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Spatial-temporal changes in *NPP* and its relationship with climate factors based on sensitivity analysis in the Shiyang River Basin

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As a typical inland river basin in China, the Shiyang River Basin is characterized by its special mountain-basin structure. The ecological health in the basin is related to the sustainable development of the economy and society. At present, there are few studies on net primary productivity (*NPP*) in the Shiyang River Basin, and the existing analysis of the relationship between *NPP* and climatic factors is lacking. The upper mountainous area and the middle and lower oasis areas in the Shiyang River Basin were selected as the study area. The *NPP* of the study area was estimated using the Thornthwaite Memorial Model. The spatial and temporal characteristics of *NPP* were analyzed by Sen's slope method. Based on the sensitivity analysis, the correlation of the main climate factors to *NPP* was estimated. According to the aforementioned work, the variation trend of the future *NPP* was predicted. The results showed that *NPP* in the study area increased from 1981 to 2015 with the increase in temperature and precipitation. The spatial heterogeneity of the change trend of *NPP* was not significant, but the spatial heterogeneity of the rangeability was strong. The *NPP* was highly sensitive to precipitation, relative humidity and net solar radiation. By integrating the changes in climatic elements, the temperature, precipitation and relative humidity contributed the main parts of the change in *NPP*. The *NPP* is predicted to increase by 4.9–8.1% by 2050 according to the amplitude of climate change over the past 35 yrs.

Keywords. Climate change; *NPP*; sensitivity analysis; Sen's slope; Shiyang River Basin.

1. Introduction

The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) (2013) showed that climate change, which is characterized by increasing temperatures (T), has been a major component of global change over the past half century (Chen *et al.* 2012; Song *et al.* 2013; Zhang *et al.* 2018). The middle latitude region of the Northern Hemisphere has experienced the fastest warming. It has been estimated that the future climate will continue to warm (Sun *et al.* 2014). Arid inland river basins in China are mainly located in the hinterland of Eurasia in the middle latitudes. The rivers originate in mountains, with precipitation

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(P) and snow-melt water constituting the water resources. In the middle and lower reaches of the plain area, the adjacent oasis-desert landscape is formed according to the condition of the water resources. Where there is water, there is an oasis; where there is no water, there is a desert. These basins are very sensitive to global climate change (Yu and Xu 2009; Chen *et al.* 2014). Under conditions of increasing water demand by economic and social systems, the health of the basin ecosystem faces a series of problems, including spatial and temporal alteration of river runoff, soil erosion intensification, water table decline, grassland degeneration, widespread desertification and ecosystem degradation (Piao *et al.* 2010; Wang *et al.* 2012; Xu *et al.* 2013; Li *et al.* 2017; Manfreda *et al.* 2018; Ti *et al.* 2018; Zhang *et al.* 2015, 2017).

Net primary productivity (*NPP*) is the amount of organic matter accumulated by green plants in an area per unit time (Li *et al.* 2014; Yuan *et al.* 2016), and can directly reflect the production capacity of vegetation under natural conditions. *NPP* is an important index to measure the production capacity of vegetation communities under natural ecological and environmental conditions (Wang *et al.* 2013, 2014). Chen *et al.* (2017) used the Carnegie–Ames–Stanford Approach (CASA) model to study the temporal and spatial distribution of *NPP* in the Hengduan Mountains and noted that the distribution of *NPP* in the Hengduan Mountains had a strong correlation with elevation. Yan *et al.* (2016) used the C-Fix model to estimate *NPP* in the Heihe River Basin and found that *NPP* had an increasing trend in the past 10 yrs. Zhou *et al.* (2015) used *NPP* as an indicator to quantify the contribution of climate change and human activities to desertification in northwest China. The results showed that human activities played an important role in the decrease in *NPP*, while the increase in *NPP* was mainly affected by climate change. Wang *et al.* (2015) used the arid–semiarid region of China as the research area and analyzed the impact of climate change on *NPP*. The results showed that T and P were the main influencing factors on *NPP*, and the seasonal difference between them was significant. Liu *et al.* (2015) analyzed the change in *NPP* and its relationship with climatic factors in Gansu Province. It was concluded that the spatial variation of *NPP* in the study period was significant, and the correlation between *NPP* and T and P was strong. Fang *et al.* (2011) used the source area of the Yangtze and Yellow Rivers as the research object. This research analyzed the influence of the change in *NPP* on permafrost, and the relationship between *NPP* and average annual T was also assessed. The results showed that there was a significant nonlinear relationship between *NPP* and average annual T, and the degree of sensitivity between *NPP* and average annual T decreased. Peng *et al.* (2010) studied climate change and the spatial and seasonal variation in *NPP* in southeastern China using Moderate Resolution Imaging Spectroradiometer (MODIS) data. The results showed that the variation in *NPP* was mainly affected by T, P and sunshine hours; additionally, *NPP* was affected by the complexity of the topography and vegetation distribution in southeastern China. The correlation between *NPP* and climatic factors and vegetation distribution was also complicated. In summary, previous studies on *NPP* have achieved fruitful results, but there are still some problems in the following aspects: (i) Models such as the CASA model, C-Fix model and so on for calculating *NPP* are widely used, but involve many parameters and are relatively complex. Although remote sensing products have the advantage of convenient acquisition and are conducive to spatial analysis and strong timeliness, it is difficult to obtain continuous data of a long time scale due to the lack of monitoring systems in the past. (ii) The sensitivity analysis of climatic factors and *NPP* has been neglected, and the analysis of the influencing factors has mainly focused on P and T. There is no research or analysis on evapotranspiration (*ET*), which is an important part of the hydrological cycle and of great significance to vegetation growth and ecosystems. (iii) Research on the relationship between *NPP* and climate change in the Shiyang River Basin is scarce, and the available time series are not up-to-date.

The Shiyang River Basin is located in the inland area of China, and the characteristics of the mountain-basin system are significant. The features of the hydrological–ecological processes in different geographic–ecological zones are notably different. The vertical zonality of vegetation is remarkable. The basin is typical and representative of the inland river basins of China (Zhu *et al.* 2004). Limited water resources in the basin mainly come from the upper mountainous area and are consumed in the middle and lower oasis areas. Due to the growth of the population and the increasing demand for water resources, the ecological conditions of the entire basin have been damaged to varying degrees. It is necessary and worth discussing the response of *NPP* to climate change in the Shiyang River Basin. Therefore, based on the extended updating of hydrometeorological series (1981–2015), this paper discussed the correlation between climatic factors and *NPP*, with a goal of achieving the following four objectives: (1) analyze the spatial and temporal distribution of *NPP* in the Shiyang River Basin to obtain a comprehensive understanding of the characteristics of *NPP* in the basin; (2) research the sensitivity degree of climatic factors to *NPP* and calibrate the main sensitive elements to *NPP* to make full sense of the relationship between *NPP* and climate factors; (3) discuss the characteristics of climate change and quantify the contribution of each climatic factor to the change in *NPP*; and (4) predict the future trend of *NPP*. The results obtained in this study were helpful in understanding the relationship between the environment and ecology and learning more about the health of land surface ecosystems and promoting the comprehensive and harmonious development of water resource ecosystems in inland river basins.

2. Materials and methods

2.1 *Study area*

As one of the three largest inland river basins in Gansu Province, the Shiyang River Basin is located in the eastern region of the Hexi Corridor. The Shiyang River Basin is geographically located between 101°22′–104°14′E and 36°57′–39°27′N and has an average Normalized Difference Vegetation Index (NDVI) between 0 and 0.94, and an elevation ranging from 1263 to 5130 m (figure 1). Based on its geographical boundary, the Shiyang River Basin is located at the northern foot of Qilian Mountain, bordering Wushaoling and the Yellow River Basin in the east and Dahuang Mountain and the Heihe River Basin in the west. The northern part of the Shiyang River Basin is the Inner Mongolia Autonomous Region and is surrounded by the Tengger Desert and the Badain Jaran Desert. The Shiyang River Basin is adjacent to the Qinghai–Tibet Plateau, and its atmospheric circulation and climatic characteristics are significantly affected by the Qinghai–Tibet Plateau. The high elevation is controlled by the mid-latitude westerly circulation, and the near-surface areas are controlled by the monsoon circulation. The climate type is a continental arid climate with dry and rainy seasons, strong sunshine and high evaporation. The upper mountainous area has a cold temperate semi-arid climate and is dominated by alpine meadows, forest and staggered pasture-shrub. The middle and lower reaches belong to the temperate arid climate and have an interlaced landscape of irrigated agriculture oasis and natural desert. The main crops in the irrigation districts are wheat, corn and sunflower.

2.2 *Data collection*

We collected and assembled hydrometeorological observation sequences from eight reference meteorological stations (Shandan, Qilian, Menyuan, Wusongling, Gulang, Wuwei, Yongchang and Minqin) in the Shiyang River Basin and adjacent areas from 1981 to 2015. These observations mainly included atmospheric pressure, wind speed (*WS*), maximum air temperature ($T_{\max}$), minimum air temperature ($T_{\min}$), relative humidity (*RH*), *P* and sunshine hours, and these data were from the China Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn). The NDVI data came from MODIS NDVI, and the spatial resolution was 250 m. The 16 days of MODIS data were combined to form yearly data to the maximum using the maximum value composite (MVC) procedure and were resampled to 100 m using the ArcGIS platform for subsequent study analysis.

According to the different geoecological intervals of the Shiyang River Basin combined with the hydrological and regional hydrogeological conditions of the basin, 13 subregions were obtained using the Soil and Water Assessment Tool (SWAT) model (figure 2), and these subregions included the Xida, Dongda, Xiying, Jinta, Zamu, Huangyang, and Gulang Rivers in the upper mountainous area, the Wuwei, Minqin, Jinchang, and Yongchang Basins in the middle and lower oasis areas, and Chaoshui and other areas of the Shiyang River Basin (i.e., desert areas). All the data calculated based on sites were spatially interpolated by the spline method using the ArcGIS platform, and spatial processing was performed based on the 13 sub-basins to obtain *T*, *P*, reference crop evapotranspiration (ET_0), actual evapotranspiration (*AET*) and *NPP* sequences in the 13 regions. The seven upstream rivers (figure 2) represent the upper mountainous area, and the Wuwei, Jinchang, Yongchang and Minqin Basins represent the middle and lower oasis areas. This paper does not cover Chaoshui and the remaining areas.

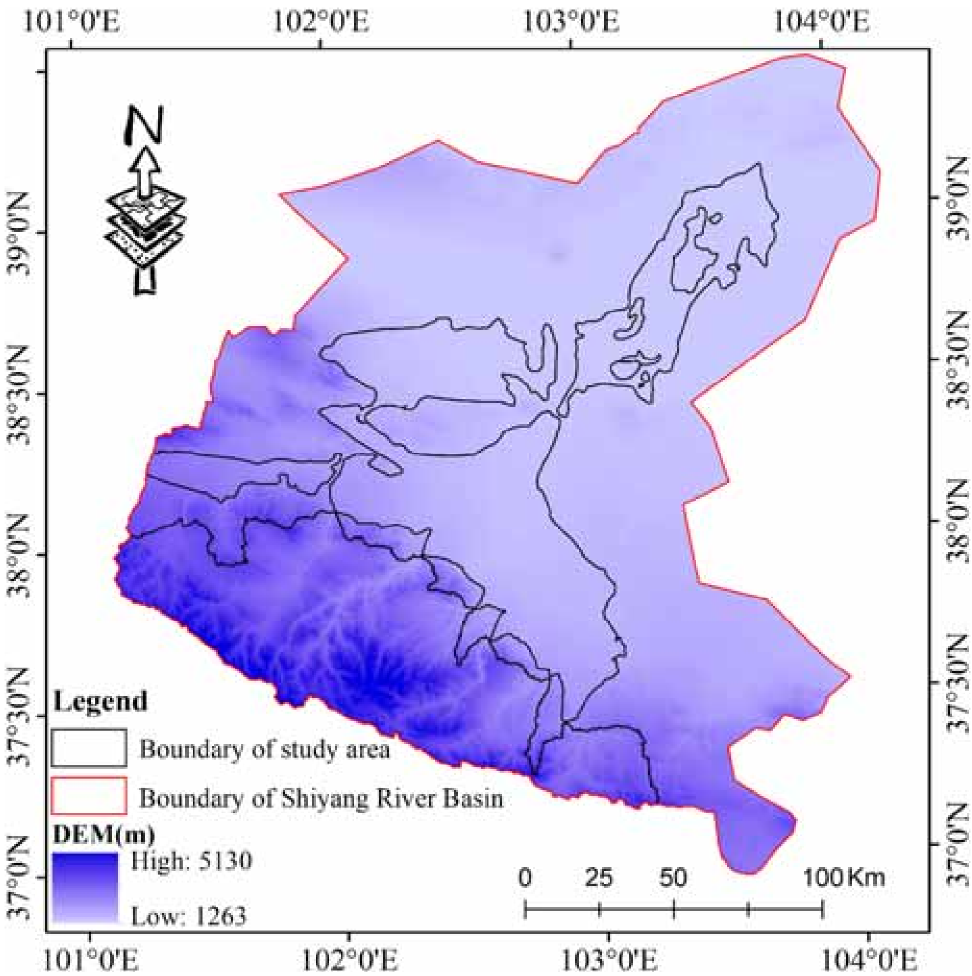

Figure 1. Location of the study area.

2.3 *Research methods*

2.3.1 *NPP*

Lieth (1975) proposed the Thornthwaite Memorial Model for estimating *NPP* by using the *AET* based on the relationship between crop yield and mean annual *T* and *P*. However, this model had a considerable limitation because it used only *T* and *P* to estimate the *AET*. According to the actual situation in the Shiyang River Basin, we used different methods to estimate the *AET* in the different geoecological regions. Therefore, the calculation of *NPP* was based on the Thornthwaite Memorial Model with the modified estimation method of the *AET*. The formula is as follows:

$$NPP = 3000 \times \{1 - \exp[-0.0009695 \times (AET - 20)]\} \quad (1)$$

where *NPP* and *AET* are the net primary productivity (gC m^{-2} yr^{-1}) and the actual evapotranspiration (mm), respectively, in the Shiyang River Basin.

2.3.2 ET_0

Among the calculation methods for ET_0 (Cain *et al.* 1997; Pirkner *et al.* 2014), the Food and Agriculture Organization (FAO) Penman–Monteith (P–M) equation is widely used for the determination of ET_0 due to its considerable representation of the regional energy balance and the aerodynamics that influence terrestrial evapotranspiration (Richard *et al.* 1998; Ortega-Farias *et al.* 2006; Ali *et al.* 2009; Li et al. 2015a, b). We used the P–M equation to calculate the ET_0 over the Shiyang River Basin.

2.3.3 *AET*

The regional *AET* is deeply influenced by water and heat circulation, especially the spatial patterns of land surface ecology and soil moisture (Donohue *et al.* 2012; Matin and Bourque 2013). Because of the obvious heterogeneity in the Shiyang River Basin, we adopted different methods that were applied and tested in each area to determine the

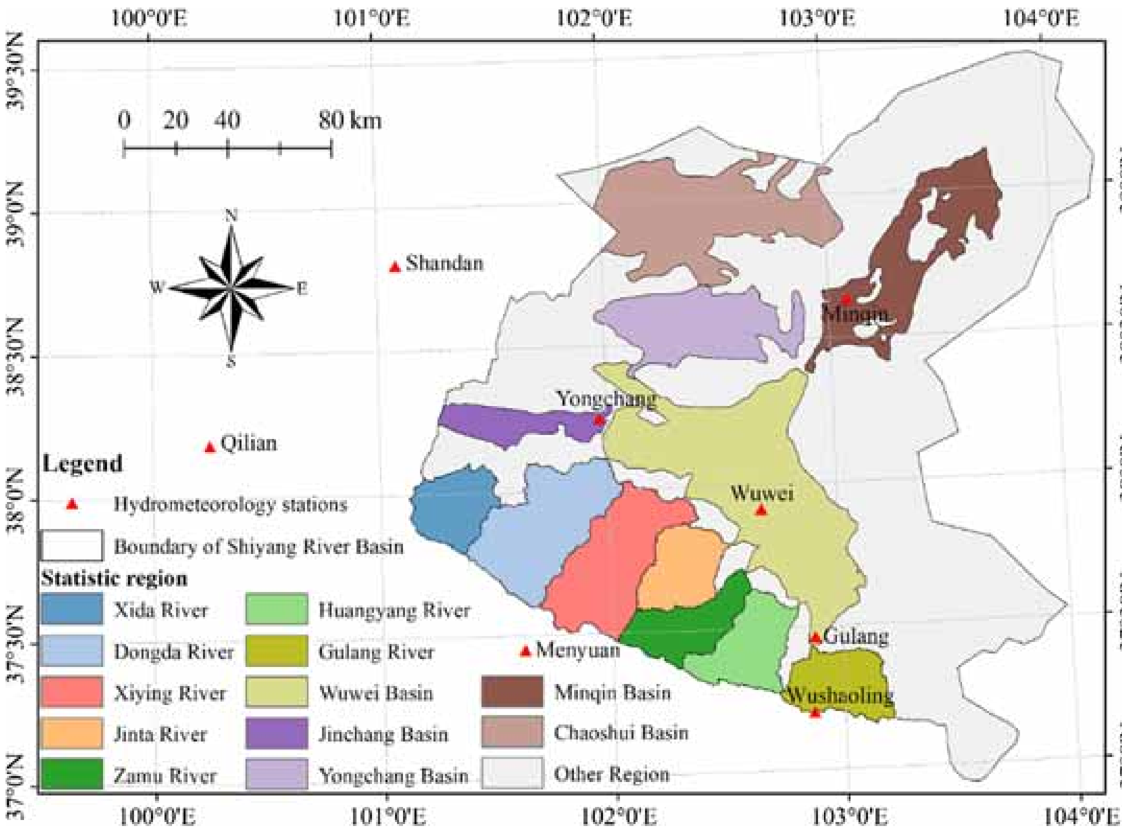

Figure 2. Distribution of the hydrometeorological stations for analysis and the 13 statistical zones across the Shiyang River Basin.

regional AET in the upper mountainous area and the middle and lower reaches.

The AET in the mountainous area in the upper reaches of the Shiyang River Basin was estimated using the Budyko equation (Xu *et al.* 2014; Cong *et al.* 2015). The equation was derived by analyzing the climatic time series data and has been successfully used to determine mountainous AET over relatively long time scales. The equation is as follows:

$$AET_1 = P \times \sqrt{\frac{ET_0}{P}\tanh\left(\frac{P}{ET_0}\right) \times \left[1 - \left(-\frac{ET_0}{P}\right)\right]} \quad (2)$$

where AET_1, ET_0 and P are the actual evapotranspiration (mm), reference evapotranspiration (mm) and precipitation (mm) in the mountainous area, respectively.

Single crop coefficients (K_c) (López-Urrea *et al.* 2009; Silva *et al.* 2012; Shahrokhnia and Sepaskhah 2013) contribute to the AET calculation without partitioning the soil evaporation and plant transpiration; however, these coefficients are more easily calibrated based on field experiments (Tong *et al.* 2007). We used the value of K_c from the study by Tong *et al.* (2007) and estimated the AET in the oasis area:

$$AET_2 = K_C \times ET_0 \quad (3)$$

where AET_2 and ET_0 are the actual evapotranspiration (mm) and reference evapotranspiration (mm) in the irrigated oasis area in the middle and lower oases, respectively.

2.3.4 *Sen's slope*

Sen's slope (Sen 1968) is a statistical method that is relatively mature in the field of geosciences and is used to analyze the trends and magnitudes of hydrological and meteorological factors in a basin (Singh and Goyal 2016; Rahman and Dawood 2017). The method uses the median value of the slope series as a basis to determine the trend and has good applicability and universality in the statistical analyses of hydrological, meteorological and other factors (Singh *et al.* 2015). We used Sen's slope to perform variable amplitude statistical analysis in this study.

2.3.5 *Sensitivity analysis*

The sensitivity coefficient calculation method proposed by Beven (1979), who made climate factors dimensionless by using the rate of change (Liu *et al.* 2009; Li *et al.* 2011; Yadupathi and Kavya 2018), facilitates the comparison between different climatic factors (Zheng *et al.* 2009; Loliyana and Patel 2018). This study used this method to calculate the coefficient of *NPP* and climate factors in the Shiyang River Basin (equation 4), and the method Zhao *et al.* (2015) used in the Heihe River Basin was used to quantify the contribution rate of meteorological factors to the change in *NPP* (equation 5):

$$Se_{\mathrm{vi}} = \lim_{\Delta \mathrm{V_i} \to 0} \left(\frac{\Delta NPP/\mathrm{NPP}}{\Delta V_{\mathrm{i}}/V_{\mathrm{i}}} \right) = \frac{\partial NPP}{\partial V_{\mathrm{i}}} \cdot \frac{V_{\mathrm{i}}}{NPP} \quad (4)$$

$$G_{\mathrm{vi}} = \frac{\Delta V_{\mathrm{i}}}{\overline{V_{\mathrm{i}}}} \cdot Se_{\mathrm{vi}} \quad (5)$$

where Se_{vi} is the sensitivity coefficient of the *i*th meteorological factor and G_{vi} is the contribution rate of the *i*th meteorological factor to the change in *NPP*. The sensitivity coefficient of a meteorological element is positive or negative, indicating that *NPP* increases or decreases as the element increases (Sharannya *et al.* 2018). As the sensitivity coefficient becomes greater, the influence of *NPP* by this meteorological factor also becomes greater (Huo *et al.* 2013).

3. Results

3.1 *Interannual variability of NPP*

The variation trend of *NPP* and the variable amplitude statistics of *NPP*, *P*, *T* and NDVI based on Sen's slope in the mountains and oases of the Shiyang River Basin are shown in figure 3 and table 1, respectively. In the past 35 yrs, the highest and the lowest values of *NPP* in mountainous areas were 910 gC $\mathrm{m^{-2}\,yr^{-1}}$ and 354 gC $\mathrm{m^{-2}\,yr^{-1}}$, respectively, and the multiyear average was 659 gC $\mathrm{m^{-2}\,yr^{-1}}$. The interannual variability was significant, with a rate of increase of 11.4 gC $\mathrm{m^{-2}10\,yr^{-1}}$. The *P* and *T* increased in this area, with change rates of 6.03 mm/10a and 0.56°C/10a, respectively. The highest and lowest *NPP* values of the oasis area were 950 gC $\mathrm{m^{-2}\,yr^{-1}}$ and 834 gC $\mathrm{m^{-2}\,yr^{-1}}$, respectively, the multiyear average was 889 gC $\mathrm{m^{-2}\,yr^{-1}}$, and *NPP* increased at a rate of 16.7 gC $\mathrm{m^{-2}10\,yr^{-1}}$. The trends of *P* and *T* were consistent with the upstream mountainous area, increasing at rates of 7.26 mm/10a and 0.51°C/10a, respectively. In comparison, the average value and rate of increase of *NPP* in the upper mountainous area were slightly lower than those in the middle and lower oasis areas. During the same period, the NDVI showed an increasing trend in the mountains and oases, with increasing rates of 0.01/10a and 0.03/10a, respectively. The increasing trend of vegetation dynamics promoted the increase in *NPP*. It needs to be noted that *NPP* in the upstream mountainous areas decreased significantly in 1991 and 2013, which was mainly caused by decreased precipitation. From the perspective of model composition, precipitation directly affected the actual evapotranspiration, and then affected the value of *NPP*. In terms of mechanism, vegetation growth in arid and semi-arid areas was mainly controlled by precipitation, the reduction of precipitation restricted vegetation growth (Wang *et al.* 2015). From the contribution rate (section 4.2), the change of precipitation has the highest contribution rate to the change of *NPP*.

3.2 *Interdecadal variability*

An anomaly analysis of *NPP*, *P* and *T* based on chronological statistics was performed to analyze the relationship between *NPP* and *P* and *T* in different decades, and the decadal average value of *NPP* was also counted in the statistical period. The results are shown in figure 4.

In the 1980s, the *P* anomaly in the upper mountains was 2.4% higher, *T* was 0.7°C lower than the average value, and the *NPP* anomaly was 1.2% higher. The *P* anomaly in the middle and lower oasis areas was 13.6% lower, *T* was 0.5°C lower than the average, and the *NPP* anomaly percentage was 1.8% lower. The mean values of *NPP* in the two regions were 667 gC $\mathrm{m^{-2}\,yr^{-1}}$ and 873 gC $\mathrm{m^{-2}\,yr^{-1}}$, respectively. The *NPP*, *P* and *T* were slightly lower in the upper reaches in the 1990s. The *P* and *NPP* anomalies were 6.4% and 4.9% lower, respectively. The *T* was lower, by 0.2°C, and the average *NPP* value was 627 gC $\mathrm{m^{-2}\,yr^{-1}}$. The changes in the three elements in oasis areas were consistent with those in mountainous area. The *P* and *NPP* anomalies were 0.2% and 0.7% lower, respectively. The *T* was lower, by 0.4°C, and the average *NPP* value was 882 gC $\mathrm{m^{-2}\,yr^{-1}}$. In the 2000s, the average *NPP* in the

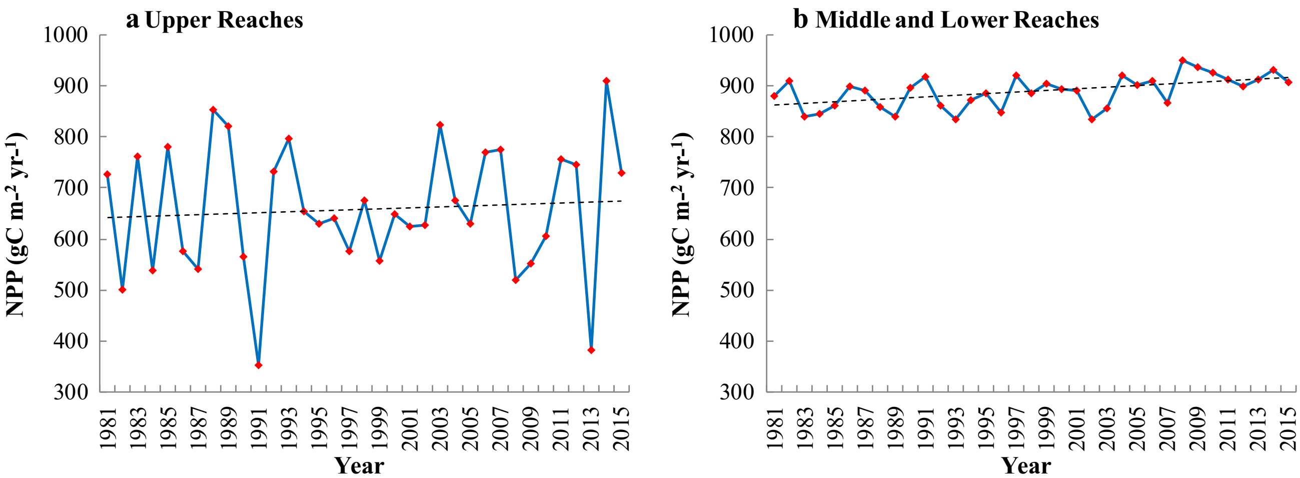

Figure 3. Variation tendency of *NPP* in the upper reaches (**a**) and the middle and lower reaches (**b**) of the Shiyang River Basin.

Table 1. *Sen's slope-tested amplitude of NPP, P, T and NDVI (/10a).*

Region	*NPP* gC m^{-2} yr^{-1}	*P* (mm)	*T* (°C)	*NDVI*
Upper reaches	11.4*	6.03*	0.56**	0.01*
Middle and lower reaches	16.7**	7.26	0.51*	0.03**

*Values are significant at $P \leq 0.1$.

**Values are significant at $P \leq 0.05$.

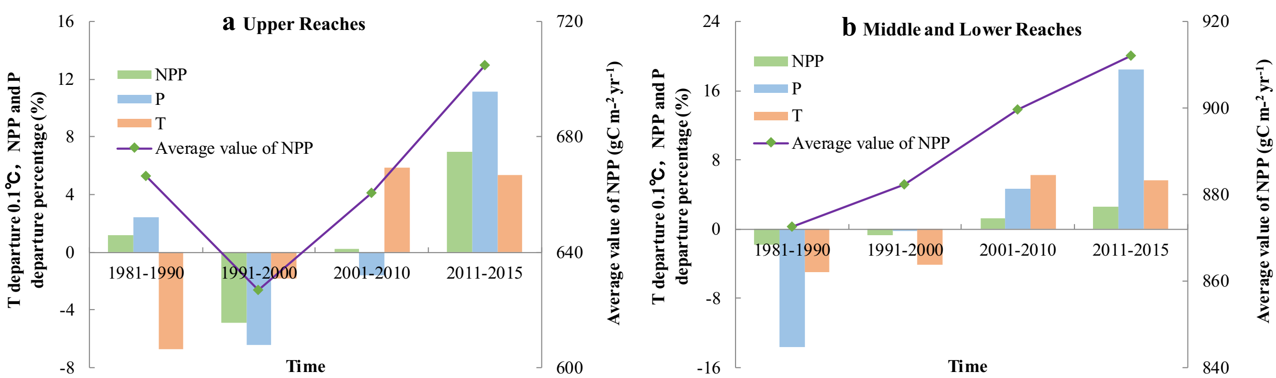

Figure 4. Change in *NPP*, *P* and *T* in the Shiyang River Basin.

mountainous area was 660 gC m^{-2} yr^{-1}, the *P* anomaly percentage was 1.6% lower, and *T* increased by 0.6°C compared to the multiyear average value. With this background, the *NPP* anomaly percentage was 0.2% higher, representing a small increase. In the middle and lower reaches of the oasis areas, the average *NPP* value was 899 gC m^{-2} yr^{-1}, *T* increased by 0.6°C, and the *P* and *NPP* anomalies were 4.6% and 1.2% higher, respectively. In the 2010s, *P*, *T* and *NPP* were higher in the two regions than the average value. The changes in the three elements relative to the average value in the upper mountainous area were 11.1%, 0.5°C and 7.0%, respectively, while they were 18.4%, 0.6°C and 2.6%, respectively, in the middle and lower reaches. The *NPP* reached its maximum during this time period and was 705 gC m^{-2} yr^{-1} in the upper mountainous area and 912 gC m^{-2} yr^{-1} in the middle and lower reaches.

Overall, *T* and *P* in the study area increased in recent years, *NPP* increased in this climate background, and the total amount and growth rate of *NPP* reached its maximum in the 2010s.

3.3 *Spatial distribution characteristics of NPP*

Figure 5 shows the spatial distribution of the multiyear averaged *NPP* and the spatial variation characteristics based on Sen's slope during the period of 1981–2015 in the mountains and oases of the Shiyang River Basin. The value of the multiyear averaged *NPP* was between 271 and 985 gC m^{-2} yr^{-1}, and the distribution of *NPP* exhibited significant spatial heterogeneity. The *NPP* decreased from southwest to northeast. For the oasis area, the value of *NPP* in the center of the oasis was the highest and decreased from the center to the boundary. The *NPP* in the middle oasis was generally higher than that in the downstream oasis. Overall, the *NPP* of the oasis area was higher than that of the mountainous area. Regarding the multiyear change characteristics of *NPP*, the spatial differentiation of *NPP* was not significant. Except for a small area in the middle of the Wuwei Basin and the northern margin of the mountainous area, the other areas showed an increasing trend and the spatial heterogeneity of the variation range was strong. The *NPP* increased from the upstream to the downstream, in which the mountainous and middle oasis areas increased from the center to the boundary.

3.4 *Sensitivity of key climate factors for NPP*

According to the revised Thornthwaite Memorial Model, the *NPP* was mainly affected by the ET_0 and P. Although P affected *NPP* by directly affecting AET, it affected AET by influencing ET_0, which in turn led to changes in the *NPP*. In the mountainous area, the impact of P on *NPP* included the above two aspects, but in the oasis area, P mainly affected *NPP* through the second approach. The ET_0 was mainly affected by factors such as $T_{\max}$, $T_{\min}$, *WS*, *RH* and net solar radiation (NSR) (Zhao *et al.* 2015; Zhang *et al.* 2017). A comprehensive analysis showed that *NPP* was mainly affected by the combined effects of P, $T_{\max}$, $T_{\min}$, *WS*, *RH* and *NSR*.

The sensitivity coefficients of *NPP* to $T_{\max}$, $T_{\min}$, P, *WS*, *RH* and *NSR* were calculated

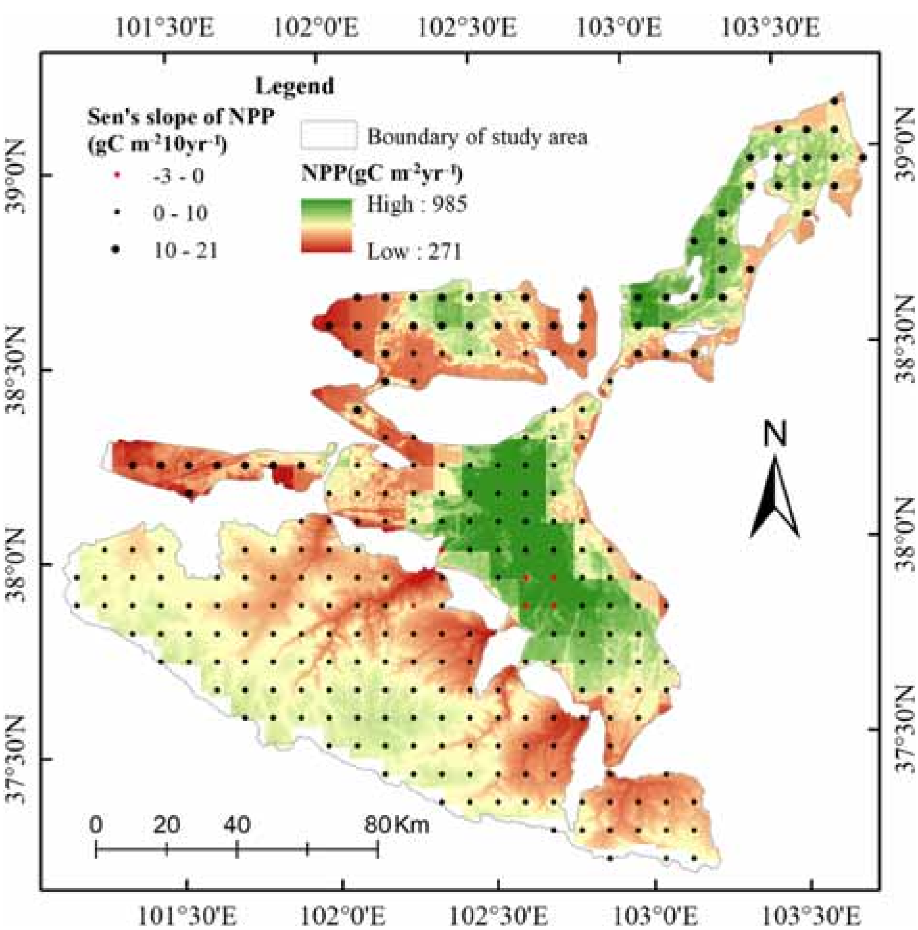

Figure 5. Distribution of *NPP* with Sen's slope-tested variation in the upper reaches and the middle and lower oasis areas in the Shiyang River Basin.

Table 2. *Sensitive coefficients of NPP to key climate factors.*

Region	T_{max}	T_{min}	P	WS	RH	NSR
Upper reaches	0.15	−0.08	0.65	0.18	−0.84	0.50
Middle and lower reaches	0.26	−0.01	0.58	0.27	−0.49	0.40

according to the method of Beven (1979), and the sensitivity of *NPP* fluctuation to various climatic factors was analyzed. The results are listed in table 2. The absolute value of the sensitivity coefficient indicated the sensitivity of the *NPP* to each meteorological factor; therefore, the analysis of the sensitivity level was based on the absolute value. It can be seen from the table that the sensitivity coefficient absolute values of *NPP* to P, *RH* and *NSR* were higher. Among them, the sensitivity coefficients of *P* and *NSR* to *NPP* were positive, indicating that the influence of *P* and *NSR* on *NPP* in the Shiyang River Basin was positively driven; moreover, the sensitivity coefficient to *RH* was negative, and *RH* produced negative drivers to *NPP* by inhibiting evapotranspiration to a certain extent. In comparison, the absolute values of the sensitivity coefficients of *NPP* to the above three factors were characterized by the fact that the mountainous area was higher than the oasis area, which indicated that *NPP* was more sensitive to climate change in the upper mountainous area. The sensitivity coefficients of *NPP* to T_{max}, T_{min} and *WS* were low, and T_{min} was the lowest, indicating that the accumulation of dry matter of vegetation was less sensitive to the change in T_{min}; T_{max} and *WS* affected the *NPP* mainly by exacerbating ET_0. The sensitivity coefficients of *NPP* to T_{max} and *WS* were higher in oases, indicating that *NPP* in the oasis area was more sensitive to T_{max} and *WS*.

4. Discussion

Based on the composition of the sensitivity analysis method, the sensitivity coefficients only reflect the relative changes of *NPP* caused by the changes of each factor; they cannot reflect the contribution of each factor to the actual changes of *NPP* during the study period. To further analyze the influences of climatic factors on *NPP*, we needed to combine the sensitivity coefficients of T_{max}, T_{min}, P, *WS*, *RH* and *NSR* to *NPP* and their actual change characteristics.

4.1 *Change characteristics of climatic factors*

Figure 6(a–f) shows the trends of T_{max}, T_{min}, *WS*, *RH*, *NSR* and *P* in the Shiyang River Basin from 1981 to 2015, respectively. The amplitude statistics based on Sen's slope of T_{max}, T_{min}, *WS*, *RH* and *NSR* are shown in table 3. It can be seen from figure 6 and table 3 that, except for the *WS*, *RH* and P, the other three factors were higher in oases than in mountains. The T_{max} and T_{min} fluctuated considerably in the middle and lower reaches, while *WS* and *RH* fluctuated more substantially in the mountains. The *NSR* had large fluctuations in both regions. In terms of the rate of change, in the upper mountains, the increase in *NSR* was 3.30 (MJ/m^2/d)/10a followed by *RH*, with an increase of 0.33/10a; the changes in T_{max}, T_{min} and *WS* were slight. The *RH* in the middle and lower oases decreased at a rate of 0.91/10a, and other factors increased. In terms of the absolute value of the variable amplitude, *NSR* was the largest followed by *RH*, and *WS* was the smallest. Overall, the variations in the meteorological elements in the middle and lower reaches were larger than those in the mountainous area, which indicated that the climatic conditions in oases were more significant than those in the upstream mountains, and the impact on *NPP* in oasis areas was also more obvious.

4.2 *Contribution of climatic factors to the change in NPP*

The contribution rates of T_{max}, T_{min}, *P*, *WS*, *RH* and *NSR* on *NPP* were calculated according to equation (5). The results are shown in table 4. From 1981 to 2015, the change in *NPP* was mainly controlled by *T*, *P* and *RH*, and the contribution rate of *P* was the highest. The *WS* and *NSR* made minimal contributions to the variation of *NPP* due to their relatively small changes. Overall, the climatic factors in the middle and lower reaches had a higher impact on *NPP* than they did in the upper mountainous area. This result showed that the relative change rate of *NPP* in the oasis area was

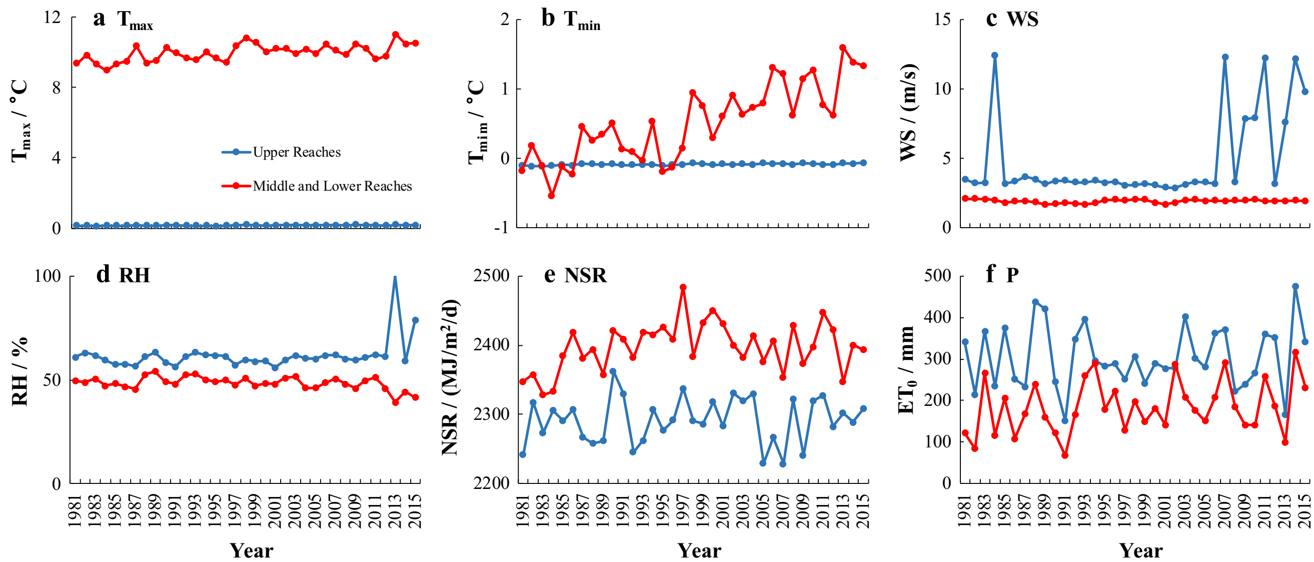

Figure 6. Variation tendency of climatic factors from 1981 to 2015 in the two divisions of the Shiyang River Basin.

higher than that in the mountainous area; however, the impact of climate change on *NPP* was more significant in the oasis area. In the upper mountains, the increase in *RH* inhibited the increase in *NPP* to a certain extent, but the overall effect was weaker than the comprehensive effect of other factors on *NPP*, and *NPP* showed an increasing trend; the comprehensive positive driving forces of various elements in the middle and lower reaches prompted an increase in *NPP*.

4.3 *Prediction of NPP*

The accurate prediction of *NPP* is very important for understanding vegetation dynamics and ecosystem productivity as they are influenced by climate change (Li *et al.* 2015a, b; Gao *et al.* 2009) and can help improve the understanding of the ecosystem, thereby improving ecological efficiency (Liu *et al.* 2018). Shi *et al.* (2002) and Qi *et al.* (2017) believed that the climate in the northwestern inland river basin tended to be warm and humid under future conditions, while *T* and *P* in the Shiyang River Basin have increased in the past 35 yrs, especially since 2000. The increasing tendency was significant; thus, it can be predicted that the climate in the Shiyang River Basin will be warmer and wetter in the future, and *NPP* will also increase.

The analysis discussed above indicated that *T* and *P* contributed considerably to the change in *NPP* in the basin; therefore, we predicted the change in *NPP* over the next 35 yrs in the future according to the increasing rate of *T* and *P* in the past 35 yrs. The *T* in mountains and oases will increase by 1.95°C and 1.80°C, and the *P* will

Table 3. *Sen's slope-tested amplitude of main climate factors (/10a).*

Region	T_{max} (°C)	T_{min} (°C)	*WS* (m/s)	*RH* (%)	*NSR* (MJ/m^2/d)
Upper reaches	0.01**	0.01*	0.01*	0.33*	3.21*
Middle and lower reaches	0.28**	0.42**	0	−0.81*	11.49

*Values are significant at $P \leq 0.1$.
**Values are significant at $P \leq 0.05$.

Table 4. *Contribution rates of key climate factors to the change in NPP (%).*

Region	T_{max}	T_{min}	*WS*	*RH*	*NSR*	*P*	Total contribution
Upper reaches	3.81	2.72	0.46	−2.31	0.43	4.5	9.61
Middle and lower reaches	3	−3.68	0.25	3.92	0.5	7.59	11.58

increase by 7% and 3% by 2050, respectively. The *NPP* will then achieve increases of 8.1% and 4.9%, respectively. In general, the future trend of *NPP* in the Shiyang River Basin is mainly increasing, and *NPP* will increase by 4.9–8.1% by 2050.

5. Conclusions

In this study, we selected the upper mountainous area and the middle and lower oasis areas in the Shiyang River Basin as the study area, estimated *NPP* using the Thornthwaite Memorial Model with *ET* as an important link and discussed the correlation between climatic factors and *NPP* using Sen's slope and sensitivity analysis. According to the tendency of climate change, we predicted the variation trend of *NPP* in the future. The primary findings in this study can be summarized as follows:

(1) From 1981 to 2015, the *NPP* of the study area showed an increasing trend, with significant fluctuations. The *NPP* of the oasis area was higher than that of the upstream mountainous area, and the average annual *NPP* values of the two regions were 889 gC m^{-2} yr^{-1} and 659 gC m^{-2} yr^{-1}, respectively.

(2) The spatial variation in *NPP* was not obvious, except for in a small area in the middle of the Wuwei Basin and a small area in the northern margin of the mountainous area; the other areas showed an increasing trend, and the variation amplitude had strong spatial heterogeneity. The *NPP* increased from upstream to downstream, and the mountainous area and the middle oasis area increased as radiation increased from the center to the border.

(3) The *NPP* was highly sensitive to *P*, *RH* and *NSR*, but combined with the change in climatic factors in the study period, the changes in *NPP* in the Shiyang River Basin were mainly dominated by *T*, *P* and *RH*. The *RH* inhibited the increase of *NPP* to a certain extent in the upper mountainous area, but the overall effect was weaker than the comprehensive effect of other factors on *NPP*. The increase in *P* and *T* and the decrease in *RH* in the oasis area resulted in an increase in *NPP*.

(4) The *T* and *P* in the Shiyang River Basin increased during the study period. According to the increase in the amplitude over the past 35 yrs, *NPP* in the Shiyang River Basin was predicted to increase by 4.9–8.1% by 2050.

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