experienced a significant vegetation degradation and desertification as a result of long-term limited water availability [14, 15]. By the end of the 20th century, a series of ecological restoration projects, including water diversion project (EWDP), were implemented by the central government of China to address these serious ecological and environmental problems [1]. The variation of vegetation in the HRB inevitably would affect the regional hydrological, ecological process and local economic development. Therefore, long-term and large-scale assessments of vegetation dynamics and their response to hydro-climatic change and human activities during recent period in the HRB are urgently needed to implement a more effective policy.

In this study, spatio-temporal variation characteristics and their responses to climatic and non-climatic factors in the HRB from 1998 to 2012 are investigated. Firstly, the SPOT and MODIS NDVI time-series data are used to analyze the spatial distribution characteristics, temporal fluctuation and variation trend for vegetated areas. Secondly, the responses of vegetation to hydro-climatic and non-climatic factors at pixel-level and regional scale in the upper, middle and lower reaches with significantly different hydro-climatic conditions are analyzed to explore the driving factors leading to vegetation variation in the HRB.

2. Study area

HRB lies between 96°30’ and 102°0’ E, and 33°30’ and 43°0’ N and covers an area of approximately 130,000 km² (figure 1). The HRB is the second largest inland river basin of China, extending over the provinces of Qinghai, Gansu and Inner Mongolia. Its upper, middle and lower reaches stretch from the middle of the Hexi Corridor in Gansu to western Inner Mongolia.

The southern Qilian Mountains covered by nature grassland and forests, with remarkable vertical zonality, is the river source area of Heihe River, with the elevation range from 2,000 m to 5,500 m and a mean annual precipitation of 250–500 mm.

The middle Hexi Corridor covered by cropland and grassland, located between the Qilian Mountains and the Beishan Mountains, is characterized with a elevation range from 1,000 m to 2,000 m and mean annual precipitation of 100–200 mm. The northern Alxa High-plain is mainly covered by the sparse shrubs, bare Gobi, and populus diversifolia, with mean elevation of 1000 m and a mean annual precipitation of <50 mm. Therefore, the characteristics of geographic distribution in the HRB result in significantly distinctive climatic conditions and associated vegetation types in the upper, middle and lower reaches.

By the end of the 20th century, an ecological restoration including EWDP and grass protective project was successfully implemented by the government of China, consequently, the severe deterioration of ecological environment in the HRB, especially for the lower reaches, has been significantly alleviated [1].
3. Materials and methods

3.1. Materials

3.1.1. Remote sensing data. NDVI was considered as an effective indicator of greenness and coverage of vegetation [4, 11]. In this study, NDVI dataset derived from satellite remote sensing data was employed to reflect spatial-temporal dynamics of vegetation. Both SPOT/VEGETATION NDVI product and MODIS Terra NDVI product were used to obtain the NDVI time-series from 1998 to 2012 in the HRB. The SPOT/VEGETATION NDVI time-series data at 10-days period temporal resolution and 1-kilometer spatial resolution was downloaded freely from the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn), covering the period from April 1998 to December 2007. The MODIS Terra monthly NDVI time-series (MOD13A3) at 1-kilometer spatial resolution was obtained from National Aeronautics and Space Administration (http://ladsweb.nascom.nasa.gov), covering the period from January 2008 to December 2012. Firstly, the SPOT/VEGETATION 10-day-period NDVI data was processed into monthly NDVI time-series using the maximum value composites method to match the temporal resolution of MODIS product, and then NDVI monthly time-series from 1998 to 2012 was obtained by combing those two NDVI products.

3.1.2. Meteorological data. In this study, monthly precipitation, temperature and sunshine hours at 16 meteorological stations and monthly solar radiation at 6 radiation stations within and nearby the HRB (figure 1) from 1998 to 2012 were downloaded from the China Meteorological Administration Data Sharing Service System (http://cde.nmic.cn/home.do). The monthly gridded precipitation, temperature and sunshine hours at a spatial resolution of 1-km were produced based on in-situ measurements from meteorological sites and gridded digital elevation model (DEM) at 1-km spatial resolution using the ANUSPLIN software package version 4.3 where the original and partial thin plate smoothing spline surface fitting technique was considered to be greatly suitable for spatially interpolating meteorological data [16]. The monthly gridded radiation data were then produced based on in-situ data from radiation sites and gridded sunshine hours at 1-km spatial resolution using ANUSPLIN.

Figure 1. The locations of the Heihe River Basin and associated meteorological, radiation and gauge stations.
3.2. Reconstruction of NDVI time-series

Although the composite NDVI used in this study is the maximum value during one month, there are always some noise effects caused by cloud and sensor in original NDVI time-series [4, 7]. Consequently, NDVI is not able to reflect the real situation of vegetation. To solve this problem, in this study, Savitzky-Golay smoothing filter method was employed to smooth contaminated pixel in the NDVI time-series, consequently, the effects from cloud and sensor on NDVI value could be eliminated to some extent.

Savitzky and Golay [17] proposed a smoothing method using simplified least-squares-fit convolution for a noise curve. In this study, the Savitzky–Golay filter was employed to smooth NDVI time series with some noise signal, and general equation of the Savitzky–Golay filter can be given as follows:

\[ Y_j^* = \frac{\sum_{i=m}^{i=m} C_i Y_{j+i}}{N} \]  

(1)

Where Y is the original NDVI, \( Y_j^* \) is the smoothed NDVI, \( C_i \) is the coefficient for the ith NDVI in the filter window, and N is the number of convoluting integers and is equal to the filter window size \((2m+1)\), where m is half-width of the filter window. In this study, \( m=2 \) was used to obtain high-quality monthly NDVI time-series according to repeated trials. The method of calculating coefficients \( C_i \) in the previous study of Steinier et al [18] was employed in this study.

3.3. Temporal trend analysis

The Mann–Kendall (MK) test was generally used to examine the significance of temporal trends (monotonic upward or downward) of time series data. This statistical method has been widely used to evaluate variation trend and its significance of hydrological and climate time series since 1945 [19, 20]. MK test is a non-parametric test, which means that the test is not influenced by the actual distribution of the data and is less sensitive to outliers [21].

The statistic \( Z \) of the MK test is expressed as follows:

\[ Z_c = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases} \]  

(2)

where,

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad (1 \leq k < j \leq n) \]

\[ 1, x_j - x_i > 0 \]

\[-1, x_j - x_i < 0 \]

\[ sgn(x_j - x_i) = \begin{cases} 0, & x_j - x_i = 0 \end{cases} \]

\[ \text{Var}(s) = \sum_{i=1}^{n} n(n-1)(2n+5)/18 \]

where, \( x_i \) and \( x_j \) are annual observations, and \( n \) is the length of sample data.

For MK trend analysis, \( H_0 \) is null hypothesis of no trend for an independent and identically distributed data samples \( X = \{x_1, x_2, ..., x_n\} \). Alternative hypothesis \( H_1 \) represents that there is a monotonic trend for the data set \( X \). For the null hypothesis \( H_0 \), if \( |Z_c| > Z_{(1-\alpha)/2} \), where \( Z_{(1-\alpha)/2} \) is the standard normal distribution, and \( \alpha \) is the significance level for the test, the null hypothesis \( H_0 \) is
rejected, which means the confidence level of this trend is less than α, and trend variation is significant under the significance level of α. Conversely, the trend is not significant. In this study, when $|Z_c| < Z_{(1-0.1)/2} = 1.645$, there is an insignificant trend, when $|Z_c| > Z_{(1-0.1)/2} = 1.645$, there is a significant trend, and when $|Z_c| > Z_{(1-0.01)/2} = 2.567$, there is a highly significant trend. Meanwhile, Z>0 reflects the increasing trend of time series. Conversely, Z<0 indicates the decay trend.

Sen’s slope is usually regarded as the absolute magnitude of trend variation, it is expressed as follows:

$$\beta = \text{Median} \left( \frac{y_i - y_j}{j - i} \right) \quad (1 \leq k < j \leq n)$$  \hspace{1cm} (3)

$$R = \frac{\beta}{\sqrt{\sum_{i=1}^{n} x_i^2}} \times 100\%$$  \hspace{1cm} (4)

$$\bar{R} = \frac{\sum_{i=1}^{M} R_i}{M}$$  \hspace{1cm} (5)

where, $\beta$ is the Sen’s slope, n is the total number of temporal epochs in time-series. A positive $\beta$ represents a rising trend, whereas a negative $\beta$ represents a decreasing trend. R is the relative Sen’s slope, which makes the variation magnitudes of time series of different pixels comparable. The higher the R is, the higher the relative magnitude of trend variation for this pixel will be. $\bar{R}$ is the spatial average of R across the whole basin, M is the total number of the pixels which have significant variation trend based on MK test in the HRB. $\bar{R}$ is able to exhibit the overall variation trend and magnitude at watershed scale, taking into account area ratio and relative variation magnitude for areas with statistically significantly change trend.

3.4. Partial correlation analysis

Correlation analysis is one of the most commonly used statistical methods to explore the influence of one variable on another. Pearson Correlation calculated using equation (6) is applied to measure the relationship between only two variables. When the variable was comprehensively influenced by multiple factors, partial correlation coefficient (equation (7)) is a more scientific indicator to exhibit the relationship between two variables while removing the effects of other variables.

$$r = \frac{\sum_{i=1}^{n} (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i-\bar{x})^2 (y_i-\bar{y})^2}}$$  \hspace{1cm} (6)

$$r_{12.34...p} = r_{12.34...p-1} - r_{1p.34...p-1}r_{2p.34...p-1} \sqrt{1-r_{1p.34...p-1}^2} \sqrt{1-r_{2p.34...p-1}^2} \quad (P \geq 3)$$  \hspace{1cm} (7)

where, $r$ is the Pearson correlation coefficient which is also called as 0-order correlation coefficient. $r_{12.34...p}$ is (p-2)-order partial correlation coefficient, which was calculated by (p-1)-order partial correlation coefficient ($r_{12.34...(p-1))}$.

In general, the t-test statistic is calculated to evaluate the significance of the correlation coefficient, as illustrated in equation (8), in this study, each partial correlation coefficient is tested using t-test value at the significant level of 0.05.

$$t = \frac{r \sqrt{n-q-2}}{\sqrt{1-r^2}}$$  \hspace{1cm} (8)

where, t is the t-test statistic, $r$ is the partial correlation coefficient, n is the sample number, q is order of partial correlation coefficient, and (n-q-2) is the degrees of freedom.

In this study, pixel-level partial correlation analysis was employed to analyze the relations between NDVI and climatic factors (temperature, precipitation and radiation) and time respectively during 1998 to 2012. The partial correlation coefficient between NDVI and time was considered as the influence of non-climatic factors on vegetation. In addition, region-level partial correlation analysis...
was used to explore the correlations between NDVI and climatic factors including temperature, precipitation, and radiation at different reaches with different dominant vegetation types during different periods.

4. Result and discussion

4.1. Vegetation spatial characteristics in the HRB

The annual maximum NDVI represent the best status of vegetation during vegetation growing season, which could effectively characterize the discrepancy for different vegetation species in different areas in HRB, in this study, the multi-year average of annual maximum NDVI was calculated to describe the overall spatial distribution of vegetation during a fifteen-year period. It is well known there is an ambiguous ecological meaning for NDVI variation in unvegetated areas [22]. Thus, all NDVI pixels of vegetated areas in the HRB were used to exhibit the local vegetation situation in this study. Firstly, the vegetated area in HRB was identified using annual maximum NDVI time-series, if the NDVI value was greater than 0.1 at least two consecutive years, the pixel was classified as the vegetation. This treatment not only guaranteed that occasionally vegetated areas were taken into account but also NDVI variations not caused by vegetation change were excluded from further analysis [11].

![Figure 2. Spatial distribution of multi-year average of annual NDVI maximum time-series for vegetated areas in the HRB.](image)

The spatial distribution characteristic of the average annual maximum NDVI of vegetation area from 1998 to 2012 was shown in figure 2. According to figure 2, it is illustrated that the vegetated area and unvegetated area account for 27.9% and 73.1% in HRB respectively, which demonstrates that the HRB is a typical arid and semi-arid inland river basin where the overall vegetation cover is very low. For different typical areas in the HRB, vegetated areas account for 90%, 56.5% and 4.9% in the upper reaches, middle reaches and lower reaches respectively, which illustrates an obvious gradient change of vegetation cover from upper reaches to lower reaches. This could be explained by the local climate
condition that more precipitation and glacier/snow meltwater in the mountainous region, whereas there is extremely low rainfall and high evapotranspiration in the desert.

It is shown that the areas with NDVI less than 0.2 are mainly distributed in the desert, transit zone between oasis and desert, transit zone between mountains and desert and Gurinai basin which is mainly due to dwarf and sparse shrubs are the dominant vegetation species in these regions where there are very limited available water resources. The NDVI of Ejin oasis dominated by Euphrates poplar forests and shrubs is lowest in all oases in HRB, with NDVI value between 0.2-0.4. The artificial oases in the middle reaches (Jinta, Jiuquan and Zhangye) have relatively higher NDVI because the cropland is the dominant vegetation in this region where there are above 90% population and production activities in the HRB, hence water resources supply is guaranteed by EWDP for necessarily economic development. Ganzhou irrigated area has the highest NDVI higher than 0.6 among artificial oases. For the Qilian monotonous region dominated by nature forests and grassland, it is observed that almost one has the NDVI higher than 0.6, and there are higher NDVIs in the eastern region of Qilian mountain than the western region (Taolaihe sub-basin and Hongshuihe sub-basin), last but not the least, the NDVI in the middle elevation is higher than that in the higher and lower elevation in Qilian mountain.

In this study, the histogram of NDVI was also constructed from all the pixels for vegetated area in the HRB to assess the overall situation of vegetation across the whole basin, as illustrated in figure 3. It is concluded that the distribution characteristic of NDVI for vegetated area in HRB is not the unimodal distribution but bimodal distribution, the two peaks of NDVI appears between 0.15-0.25 and between 0.59-0.68, which means a large number of vegetation with low cover and high cover coexist in the HRB.

![Figure 3](image)

**Figure 3.** The histogram of NDVI for vegetated areas in the HRB.

### 4.2. NDVI temporal and spatial variation from 1998 to 2012 in the HRB

#### 4.2.1. Variation trends of pixel-level NDVI in the HRB

The leaves of vegetation only keep green in annual growing season in this arid and semi-arid zone, so in this study, the average NDVI during the growing season (April to November for this region) was employed to represent the overall condition and status of vegetation during one year. The MK test and relative Sen’s slope were employed to explore the temporal variation trend of average NDVI during the growing season time-series from 1998 to 2012. The spatial pattern of statistic Z for NDVI in HRB was obtained by calculating statistic Z of NDVI time series for each pixel. The degrees of vegetation change were divided into five levels (figure 4(a)), consisting of highly significant decrease \((Z\leq-2.567)\), significant decrease \((-2.567<Z<-2.567)\),
1.645), insignificance change (-1.645<Z<1.645), significant increase (1.645≤Z<2.567) and highly significant increase (Z≥2.567). For the areas with significant change trend, four levels were divided, including -23.2%~3%, -3%~0.1%, 0.1%~3% and 3%~15.8%, based on relative Sen’s slope of variation trend in order to demonstrate the spatial distribution of variation magnitude, as illustrated in figure 4(b).

Figure 4. Spatial distributions of variation trend and significance (a) and relative Sen’s slope of NDVI time-series.

MK test result shows that the variation trends of NDVI pixels are not significant in the area, accounting for 44.9% in the total vegetated area, located at Sandan, Minle, Ganzhou and transit zone between mountain and oasis, and parts of grassland in the upper reaches. The variation trend is significantly increasing for the majority of vegetated area, accounting for 46.3%, and there is only 8.8% of the vegetation covered area shows a significantly decreasing trend, furthermore, the highly significantly decreasing (P<0.01) areas where water resources supply is very limited only account for 3% in vegetated area, however, the highly significantly increasing (P<0.01) areas account for 27.4%, which demonstrates that the overall area of ecologically improved vegetated area overweight that of degraded vegetated area during 1998-2012.

The spatial distribution of NDVI pixels with significant variation has distinct regional characteristics. According to the figure 4(a), the significantly deteriorated areas in the upper reaches are mainly located in the mountainous region where the elevation is higher than 4200 m in the Qilian Mountain, which proves that the alpine vegetation is experiencing degradation. For the oasis plains, the areas with a declining trend of NDVI are located at the northern part of Hexi Corridor and southern part of Linze. For the desert in the lower reaches which is traditional area characterized with vegetation degradation, a significant decreasing trend is still observed in the areas discretely distributed near the downstream channel and northern part of Ejin oasis. The areas with significant and highly significant improvement in the upper reaches are mainly located at the Taolaihe sub-basin and Hongshuihe sub-basin in the western parts of Qilian Mountain, some scattered regions with middle
elevation in Qilian Mountain, and the foot of the Northern mountain. For the oasis plains, the majority of areas with increasing trend are characterized with highly significant increase, especially for the Jinta, Jiuquan, Gaotai, Linze and Ganzhou, which demonstrates that the condition of cropland in this area is experiencing an increasing trend. The herbs and shrubs on both sides of downstream river channel and parts of Ejin oasis exhibit the highly significant improving trend according to the Figure 4(a).

The pixels showing significant change trend based on MK test (figure 4(a)) were selected to further analyze the relative change magnitude which reflects the changing degree. In this study, relative Sen’s slope (R) of variation trend was proposed to represent the variation magnitude from 1998 to 2012. The spatial distribution of relative Sen’s slope in NDVI was shown in figure 4(b). For the significantly increasing vegetated area, the areas with R less than -3% and higher than -3% account for 42.1% and 57.9% respectively; for the significantly decreasing vegetated area, the areas with R less than 3% and higher than 3% account for 74.1% and 25.9%.

For the spatial distribution characteristic of R, the pixels exhibiting decreasing trend, with R less than -0.01%, are scattered in the whole basin. The pixels with R higher than 3% are mainly distributed in oasis plain, Minle and Sandan grassland in the middle reaches, the both sides of downstream river and the Ejin oasis. The relative magnitude of pixels characterized with increasing trend in the upper reaches is mainly between 0.1%-3%. It is illustrated that the lowest R (-23.2%) appears in the western part of Qilian mountain, and the highest R (15.8%) appears in the Ejin oasis. In this study, the R was proposed to represent the overall variation trend and magnitude at watershed scale. The \( \bar{R} \) calculated using equation (5) for the HRB during 1998 to 2012 is 1.5%, which illustrates that vegetation in the HRB was improved by 1.5% of annual average level from 1998 to 2012.

4.2.2. Variation trends of region-level NDVI for different reaches in the HRB. There are different dominant vegetation species in the upper, middle and lower reaches with significantly different climatic conditions in the HRB, the variation trend of region-level NDVI time-series was also analyzed to explore the change characteristics of vegetation under different environment. The average NDVI values were calculated within the upper, middle and lower reaches respectively in each year, and region-level NDVI time-series in three areas were shown in figure 5.

![Figure 5](image_url)

**Figure 5.** Variation trends of region-level NDVI in the upper, middle and lower reaches respectively.

The MK test was employed to analyze the time-series variation trend, and the same varying patterns were found in different regions: 1) the year of 2001 is the abrupt point, which coincides with
the implement time of EWDP proposed by Chinese central government; 2) there is an obvious decreasing trend during 1998-2001; 3) a significantly increasing trend was observed from 2001 to 2012, which could explain that the relative variation magnitude is very low in the HRB during 1998 to 2012, and the variation degree is expected to be greater during 2001 to 2012. For the upper reaches, there is a highly significant increase (P<0.01), with a relative increasing magnitude of 0.8%; for the middle reaches, there is a significant increase (P<0.1), with a relative increasing magnitude of 0.86%; for the lower reaches, there is a highly significant increase (P<0.01), with a relative increasing magnitude of 1.06%. It is observed according to comparison that there is a highest NDVI value but lowest increasing magnitude for the upper reaches, however, there is a lowest NDVI value but highest increasing magnitude in the lower reaches. It is concluded that the changing degree of vegetation is greatest for the sparse shrubs in the lower reaches, and is smallest for the forest and grassland in the upper reaches.

4.3. Correlation between pixel-level NDVI and climatic and non-climatic factors
Precipitation, solar radiation and temperature are the key climatic factors constraining the vegetation growth [23, 24]. Meanwhile, the effect from human activities on vegetation is also non-ignorable, especially in the human living areas. The partial correlation analysis was used to determine the influence of one factor on vegetation, taking away the influence from other factors. In this study, the partial correlation analysis between NDVI and four variables including precipitation (P), temperature (T), Radiation (R), time (t) at pixel scale was performed in the HRB according to equation (7), and the significance of partial correlation coefficients between NDVI and variables were determined based on t-test (equation (8)) at the significant level of 0.05. If the partial correlations between NDVI and multiple variables are significant, it is demonstrated that the variation of NDVI is affected by the multiple variables. It should be noted that partial correlation coefficient between NDVI and time, taking away the impacts from all climatic factors, was considered to be the influence from non-climatic factor mainly including human activities on vegetation.

In this study, overlay analysis of pixel-level NDVI variation trend produced in the 4.2.1 section and pixel-level partial correlations between NDVI and four variables were performed to determine which factor(s) result in an increase or decrease of NDVI during 1998 to 2012, as illustrated in the figure 6. It is observed that there are no significant partial correlation between NDVI and meteorological factors involving temperature and radiation, which demonstrates that temperature and radiation are not the driving factors constraining vegetation dynamics in the HRB. According to the figure 6, the precipitation and time are the two main driving factors affecting vegetation variation. Spatially, the significant vegetation degradation in the northern part of HeiXi Corridor and some southern parts in the Linze is caused by decreasing precipitation. Although the transit zone between desert and southern part of the Ganzhou oasis and Minle are not characterized with significant NDVI change trend, the precipitation and time are still the driving factors influencing the fluctuate up and down of vegetation. It is very obvious that the time is the most important factor which leads to NDVI increase significantly. The NDVI increasing trend in the foot of west-end of Qilian Mountain and east-end of Taolaihe is mainly caused by increasing precipitation. It is shown that NDVI increase at the transit zones between mountain and oasis in the middle reaches as a result of combined effects from precipitation and time. More importantly, the vegetation improvement in the areas with middle elevation in the Qilian Mountain, the oasis plains involving Jinta, Jiuquan, Gaotai, Linze in the middle reaches, the areas along downstream river channel, Ejin oasis and Gurinai basin was only influenced by non-climatic factor. In the middle reaches and lower reaches, the influence of non-climatic factor is reasonably considered as effects from EWDP implementation, which indicates that the ecological and economic effects of EWDP implementation are positive for the HRB during past fifteen years.
4.4. Effects of climatic factors on region-level NDVI for different periods
To explore the driving factor affecting region-level NDVI variation, in this study, the spatial average of annual average temperature (°C), annual total precipitation (mm) and annual total radiation (MJ/m²) were calculated based on gridded meteorological dataset within the upper, middle and lower reaches respectively.

The linear regression analysis between NDVI and climatic factors were used to derive determination coefficient for different reaches during different periods, as illustrated in the figure 7. The result shows that 1) for the period from 1998 to 2001, rainfall is an important climatic factor influencing NDVI in the upper reaches ($R^2=0.54$) and middle reaches ($R^2=0.83$), and radiation is a significant factor influencing NDVI in the lower reaches ($R^2=0.96$), and the higher the radiation is, the lower the NDVI in the lower reaches will be; 2) for the period from 2001 to 2012, the influence of rainfall on NDVI is still significant, however determination coefficient has reduced to 0.42, and influence of other climatic factors on NDVI in each reaches were not so significant as the period from 1998 to 2001.

For determining the driving factor leading to the vegetation variation in different reaches for different , the partial correlations between NDVI and three climatic variables at region-level were calculated and significance testing was performed using t-test statistic method, if the significance level is greater than 0.1, there is no statistical significance for this correlation. The significance levels of partial correlation between NDVI and all factors were illustrated in the table 1. It is indicated that effects of climatic factors on NDVI varied with intervention of intensive human activities since 2001. The rainfall is proved to be the most significant factor relating with NDVI variation in the upper reaches, and rainfall and temperature are significant factors influencing NDVI variation in the middle reaches, and rainfall and radiation are significant factors influencing NDVI variation in the lower reaches during the period (1998-2001) when there are relative small amount of anthropogenic activities in the HRB. However, there is only a significant climatic factor (rainfall) relating NDVI variation in the middle reaches, and all climatic factors are not significantly related with NDVI in the
upper reaches and lower reaches during the period (2001-2012) when lots of ecological restoration projects were implemented. This could demonstrate that due to implementation of lots of ecological restoration projects since 2001, the effect of climatic factors on vegetation change in the HRB is getting weak from 2001 to 2012, and influence of human activities is getting strong.

**Figure 7.** Linear regression analysis between NDVI and climatic factors in the different reaches for different periods in the HRB.
Table 1. The partial correlation coefficients between region-level NDVI and climatic factors (precipitation, temperature and radiation) based on t-test for different periods.

| Periods      | 1998-2001 | 2001-2012 |
|--------------|-----------|-----------|
|              | Upper reaches | Middle reaches | Lower reaches | Upper reaches | Middle reaches | Lower reaches |
| Factors      |            |            |              |            |            |              |
| Precipitation | 0.72*     | 0.91*     | 0.71*      | 0.07    | 0.64*     | 0.41         |
| Temperature  | 0.20      | 0.64*     | 0.4        | 0.27    | 0.31      | 0.50         |
| Radiation    | 0         | 0         | 0.96*      | 0.48    | 0.46      | 0            |

*P<0.05

5. Conclusion

In this study, spatial-temporal dynamics of vegetation and its response to climatic change in the HRB, a typical arid region with vulnerable ecosystems were explored. The Mann–Kendall test was used in combination with relative Sen’s slope to analyze the NDVI time-series at pixel and regional scale respectively. The linear regression and partial correlation analysis were then employed for exploring the driving forces affecting the vegetation changes at pixel and regional scale respectively. According to the analysis and discussion of results presented, we may come to the following conclusions:

- It is concluded that the vegetated area and unvegetated area account for 27.9% and 73.1% in the HRB respectively, and vegetated area account for 90%, 56.5% and 4.9% in the upper reaches, middle reaches and lower reaches respectively. The NDVI of Ejin oasis dominated by *Euphrates poplar* forests and shrubs is lowest in all oases in the HRB, and Ganzhou irrigated district has the highest NDVI higher than 0.6 among artificial oases. For the Qilian monotonous region dominated by nature forests and grassland, it is observed that almost one-third of this area has the NDVI higher than 0.6, and the NDVI in the middle elevation is higher than that in the higher and lower elevation in Qilian mountain. It is shown that the distribution characteristic of NDVI histogram for vegetated area in the HRB is not the unimodal distribution but bimodal distribution.

- The area where the variation trend of vegetation is significantly increasing accounting for 46.3% in the vegetated area in the HRB during 1998-2012, and there is only 8.8% of the vegetation covered area shows a significantly decreasing trend. The relative Sen’s slope (R) of variation trend was proposed to represent the variation magnitude from 1998 to 2012. For the significantly increasing vegetated area, the areas with R less than -3% and higher than -3% account for 42.1% and 57.9% respectively; for the significantly decreasing vegetated area, the areas with R less than 3% and higher than 3% account for 74.1% and 25.9%. The $R$ was proposed to represent the overall variation trend and magnitude at watershed scale, which illustrates that vegetation in the HRB was improved by 1.5% of annual average level from 1998 to 2012.

- On the regional scale, same variation trajectories of vegetation were found in different regions: 1) the year of 2001 is the catastrophe point, which coincides with the implement time of EWDP proposed by Chinese central government; 2) there is an obvious decreasing trend during 1998-2001; 3) a significantly increasing trend was observed from 2001 to 2012. The relative Sen’s slope is 0.8%, 0.86% and 1.06% for the upper, middle and lower reaches respectively. It is concluded that the changing degree of vegetation is greatest for the sparse shrubs in the lower reaches, and is smallest for the forest and grassland in the upper reaches.

- Effects of climatic factors on NDVI varied with intervention of intensive human activities since 2001. The rainfall is proved to be the most significant factor relating with NDVI variation in the upper reaches, and rainfall and temperature are significant factors influencing NDVI variation in the middle reaches, and rainfall and radiation are significant factors influencing NDVI variation in the lower reaches during the period (1998-2001) when there are relative small amount of anthropogenic activities in the HRB. However, there is only a
significant climatic factor (rainfall) relating NDVI variation in the middle reaches, and all climatic factors are not significantly influence the NDVI change in the upper reaches and lower reaches during the period (2001-2012) when lots of ecological restoration projects were implemented to improve ecological effects of Heihe River.

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