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RESEARCH ARTICLE

Climate change in different geographical units and its impact on land production potential: a case study of Shaanxi Province, China

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Abstract

Land production potential (LPP) was the maximum grain yield in one year that can be produced by land under the limitations of climate conditions and in the absence of pests and diseases and other factors. Whether climate change was increasing or reducing the LPP in a given region was uncertain. Therefore, Shaanxi Province was selected to analyze the regional differences in climate change and its effects on LPP change and to identify the main climatic factor restricting LPP in different regions by combining Global Agro-Ecological Zone (GAEZ) model with the Geodetector model. Results showed that the temperature in Shaanxi Province showed an upward trend in 2000–2015; the rise in temperature to the north of Qinling Mountain (QM) was less than that to the south of QM. However, rising temperature had a yield-improving effect to the north of QM and a yield-decreasing effect to the south of QM. There was a precipitation increase in Arid Sandy (AS) area and Loess Plateau (LP), and the precipitation reduced in all other geographical units. The increase in LPP of Shaanxi mostly was caused by increasing precipitation. However, precipitation was declined and reduced LPP to the south of QM; that is, precipitation decline was the dominated climatic factor for LPP decrease in QM, Hanjiang Basin (HB), and Daba Mountain (DM). To the north of QM, LPP in AS, LP, and Guanzhong Plain (GP) both dramatically increased, mainly improved by rising temperature, increasing precipitation, and rising temperature, respectively.

Keywords Climate change · Land production potential · Geographical units · GAEZ · Geodetector

Introduction

Global climate change was the biggest and most complex ecological environment problem faced by human survival in the twenty-first century. Scientific researches and observations showed that the Earth's climate was undergoing global warming as the main characteristics of significant change in the past century (Houghton 2001; IPCC 2014). The IPCC's fifth assessment report noted that the global average temperature rose by 0.85 °C between 1880 and 2012, and the rate of rise in temperature from 1951 to 2012 was almost double that of since 1880 (IPCC 2014). The climate resource provided material and energy for crop growth and was also an important limiting factor in the effective implementation of agricultural technology (Lobell and Asner 2003; Lobell et al. 2011). Thus, the agricultural system was one of the most sensitive systems to climate change (Gay et al. 2006). Global climate change had altered the quantity and quality of agricultural climate resources associated with food production spatially and temporally (Moriondo et al. 2011; Chourghal et al. 2016; Kumar 2016). The number of agricultural climatic resources and their matching changes also affected the agricultural climate production potential, agricultural production layout, planting system, and so on, which ultimately had a serious impact on global food production safety (Schmidhuber and Tubiello 2007; Piao et al. 2010; Harrison et al. 2016; Drabo 2017).

There was no doubt that climate change had a profound impact on land production potential (LPP), which was the maximum grain yield in one year that can be produced by land

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under the limitations of climate conditions and in the absence of pests and diseases and other factors. However, whether climate change was increasing or reducing the grain production in a given region was uncertain, due to the inconsistency in the impact direction and degree of the change in precipitation, temperature, and other factors on LPP (Schmidhuber and Tubiello 2007; Wilcox and Makowski 2014). Lobell et al. (2011) indicated that, at least on the continental or national scale, the effect of temperature changes on LPP was more pronounced. Rising temperatures increase the crop's potential for production, and there was no significant correlation between precipitation or solar radiation trends and crop yields (Abraha and Savage 2006; Lobell and Gourdji 2012). However, there were also some studies that came to the opposite conclusion that the impact of precipitation change on the LPP was much greater than the temperature changes (Ciais et al. 2005).

Due to the objective existence of difference in impact of climate change on different areas, such as traditional agricultural areas, agro-pasture ecotone, and ecological fragile areas, there was an urgent need to analyze the influence of different climatic factors on LPP in different regions for identifying the main factors that restrict the LPP and implementing effective response measures and control strategies for different agricultural types and different agricultural production methods (Manandhar et al. 2011; Zhang et al. 2015; Chun et al. 2016; Touch et al. 2016; Stöckle et al. 2017; Thamo et al. 2017). Therefore, the Shaanxi Province with diverse landforms was selected as the research area to analyze the trend of LPP in different geographical units and identify the main factors influencing the change in LPP by using Global Agro-Ecological Zone (GAEZ) and Geodetector models. The study on the change trends and influencing factors of LPP in different geographical units under the background of climate change not only can directly reflect the coordination and differences between LPP level and light, temperature, and water resources but also can analyze the impact of different climatic factors on LPP in each geographical unit, so as to find the main factor limiting regional food production. There were important theoretical and practical significance for rational use of climate resources, giving full play to crop production potential, and finding ways to improve productivity.

Data and methodology

Study area

Shaanxi Province is located in the northwest of China (105°29′–111°15′ E, 31°42′–39°35′ N) with a total area of about 205,700 km^2. The study area had typical continental monsoon climate that stretched across the North Temperate Zone and Semitropics Zone; the average annual rainfall was 576.9 mm; and the annual average temperature was about 13.0 °C with frost-free period that was about 218 days. Planted crops were mainly maize and wheat in the Shaanxi Province, the two crops accounted for about 80% of total grain production.

According to geomorphology, topography, hydrology, population, and other factors, the Shaanxi Province was divided into six geographical units, from north to south, named Arid Sandy (AS), Loess Plateau (LP), Guanzhong Plain (GP), Qinling Mountain (QM), Hanjiang Basin (HB), and Daba Mountain (DM), respectively. The average elevation of AS, LP, GP, QM, HB, and DM were 1265, 1214, 545, 1297, 582, and 1164 m, respectively (Fig. 1).

Data sources

The data used in this study mainly included climate data, soil data, topographic data, and socioeconomic data (mainly referring to actual grain yield). The National Meteorological Information Centre (http://data.cma.cn/site/index.html) included monthly precipitation, average maximum temperature, average minimum temperature, wind speed, relative humidity, wet day frequency, and solar radiation from 2000 to 2015. The meteorological data was interpolated by using Anusplin interpolation model, which was based on the smooth spline function and took into account the influences of terrain and other factors (Hutchinson 2001). Therefore, the interpolation results were more accurate than those of the general interpolation method. Soil data was obtained from the 1:1 million soil database of the Resources and Environment Data Cloud Platform of the Chinese Academy of Sciences (http://www.resdc.cn/), including soil type, composition, depth, and water-holding capacity, among other properties. Terrain data was derived from the Digital Elevation Model (DEM) provided by the Shuttle Radar Topography Mission (SRTM) system (https://dds.cr.usgs.gov/srtm/). The SRTM-DEM used in the current study has a spatial resolution of 90 m. Socioeconomic data were obtained from the Shaanxi Province Statistical Yearbook (2000–2015). The climate, soil, and DEM data were converted to a grid format with a grid size of 10 km × 10 km.

Global agro-ecological zone model

The global agro-ecological zone (GAEZ) model was used to estimate the LPP; this is a large-scale land productivity model developed jointly by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). It firstly estimates the climatological suitability of a crop based on climatic conditions and then calculates GrPP by using a progressively limiting method (Fischer et al. 2006). For the detailed computation process of GAEZ, please refer to IIASA/FAO (2010).

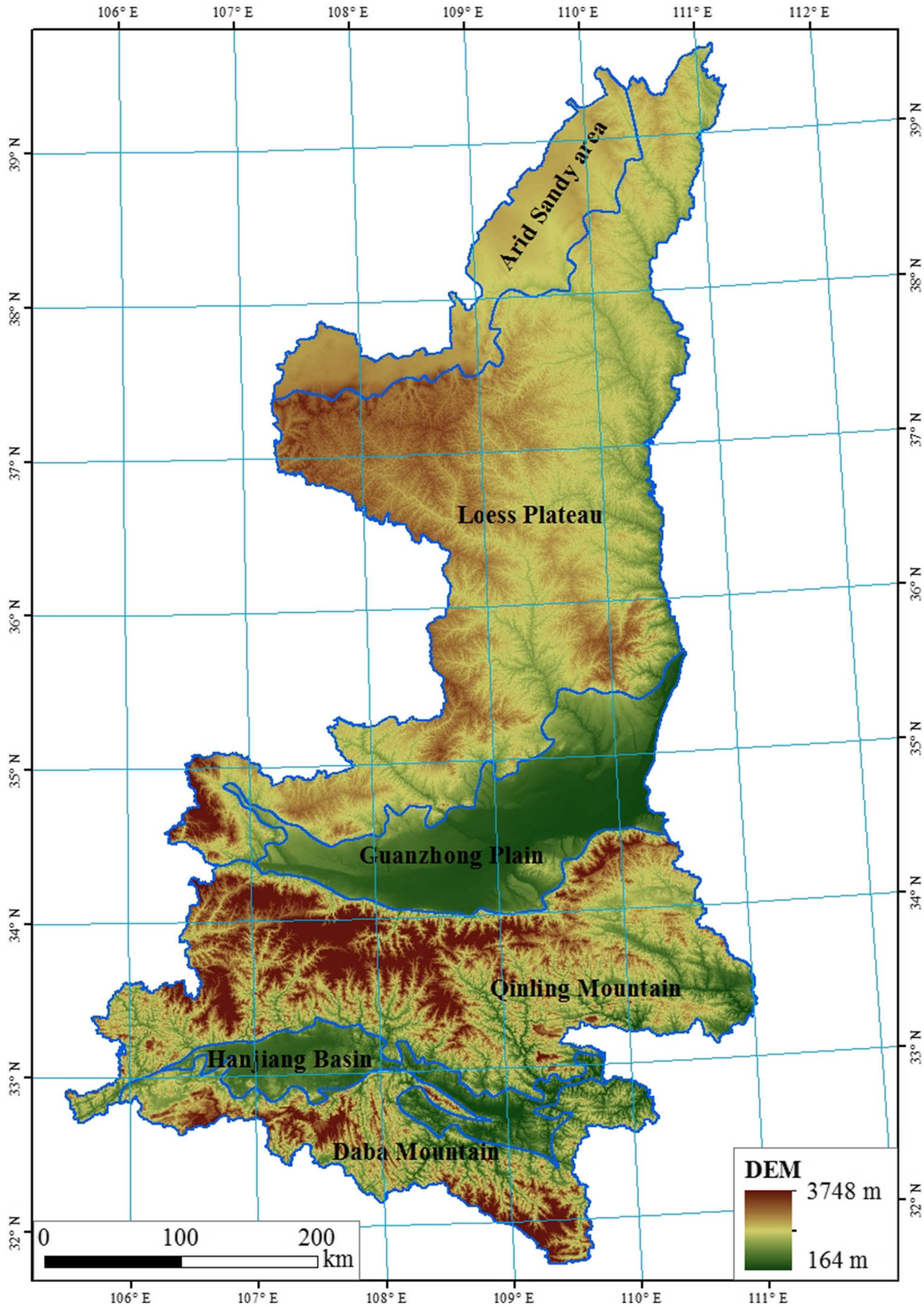

Fig. 1 Study area

Applicability of the GAEZ model in China has been verified extensively with relevant parameters revised (Liu et al. 2015; Xu et al. 2017).

Statistics data on actual grain production showed that the yield of summer maize and winter wheat accounts for > 80% of the total grain production in the Shaanxi Province. Considering that the planting system in the Shaanxi Province is an annual double-crop rotation system (summer maize and winter wheat), land production potentials of summer maize and winter wheat are modeled individually using GAEZ. LPP used in the current study is the sum of land production potential of summer maize and winter wheat. The GAEZ model runs used in the current study modeled LPP under rain-fed conditions.

Geodetector

Geodetector, a tool for detecting and utilizing spatial variability, included differentiation and factor detection, interaction detection, risk area detection, and ecological detection (Wang and Xu 2017).

Differentiation and factor detection The aim of differentiation and factor detection was to detect the spatial dissimilarity of *Y* and how much of a factor *X* explained the spatial differentiation of attribute *Y*, which is measured with *q*.

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2$$

$$SST = N\sigma^2$$

where $h = 1, 2, 3 \ldots$; L was the stratification of the variable Y or factor X; N_h and N were the number of units in layer h and the whole region, respectively; ${\sigma_h}^2$ and σ^2 were the variance of Y value in layer h and the whole region, respectively; SSW and SST were the within sum of squares and total sum of squares, respectively; the value of q was [0, 1], the larger the value of q, the stronger the explanatory power of the independent variable X to the attribute Y.

Interaction detection The aim of interaction detection was to identify the interaction between different factors X_s, that is, assessing whether the interaction of X_1 and X_2 will increase or decrease the explanatory power to the dependent variable Y. The relationship between the two factors could be divided into the following categories (Fig. 2).

Risk area detection The aim of risk area detection was to determine whether there was a significant difference in the mean of the attributes between the two sub-regions.

Ecological detection The aim of ecological detection was to compare whether there was a significant difference in the influence of the two factors, X_1 and X_2, on the spatial distribution of the attribute Y, measured by F statistic,

$$F = \frac{N_{X_1}(N_{X_2}-1)SSW_{X_1}}{N_{X_2}(N_{X_1}-1)SSW_{X_2}}$$

$$SSW_{X_1} = \sum_{h=1}^{L_1} N_h \sigma_h^2$$

$$SSW_{X_2} = \sum_{h=1}^{L_2} N_h \sigma_h^2$$

where N_{X1} and N_{X2} represented the sample quantities of the two factors X_1 and X_2, respectively; SSW_{X1} and SSW_{X2} represented the within sum of squares in the layers formed by X_1 and X_2, respectively; L_1 and L_2 represented the layer number of X_1 and X_2, respectively; zero hypothesis H_0: $SSW_{X1} = SSW_{X2}$; if H_0 was rejected at the significance level of α ($\alpha = 0.05$ in this research), indicating that there was a significant difference in the effect of the two factors X_1 and X_2 on the spatial distribution of the attribute Y. For more details, please refer to the *Geodetector: Principle and prospective* (Wang and Xu 2017).

Results

In order to verify the model simulation results, the correlation between actual yield from the Shaanxi Province Statistical Yearbook (2015) and LPP in 2015 as simulated by GAEZ in each region of Shaanxi Province was analyzed (Fig. 3). The results showed that the two were significantly correlated

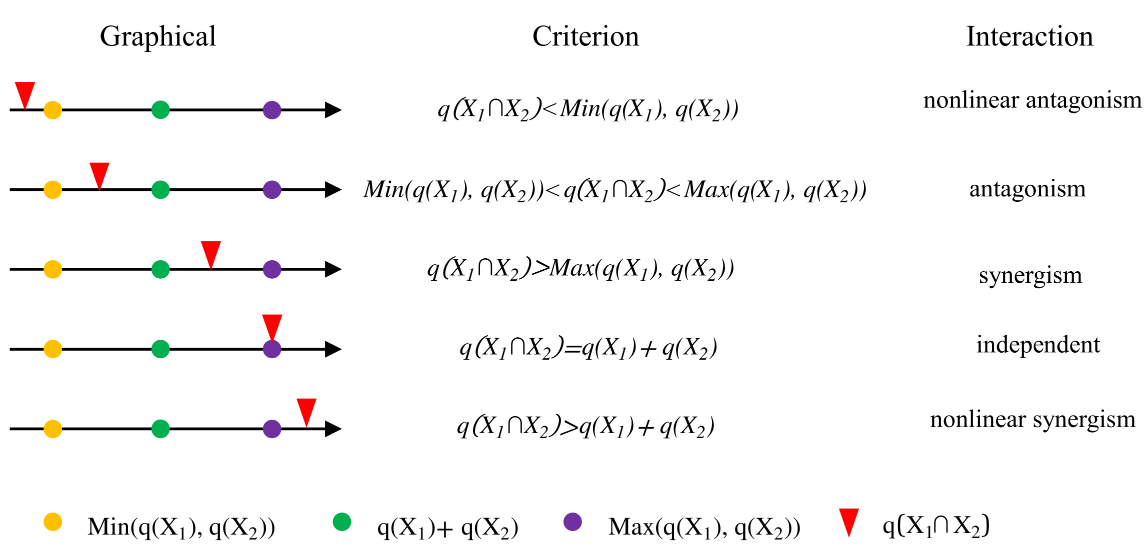

Fig. 2 Types of interaction between two covariates

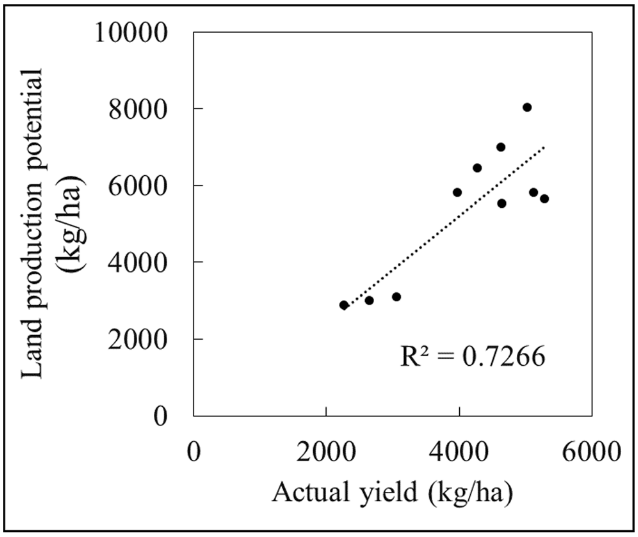

Fig. 3 Correlation analysis between land production potential and actual yield in 2015

($P < 0.01$, $R^2 = 0.7266$). Therefore, the simulation results can be considered to realistically reflect the temporal–spatial changes in LPP with a high degree of credibility.

Climate change in different geographical units

Climate change characteristics in the Shaanxi Province presented as rising temperature, increasing precipitation and radiation, and reducing relative humidity in recent 15 years. Shaanxi is located in the mid-latitude region and the QM, which was the dividing line of China's north–south climate zone that traversed the central and southern Shaanxi; there was obvious climate difference to the north and south of QM. Therefore, the climate of Shaanxi had a unique spatial distribution and changing characteristics.

The temperature in Shaanxi reduced from south to north (Fig. 4a); QM, HB, and DM got a high annual average temperature that ranged from 13 to 16 °C; AS, LP, and GP got a lower temperature that ranged from 8 to 11 °C. The temperature to the north and south of QM both increased, but the temperature increase to the south of QM was greater than that to the north of QM during 2000–2015; it increased by 0.2–0.4 °C to the north of QM, while it rose by about 0.7 °C to the south of QM. However, the interannual variation of temperature to the south of QM was less than that to the north of QM, indicating the temperature to the north of QM was relatively high in some years, while it was relatively low in other years.

Figure 4b showed the spatial distribution characteristics of annual precipitation in Shaanxi, often manifesting as decrease from south to north. The annual precipitation to the south of QM reached 600–1200 mm; however, it was only 300–600 mm to the north of QM, and AS was the geographical unit with least annual precipitation. During 2000–2015, the range of precipitation change reduced from north to south to the north of QM, while it increased from north to south to the south of QM; that is, there was a precipitation increase in AS and LP, and the precipitation reduced in all other geographical units. Especially in DM, the annual precipitation reduced by 241.35 mm since 2000. Moreover, the interannual variability of precipitation to the north of QM was greater than that to the south of QM.

The annual total radiation in Shaanxi also presented as spatial characteristics of increasing from south to north (Fig. 4c). During 2000–2015, the radiation of Shaanxi increased by 254.25 MJ/m^2, especially in AS and GP, which was the two geographical units with greatest increase in annual total radiation (281.06 and 286.86 MJ/m^2); it also got a great increase of 264.53 and 267.12 MJ/m^2 in LP and QM; geographical units to the south of QM had the smallest increase in radiation.

Similarly, there was a trend of increase from north to south in relative humidity. AS and LP had the smallest relative humidity, which was 50–60%; the relative humidity in GP and QM was 60–75%; HB and DM were the geographical units with greatest relative humidity which was higher than 70%. However, the relative humidity reduced in each geographical unit since 2000, because of rising temperature, reducing precipitation, and increasing radiation (Fig. 4d).

LPP change caused by climate change

As a result of climate change, LPP in the Shaanxi Province increased by 1417.78 kg/ha in 2000–2015 and it reached 5002.99 kg/ha in 2015 (Table 1; Fig. 5). However, climate change had a yield-improving effect on AS, LP, and GP, which are located to the north of QM; and it presented a yield-decreasing effect to the south of QM. In addition, the yield-improving effect on the geographical units to the north of QM declined from north to south. AS was the geographical unit with great change in LPP; it was only 597.34 kg/ha in 2000 and increased to 7462.83 kg/ha in 2015. The LPP in LP kept increasing in the past 15 years, with an annual increase of 160.19 kg/ha. There was a trend of increased first and then decreased in LPP in GP, resulting an increase by only 461.37 kg/ha from 2000 to 2015. Interestingly, the LPP in QM, HB, and DM changed similarly, all decreased first and then increased. Besides, the decrease in LPP in these three geographical units decreased from south to north.

GP was the geographical unit with the greatest LPP both in 2000 and 2015 (Table 1). The LPP in AS was the smallest among the six geographical units in 2000; however, the AS became the geographical unit with the greatest LPP only second to GP in 2015. Thus, the geographical unit with smallest LPP was DM where the LPP was only 1293.28 kg/ha in 2015; the rank of LPP of each geographical unit in 2015 can be summarized as GP > AS > HB > LP > QM > DM.

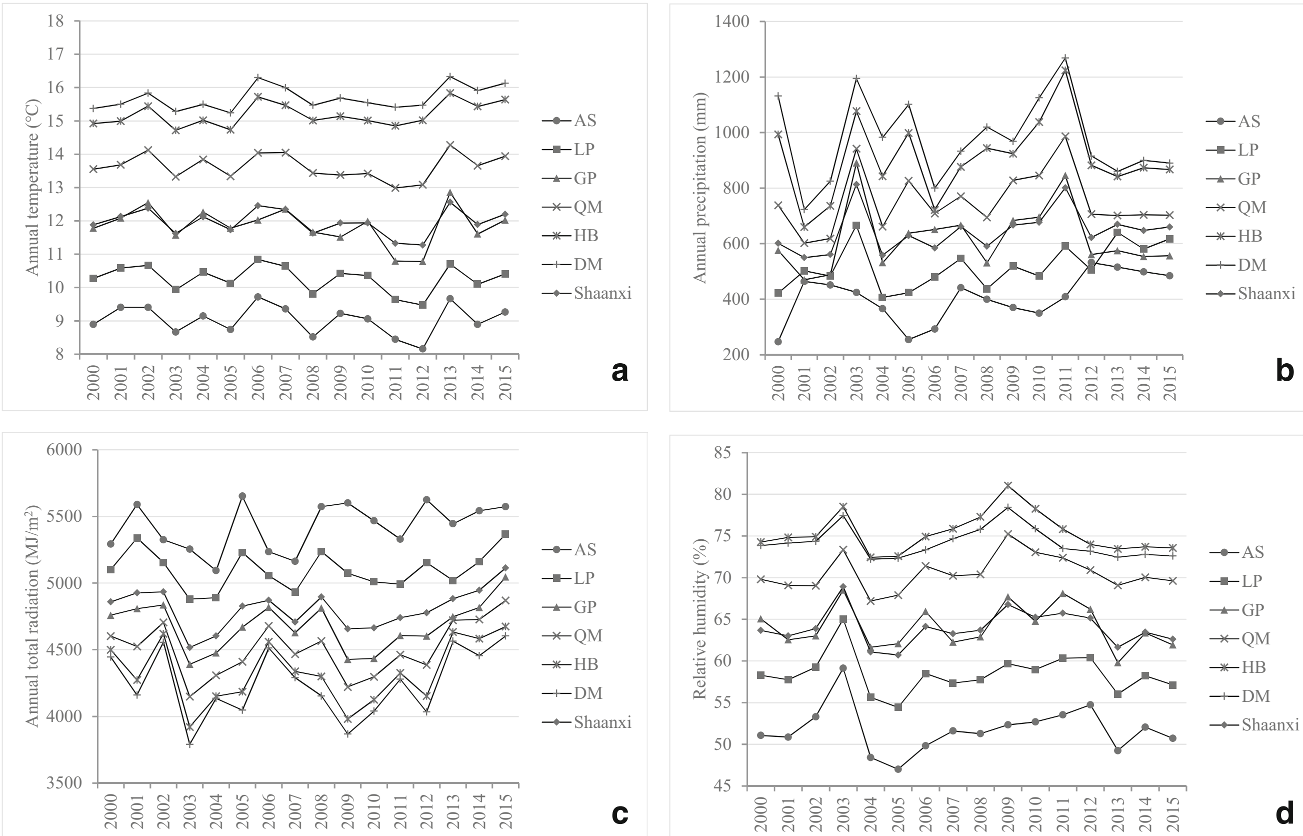

Fig. 4 Temperature (**a**), precipitation (**b**), radiation (**c**), and relative humidity (**d**) change in different geographical units during 2000–2015

Main climatic factors influencing LPP change

Many studies had shown that precipitation (Pre), temperature (Tmp), solar radiation (Rad), and relative humidity (Rhu) were the main climatic factors affecting LPP (Lobell et al. 2011; Constantinidou et al. 2016; Li et al. 2019). Therefore, this study used the geodetector model to analyze the impact of these four climatic factors on changes in LPP. In the Shaanxi Province, the main climatic factor influencing LPP change was Pre, followed by Rad and Tmp. The interactions of Pre and Tmp and Pre and Rad showed a synergism on LPP change, and the latter has a greater impact on LPP change than the former. Other interactions among Pre, Tmp, Rad, and Rhu presented as nonlinear synergism (Fig. 6a).

Arid Sandy area LPP change in AS was most affected by Tmp and Rhu; the q value of these two factors was both 0.92; Pre also was an important factor for the increasing LPP in AS. The interactions between Pre, Tmp, Rad, and Rhu have a synergism effect on LPP change (Fig. 6b). In AS, although Rad's individual impact on LPP was less than the other climatic factors, the synergistic effect of Rad and Rhu on LPP change was greater than the independent action of Tmp, Rad, or Rhu.

Table 1 Changes in land production potential for each geographical unit

Geographical unit	LPP (kg/ha)				LPP change in 2000–2015 (kg/ha)
	2000	2005	2010	2015	
Arid Sandy area	597.34	889.80	4343.87	7462.83	6865.49
Loess Plateau	3542.02	3704.33	5026.53	5944.87	2402.85
Guanzhong Plain	8539.83	10,300.69	11,705.95	9001.20	461.37
Qinling Mountain	2671.25	1981.39	1888.15	2207.74	− 463.51
Hanjiang Basin	6516.50	5515.64	5027.21	6449.97	− 66.53
Daba Mountain	1324.25	948.67	761.26	1293.28	− 30.97
Shaanxi Province	3585.21	3606.80	4494.50	5002.99	1417.78

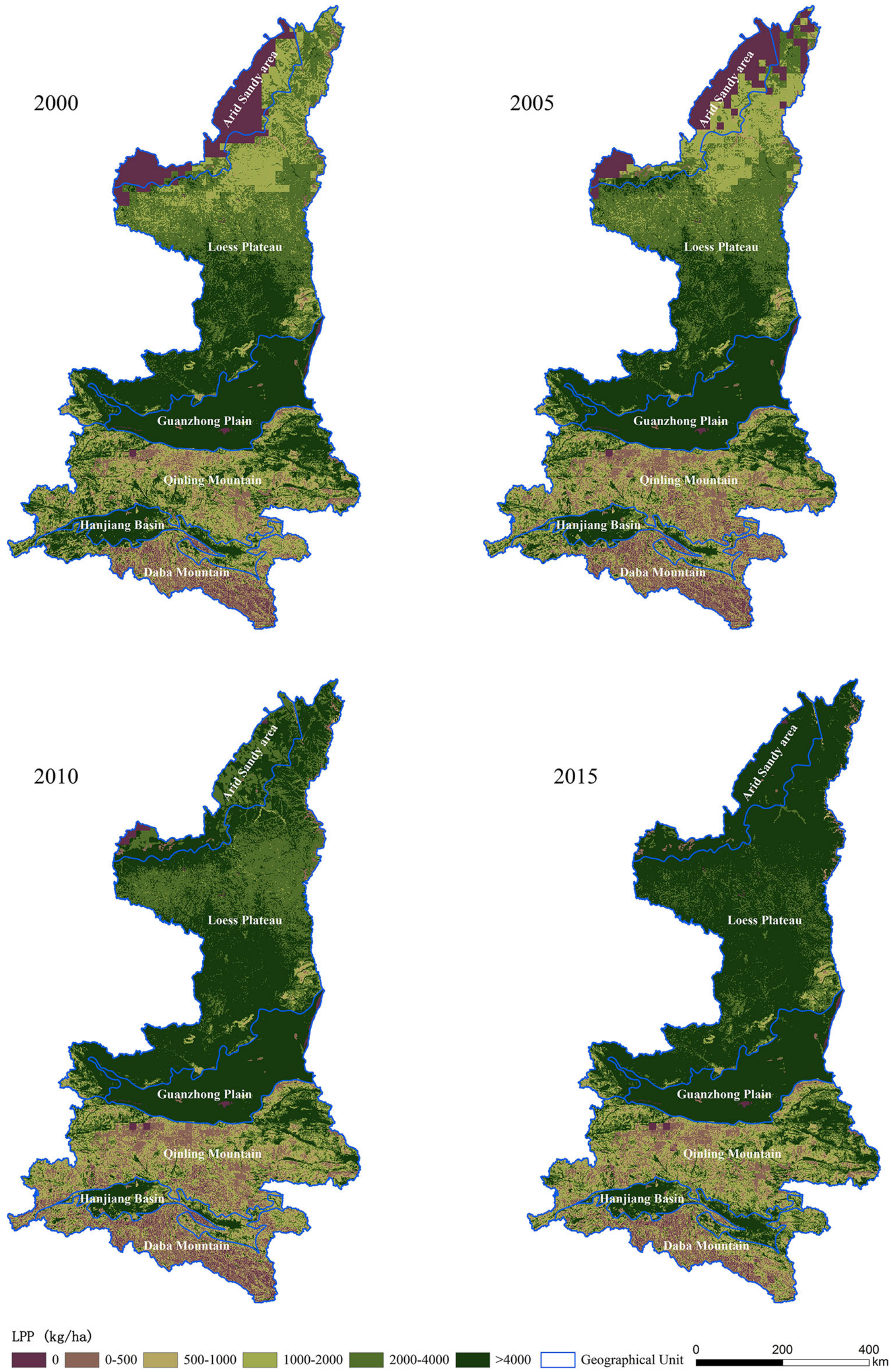

Fig. 5 Land production potential spatial pattern in different times

Loess Plateau From the perspective of single climate elements, LPP increase in LP mostly was caused by increasing precipitation ($q(\text{Pre}) = 0.53$). The value of q(Tmp) was less than that of other climatic factors, indicating that change in Tmp had the least impact on LPP change. From the perspective of the combination of dual climate elements, the interactions between Pre and Tmp were non-linear synergism, indicating the combined action is greater than the sum of independent effect of each factor (Fig. 6c), and the interaction between increasing precipitation and rising temperature was the most important reason for LPP increase in LP.

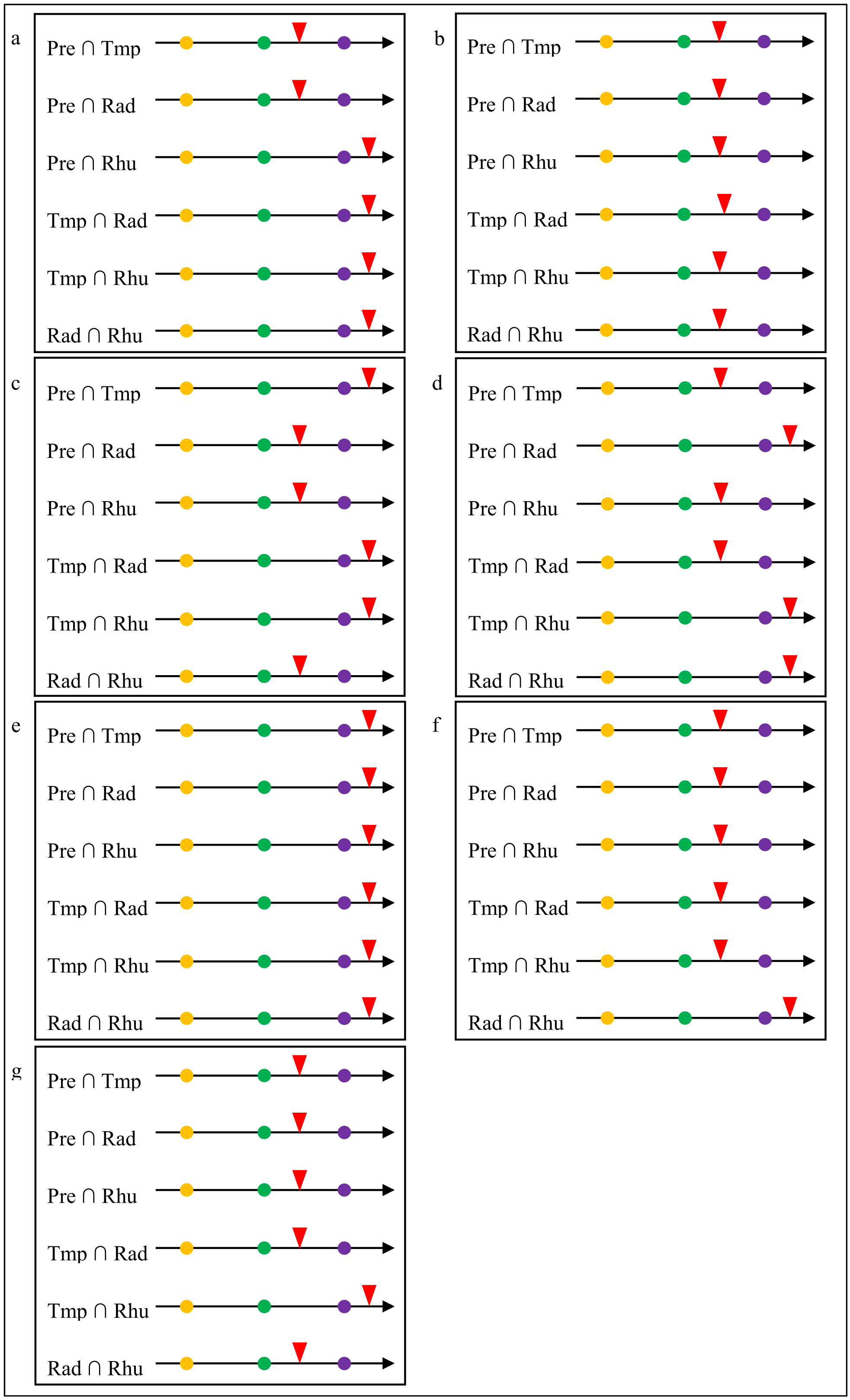

Fig. 6 Climatic factor interaction on land production potential change of Shaanxi (**a**), Arid Sandy area (**b**), Loess Plateau (**c**), Guanzhong Plain (**d**), Qinling Mountain (**e**), Hanjiang Basin (**f**), and Daba Mountain (**g**)

Guanzhong Plain According to the value of q, the rank of each factor influencing LPP change in GP was Tmp (0.33) > Pre (0.32) > Rhu (0.26) > Rad (0.25). This showed that the spatial distribution of LPP change was mostly affected by rising temperature. The impact of Rad on LPP change was the smallest; however, there was a non-linear synergism between Rad and Rhu, and the interaction of Rad and Rhu was the greatest driving force for LPP changes in GP, followed by Tmp ∩ Rhu. Interestingly, GP was the geographical unit with greatest decrease in relative humidity, while, the impact of Rhu on LPP change was different with other factors.

Qinling Mountain Decreasing precipitation had the greatest effect on LPP decrease in QM. With a q(Tmp) value of 0.22, rising temperature also was a main factor affecting LPP change. However, the impact of Rhu on LPP decrease was less than all of the other factors. Dramatically, the interaction between any two factors showed a non-linear synergism on LPP change (Fig. 6e).

Hanjiang Basin Same as QM, LPP decrease was mostly caused by decreasing precipitation in HB, which was the geographical unit with second greatest decrease in precipitation. Although the temperature rise in HB was only less than that of DM, the impact of temperature change on LPP change was much less than that of precipitation change. While the impact of decreasing Rhu on LPP change was the smallest, the impact of interactions between Rhu and Pre on LPP change, however, was greater than any other pairwise interactions. Furthermore, except for the interaction between Rhu and Rad presented as a non-linear synergism, all of other pairwise interaction had a synergism on LPP change (Fig. 6f). At a significant level of 0.05, impacts of Pre on LPP change were significantly different with those of Rad. This is mainly because decreasing precipitation declined LPP; however, increasing annual total radiation had a yield-improving effect.

Daba Mountain Although the Rad increase in DM was less than in any other geographical unit, it was the most important factor for LPP decrease in DM. Precipitation in DM decreased by more than 241 mm, greater than that in any other geographical unit; therefore, Pre also had a great impact on LPP decline. DM was the geographical unit with greatest rise in temperature, but the q value of Tmp was the smallest compared with other factors. In addition, the interaction between Tmp and Rhu presented as a non-linear synergism, which was the only one, and the influence of non-linear synergism of Tmp and Rhu on LPP change was less than the synergism of Pre ∩ Tmp, Pre ∩ Rad, Pre ∩ Rhu, Tmp ∩ Rad, and Rad ∩ Rhu (Fig. 6g). Especially, the synergism between Pre and Rad was the greatest driving force for LPP changes in DM.

Discussion

Climate change had led to a decline in LPP in most countries and regions around the world (Liu et al. 2012; Folberth et al. 2014; Gaál et al. 2014; Uleberg et al. 2014). However, climate change benefited the growth of grain crops in high latitudes and mid-high latitudes and was not conducive to crops in low latitudes; high and mid-high latitudes areas and current cold areas would be more suitable for crop growth due to climate change (Rosenzweig and Parry 1994; Tan and Shibasaki 2003; Tatsumi et al. 2011). LPP change in the Shaanxi Province was another strong proof of this conclusion. The Shaanxi Province stretched from south to north in a long strip shape and ran through eight latitudes, coupled with QM spread across central of Shaanxi, resulting in a quite difference in climate change to the south and north of QM. Spatial difference of climate change caused a great increase in LPP to the north of QM and a sharp decrease in LPP to the south of QM.

Temperature and precipitation were the most important climatic factors influencing LPP change in the Shaanxi Province. Although temperature both rose to the north and south of QM, the direction of its impact on LPP was diametrically opposed. To the north of QM, growth and yield formation of crops were often subject to low temperature and frost damage; therefore, rising temperature had a yield-improving effect. LP was the geographical unit with smallest temperature rise and the q(Tmp) less than any other climatic factors; rising temperature still had great impacts on LPP change when it combined with increasing precipitation. However, rising temperature resulted in the LPP declined to the south of QM. Temperature to the south of QM rose by more than 0.7 °C in the past 15 years, much greater than that to the north of QM. Increase in temperature would accelerate crop growth and shorten the growth period, or let the temperature exceeds the optimal range for crop growth, ultimately reduce crop productivity (Liu et al. 2012; Lobell and Gourdji 2012; Kassie et al. 2014; Li et al. 2019).

Some studies had shown that the increase in precipitation had little effect on LPP and the reduction in precipitation almost always reduced LPP (Lobell and Asner 2003; Ciais et al. 2005; Lobell and Gourdji 2012; Wilcox and Makowski 2014). Whether seen from the single factor role, or from the interaction of two factors, decreasing precipitation was the most important reason for the decline in LPP to the south of QM. The change in precipitation to the north of QM was much greater than that to the south of QM and the temperature change in contrast. However, to the north of QM, the impact of increasing precipitation on LPP was less than that of temperature change except in LP. Even so, the increasing precipitation also was an important climatic factor influencing LPP improving to the north of QM.

For the objective existence of regional differences in climate change and dominated climatic factor limiting LPP, urgent work is needed to strengthen capacity building to adapt to climate change and make full use of the benefits of climate change. To the north of QM, corresponding agricultural activities should be adjusted based on the characteristics of agroclimatic resource change to ensure the normal growth of crops. Artificially creating a local production environment according to the main climatic factors limiting the LPP would effectively enhance the regional grain production capacity to the south of QM.

In this study, the effects of precipitation, temperature, solar radiation, and relative humidity on LPP were analyzed based on geo-detectors; however, the specific values of LPP increase or decrease caused by changes in different climatic factors were not given. There were many climatic factors affecting LPP, and other climatic factors, such as wind speed and carbon dioxide concentration, were not considered in this study. In addition, the volatility of climate change would lead to uncertainty in LPP in a single year, and the results may be biased. These problems will be gradually solved in our future research.

Conclusion

Climate change was a global concern and had profoundly affected global agricultural production. The impact of climate change however had obvious regional differences, and whether climate change was increasing or reducing the grain production in a given region was uncertain. Therefore, the six geographical units of the Shaanxi Province were selected as research areas, and the climate change characteristics of different geographical units and their impact on LPP were analyzed. It can be summarized that the climate change and its effect on LPP change had differences between the south and north of QM. The rise in temperature to the north of QM was less than that to the south of QM; however, rising temperature had a yield-improving effect to the north of QM and reduced LPP to the south of QM. Annual precipitation was increased to the north of QM and declined to the south of QM. As a consequence of climate change, LPP of Shaanxi Province increased by 1417.78 kg/ha, mainly caused by increasing precipitation. LPP to the north of QM dramatically increased because of rising temperature and increasing precipitation; specifically, rising temperature was the most important climatic factor for LPP increase in AS and GP; LPP in LP mainly improved by increasing precipitation. To the south of QM, precipitation decline was the dominated climatic factor reducing LPP in QM, HB, and DM.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest regarding the publication of this paper.

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