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Effects of Climate Change on the Climatic Production Potential of Potatoes in Inner Mongolia, China

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Abstract: Understanding the impacts of regional climate change on crop production will benefit strategic decisions for future agricultural adaptation in China. In this study, the climatic production potential of potato over the past 61 years in Inner Mongolia was simulated based on long-term observed data and the step-by-step correction method. The results show that the annual average potential for potato climatic production in Inner Mongolia is 19,318 kg·hm^{-2}, fluctuating between the highest value (25,623 kg·hm^{-2}) and the lowest value (15,354 kg·hm^{-2}). Over the past 61 years, the climatic production potential exhibited an insignificant decreasing trend, with large interannual fluctuation, especially since 2000. The high-value areas of the climatic production potential were mainly located in the central and southern regions. The climatic production potential of potato in most areas showed a decreasing trend. The influence of radiation changes on the potato climatic production potential was not obvious in most areas. The effects of temperature changes on the climatic production potential of potato were mostly negative, and were most obvious in the central and western regions and in the southeastern region. The change in precipitation in most parts of western Inner Mongolia, Hohhot, Chifeng and eastern Xingan League had a positive effect on the climatic production potential of potato. However, the change in precipitation in southern Ulanchabu, eastern Chifeng, Hulunbuir and western and eastern regions had a negative effect on the climatic production potential of potato. The main limiting factor for the climatic production potential of potato in Inner Mongolia is precipitation. Our findings have important implications for local potato production to cope with ongoing climate change in China.

Keywords: climate change; potato climatic productivity potential; Inner Mongolia; effect

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1. Introduction

Under global warming, extreme weather occurs frequently, and meteorological disasters bring more and more risks to agricultural production. Food is an important commodity related to the national economy and people's livelihood. It is the basis of economic development, social stability and national independence. Ensuring national food security is always the top priority in governing a country. The Intergovernmental Panel on Climate Change (IPCC) officially released on 28 February the contribution of Working Group II to the Sixth Assessment Report (Ar6) on climate change in 2022, highlighting impacts, adaptation and vulnerability. The report further points out the severe food security situation faced at home and abroad against the background of global warming. Food security has once again received extensive attention all over the world. In order to cope with meteorological disasters, it is a challenge to understand the impact mechanisms of climate change on staple crops, and to adapt to and cope with the negative impact of climate change. Potato is one of the main climatic characteristic crops in Inner Mongolia, China. Therefore, it is urgent to acquire a more in-depth understanding of how climate change affects potato production for agricultural disaster prevention and mitigation and the healthy development of the potato industry in Inner Mongolia, China.

The climatic production potential of crops refers to the crop yields when light, heat and water resources are optimally matched under ideal conditions [1], and it is one of the important criteria for evaluating agroclimatic resources [2]. The responses of the climatic production potential of crops to climate change differ significantly among regions and crops [3–5]. At present, the commonly used models for calculating the crop production potential include the Miami model [6,7], the Thornthwaite Memory model [8,9], the AEZ model by FAO [10,11] and the step-by-step revision model [12–14]. Among these models, the step-by-step correction model is a statistical model for calculating the climatic production potential of different crops during the growing season. It can effectively reflect the matching status of climatic resources such as light, heat, and water. Its physical meaning and the causal relationships are clear. The step-by-step correction model is one of the most extensively used research methods for analyzing the food production potential [15,16].

The impacts of climate change on the climatic production potential of crops over the past few decades in China have attracted serious concern [14,17–21]. Based on the potential attenuation method, Wang et al. [14] studied the spatial variation in climatic production potential of maize, rice and soybean in the Songnen Plain, and analyzed the utilization efficiency of natural resources. Lu et al. [17] evaluated the evolution of climatic production potential in Anhui Province in the past 50 years. Wang studied and analyzed the climatic production potential of one-season rice in Anhui Province [18]. Wang et al. [19] studied the climatic production potential of winter wheat in northern China and the influence of separated water. Duan et al. [20] estimated the climatic production potential of potato in Jixi County, Ningxia, and analyzed its stability. Lai simulated the climatic production potential of five crops in Ningxia, including soybean, corn, rice, wheat and potato [21]. However, few studies have been conducted to quantitatively assess the long-term impacts of regional climate change on the climatic production potential of potato in Inner Mongolia based on the step-by-step correction model. A better understanding of how potato responds to regional climate change is essential for mitigating the negative effects of potato production to local climate change.

The objectives of the present study were to (1) determine the main parameters in a climatic production potential model for potato based on long-term historical data in Inner Mongolia and (2) explore the advantages and disadvantages of impacts of changes in main meteorological factors (light, temperature and water) on potato production in Inner Mongolia. These findings are significant for substantially improving our understanding of the impacts of regional climate change on agriculture in China.

2. Materials and Methods

2.1. Study Area

The Inner Mongolia Autonomous Region is one of 13 key grain-producing provinces (regions) in China. As of 2017, the region has 9.271 million hectares of cultivated land, accounting for 7.8% of the region's area, and the per capita cultivated land area is 3.7 times that of the whole country. The effective irrigation area is 3.175 million hectares. The soil in this area shows obvious meridional differentiation. Black soil, dark brown soil, chernozem, chestnut soil, brown calcium soil, brown desert soil and gray desert soil are distributed from east to west [22]. In some areas, cinnamon soil, calcareous soil, meadow soil and aeolian sandy soil are distributed. The content of soil organic matter (9.75~0.56%) [22] and clay particles (12.41~3.65%) [23] decreases gradually from east to west, while the soil pH value (7.39~8.90) increases gradually from east to west [23]. The soil is mostly neutral and alkaline [23,24]. Inner Mongolia covers a vast territory, with large east–west and north–south spans, complex landforms (e.g., plateaus, mountains, hills and plains) and special geographical locations, which form complex and diverse climate conditions dominated by a temperate continental monsoon climate, with varied temperature, rainfall and heat waves. In the same season, the cold climate is more suitable for the growth of potatoes, which prefer cold and cool conditions.

2.2. Data

The data are from the climate center of the Inner Mongolia Autonomous Region. The data used consist of the daily surface meteorological observation data, including sunshine hours, average temperature, precipitation, relative humidity, average wind speed and evapotranspiration. These meteorological data were obtained from 119 meteorological stations in the Inner Mongolia Autonomous Region from 1961 to 2021 (Figure 1). The long-term field observation datasets of potato were collected from 11 agricultural meteorological data stations of the Inner Mongolia Autonomous Region from 1981 to 2020 (Figure 1). The administrative boundaries of Inner Mongolia and the cities (alliances) that are involved in this article are based on the standard map with the approval number of Mongolia S (2019) 33, from the Map Institute of the Inner Mongolia Autonomous Region.

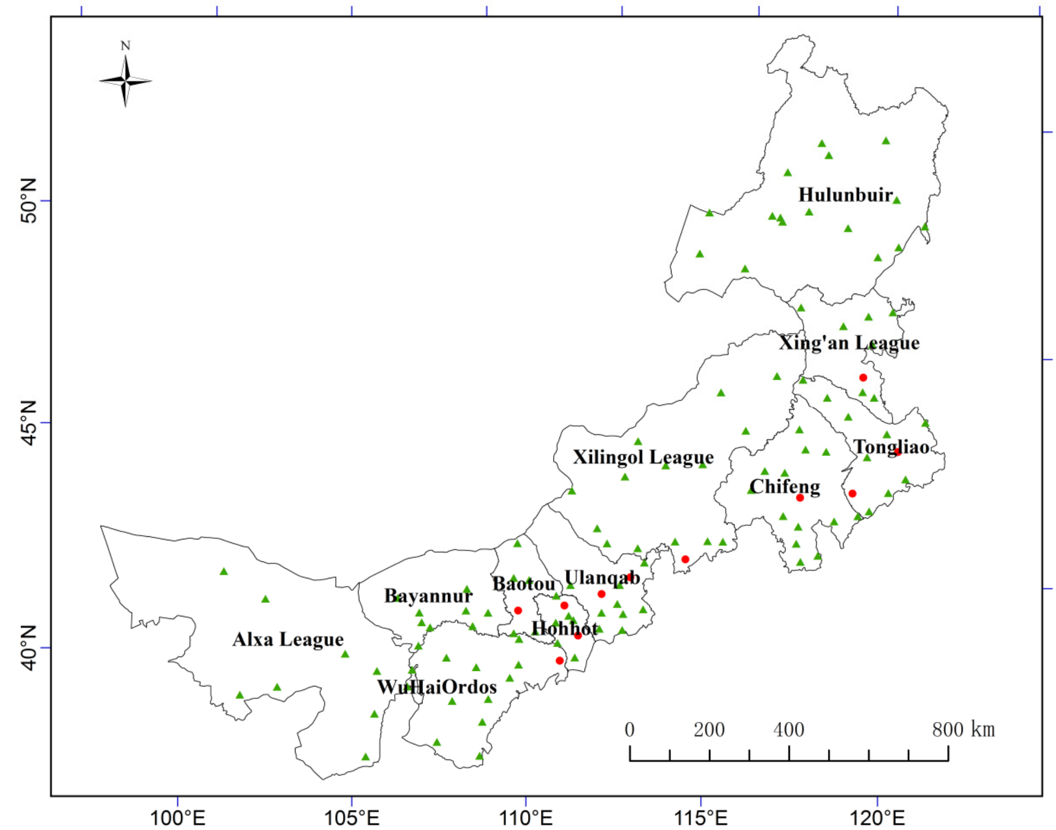

Figure 1. Distribution of 119 meteorological stations (green triangles) and 11 agrometeorological observation stations (red dots) in the Inner Mongolia Autonomous Region of China.

2.3. Research Methods

2.3.1. Calculation of the Climatic Production Potential

The step-by-step correction method was used, starting from crop photosynthesis, according to the process of crop energy conversion and yield formation, and gradually estimating the agricultural climatic production potential. It is a model that was developed from the step-by-step revision of the climatic factor function based on the photosynthetic production potential. The calculation formula is as follows [25]:

$$Y_{\mathrm{CPP}} = Y_{\mathrm{PPP}} \times f(T_{ij}) \times f(R_{ij}) = Y_{\mathrm{TPP}} \times f(R_{ij}) \tag{1}$$

where Y_{CPP}, Y_{PPP} and Y_{TPP} are the climatic production potential, photosynthetic production potential and light–temperature production potential (kg·hm^{-2}), respectively; $f(T_{ij})$ is the effective temperature coefficient of the ith growth period in the jth year; and $f(R_{ij})$ is the effective water coefficient of the ith growth period in the jth year.

(1) Photosynthetic production potential of potato

The photosynthetic production potential of potato refers to the potato yields that are uniquely determined by the local solar radiation under the assumption that the most suitable temperature, water, soil fertility, crop population and agricultural technical measures are provided. It is the theoretical upper limit of potato yield. The photosynthetic production potential model of potato adopts the state of energy utilization and loss during yield formation, takes the total solar radiation value of potato in each growth period as the basic data, and corrects it. The calculation formula is as follows [18,19]:

$$Y_{\mathrm{PPP}} = Cf(Q) \tag{2}$$

$$f(Q) = \Omega\varepsilon\varphi(1-\alpha)(1-\beta)(1-\rho)(1-\gamma)(1-\omega)(1-\eta)^{-1}(1-\xi)sq^{-1}f(L)\sum Q_i \tag{3}$$

where C is the unit conversion factor, which is 10,000; $\sum Q_i$ is the total radiation during the growing season (MJ·m^{-2}); i represents the different growth periods; Ω is the ratio of the photosynthetic ability of crops to fix CO_2, which is 0.6; ε is the ratio of photosynthetic radiation to total radiation, which is taken as 0.47; φ is the quantum efficiency of photosynthesis, which is taken as 0.224; α is the crop population reflectivity, which is taken as 0.17; β is the leakage rate of solar radiation by the crop population, which is taken as 0.1; ρ is the ineffective absorption rate of non-photosynthetic organs, which is 0.1; γ is the light saturation limitation rate, which is 0.01; ω is the respiration loss rate, which is 0.3; η is the moisture content of mature grains, which is 0.14; ξ is the proportion of crop inorganic ash content, which is taken as 0.08; s is the crop economic coefficient, which is taken as 0.75; q is the heat required to form one unit of dry matter (MJ·kg^{-1}), which is taken as 18; and $f(L)$ is the corrected value of the dynamic change in leaf area, which is taken as 0.556.

(2) Light–temperature production potential of potato

Based on the photosynthetic production potential of potato, by considering the effect of temperature on plant photosynthesis and correcting the temperature coefficient, the light–temperature production potential of potato, determined by the two factors of light and temperature, can be obtained. The calculation formula is as follows [18]:

$$Y_{\mathrm{TPP}} = Y_{\mathrm{PPP}} f(T_{ij}) \tag{4}$$

$$f(T_{ij}) = \begin{cases} \dfrac{(T_{ij}-T_1)\times(T_2-T_{ij})^b}{(T_0-T_1)\times(T_2-T_0)^b} & T_1 < T < T_2 \\ 0 & T \le T_1 \text{ or } T \ge T_2 \end{cases} \tag{5}$$

$$b = \frac{T_2 - T_0}{T_0 - T_1} \tag{6}$$

where $f(T_{ij})$ is the temperature correction function of the ith growth period in the jth year; T_{ij} is the average temperature of the ith growth period in the jth year (°C); and T_1, T_2 and T_0 are the lower and the upper limits of temperature and the optimum temperature of crop growth in each growth period (°C), respectively (Table 1) [25–27].

Table 1. Three cardinal temperature points in each potato growth period (°C).

Growth Period	T_1	T_2	T_0
Sowing–emergence	5.0	29.0	14.0
Emergence–branch	9.0	32.0	18.3
Branch–inflorescence	10.0	30.0	19.5
Inflorescence–bloom	10.0	30.0	19.3
Flowering–harvestable	10.0	29.0	18.0
Full reproductive period	5.0	32.0	17.8

(3) climatic production potential of potato

The climatic production potential is the upper limit of production that can be achieved under the combined influence of radiation, temperature and precipitation. After the light–temperature production potential is corrected by the moisture correction function, the climatic production potential can be obtained, and its expression is as follows [18]:

$$Y_{\text{CPP}} = Y_{\text{TPP}} f(R_{ij}) \tag{7}$$

$$f(R_{ij}) = \begin{cases} R_{ij}/R_{i0} & R_{ij} < R_{i0} \\ 1 & R_{i0} \geq R_{ij} \end{cases} \tag{8}$$

where $f(R_{ij})$ is the water correction function of the ith growth period of the jth year, R_{ij} is the precipitation during the ith growth period of the jth year (mm) and R_{i0} is the physiological water demand during the ith growth period (mm). The water requirement of potatoes in the entire growth period is approximately 372.5 mm; the physiological water requirements in the sowing–seedling, seedling–branching, branching–inflorescence, inflorescence–flowering and flowering–returnable stages are 50 mm, 40 mm, 30 mm, 52.5 mm and 200 mm, respectively.

2.3.2. Impacts of Climate Change on the Climatic Production Potential of Potato

The climatic production potential of potato reflects the comprehensive impact of various meteorological factors on potato production. The photosynthetic production potential directly corresponds to the impact of light, the light–temperature production potential corresponds to the comprehensive impact of light and heat, and the climatic production potential corresponds to the comprehensive impact of the three factors of light, heat and water. The effects of light, heat, water and the comprehensive climatic conditions on the potato production potential are expressed as Y_{r}, Y_{t}, Y_{p} and Y_{c} ($\text{kg}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$), respectively. The calculation method is as follows [25,28]:

$$Y_{\text{r}} = (a_{\text{r}}/Y_1) \times Y_3 \tag{9}$$

$$Y_{\text{t}} = (a_{\text{t}}/Y_2 - a_{\text{r}}/Y_1) \times Y_3 \tag{10}$$

$$Y_{\text{t}} = (a_{\text{t}}/Y_2 - a_{\text{r}}/Y_1) \times Y_3 \tag{11}$$

$$Y_{\text{c}} = a_{\text{c}} \tag{12}$$

where a_{r}, a_{t} and a_{c} are the propensity rates of photosynthesis, light–temperature and the climatic production potential with time (year) ($\text{kg}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$), respectively; Y_1, Y_2 and Y_3 are the multiyear averages of photosynthesis, light–temperature and the climatic production potential ($\text{kg}\cdot\text{hm}^{-2}$), respectively.

3. Results

3.1. Annual and Interdecadal Variations in the Production Potential of Potato

It can be seen from the change in the abnormal percentage of potato climatic production potential in Inner Mongolia (Figure 2) that before 2000, the abnormal percentage of potato climatic production potential in Inner Mongolia was mainly positive, and after

2000, it was mainly negative. Over the past 61 years, the climatic production potential of potato during the growth period in most of the central and western parts of Inner Mongolia and the southeast parts has shown a decreasing trend, with a decreasing range of 10~164 kg·hm^{-2}·a^{-1}; the decrease is in the areas that are above 40 kg·hm^{-2}·a^{-1} and are mainly located in most of Bayannaoer city, the southwest and northern parts of Ordos city, the southern part of Baotou city, the central part of Hohhot city, the southwest and eastern parts of Ulanqab city, west of Xilin Gol League, east of Chifeng city, most of Tongliao city, south of Xing'an League and west and southeast of Hulunbuir city. The central part of Hulunbuir city, north of Xing'an League, northeast of Xilingol League, west of Chifeng city, north parts of Baotou city, the south part of Ordos city, the northwest part of Bayannaoer city and southeast of Alxa League experienced increasing trends, with increases of 10~40 kg·hm^{-2}·a^{-1}. The increase areas greater than 20 kg·hm^{-2}·a^{-1} were mainly located in the central and northern parts of Hulunbuir city, the north part of Xing'an League, the western part of Chifeng city and the northeastern part of Xilingol League. The change trends of the climatic production potential of potato during the growth period were not obvious in other areas (Figure 3). On the whole, the climatic production potential of potato during the growth period of Inner Mongolia mainly exhibits a decreasing trend, and the increases in temperature, radiation and precipitation during the growth period are not conducive to improving the climatic production potential.

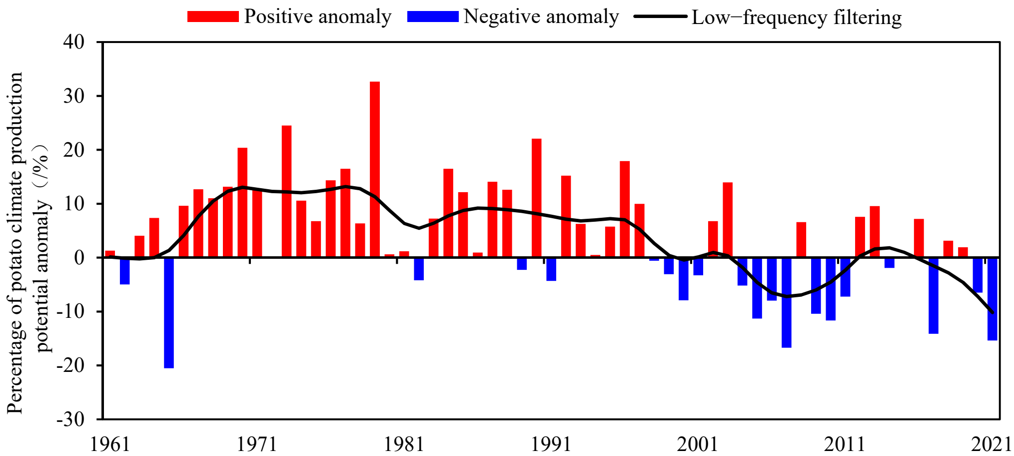

Figure 2. The anomaly (low–frequency filtering) changes in the potato potential productivity in Inner Mongolia, China, from 1961 to 2021.

Figure 4 shows the interannual and interdecadal variations in the potato production potential at all levels in Inner Mongolia. Figure 4a shows that over the past 61 years, the interannual fluctuations in the production potential of potatoes at all levels in Inner Mongolia have been relatively large, and the overall trend has decreased significantly ($p < 0.005$). The potential and climatic production potentials decreased at rates of 574 kg·hm^{-2}·(10 a)$^{-1}$, 1048 kg·hm^{-2}·(10 a)$^{-1}$ and 465 kg·hm^{-2}·(10 a)$^{-1}$. The photosynthetic production potential and light–temperature production potential were relatively close, with averages of 42,417 kg·hm^{-2} and 36,244 kg·hm^{-2} in the whole area, respectively, and the average climatic production potential was 19,318 kg·hm^{-2}, which is significantly lower than the production potential of the first two levels. The highest value of the photosynthetic production potential occurred in 1965 (45,952 kg·hm^{-2}). The highest value of the light–temperature production potential occurred in 1977 (41,001 kg·hm^{-2}). The highest value of the climatic production potential occurred in 1979 (25,623 kg·hm^{-2}). The lowest values of photosynthetic production potential, light–temperature production potential and climatic production potential occurred in 2021 (34,045 kg·hm^{-2}), 2021 (29,553 kg·hm^{-2}) and 1965 (15,354 kg·hm^{-2}), respectively.

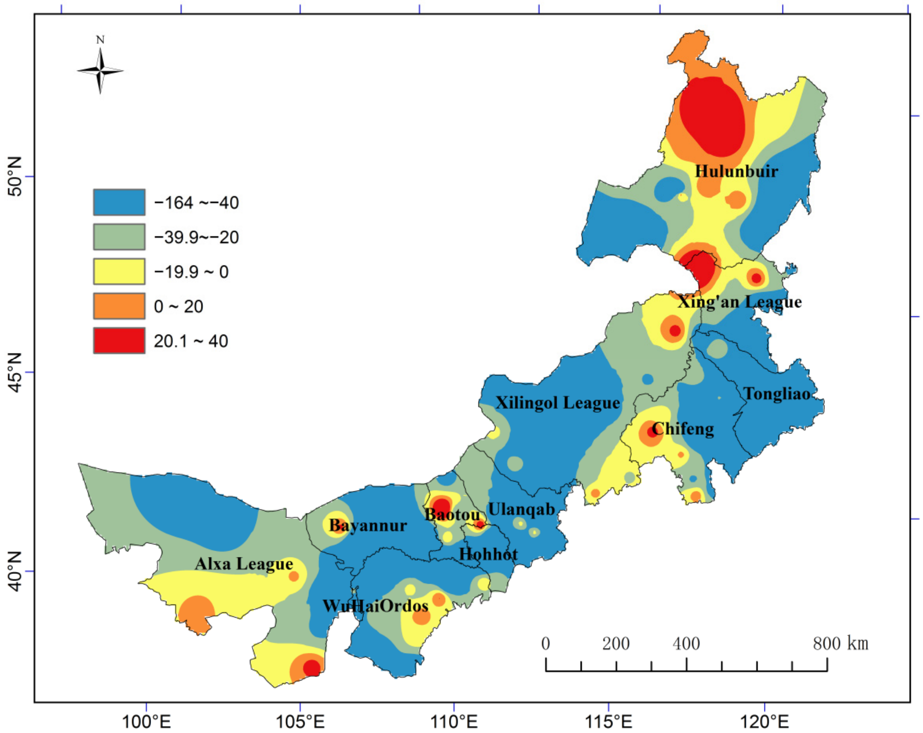

Figure 3. Change trends of climatic production potential of potato in Inner Mongolia, China (kg·hm^{-2}·a^{-1}).

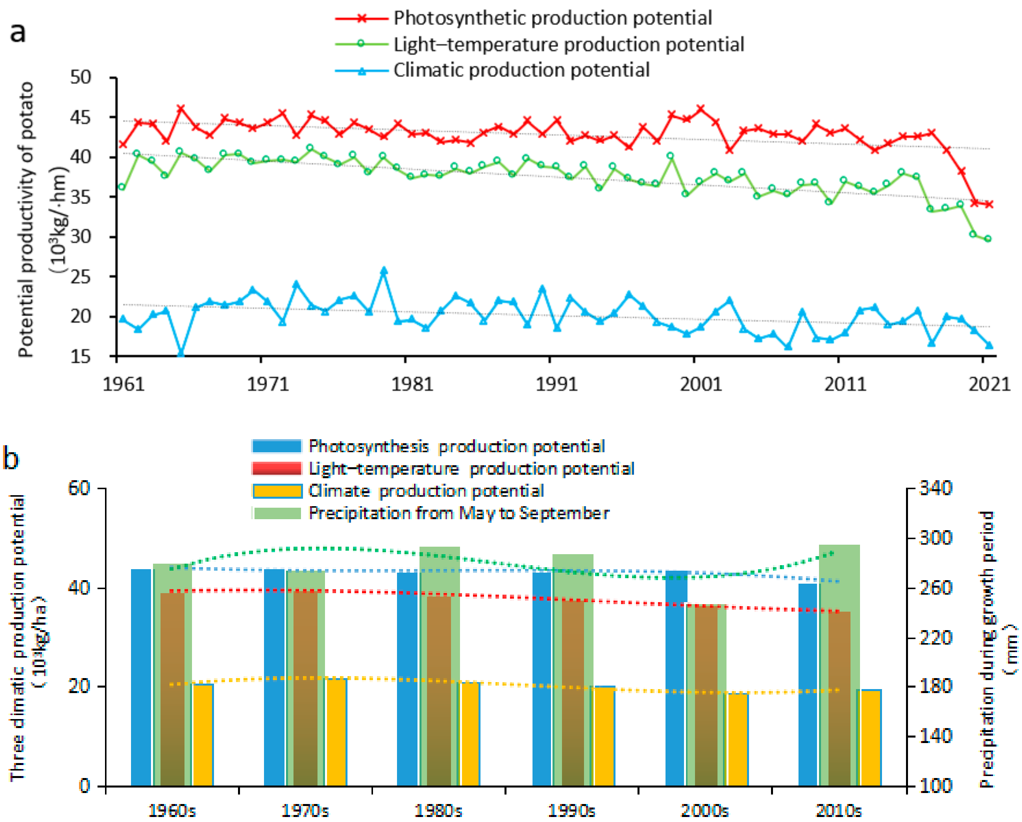

Figure 4. The annual (**a**) and decadal (**b**) changes in the potential productivity of potato of each grade in Inner Mongolia, China, from 1961 to 2021 (The red column in Figure (**b**) is brown because it overlaps with the green column.).

Judging from the interdecadal changes shown in Figure 4b, the changing trends of the production potentials at all levels are not consistent. Among them, the characteristics of the interdecadal variations in photosynthesis and the light–temperature production potential are consistent, being the largest in the 1970s and smallest in the 2010s, while the climatic production potential were the largest in the 1970s and smallest in the 2000s. The climatic production potential exhibited greater fluctuations than the previous two levels, and its variation trend had a significant positive correlation with the interdecadal variations in precipitation ($p < 0.01$), which indicated that the main limiting factor for the potato climatic production potential in Inner Mongolia was precipitation.

3.2. Characteristics of the Spatial Distribution of the Potato Production Potential

The climatic production potential of potato in Inner Mongolia decreased from the central and southern parts to the periphery, and the climatic production potential in the central and western regions had an obvious geographical distribution. The central and eastern part of Ulanqab city, the southern part of Xilin Gol League, the western part of Chifeng city and the central part of Hulunbuir city were more consistent with the dominant potato-producing areas. Among them, the highest value of the potato climatic production potential was in the Zhenglan Banner of Xilin Gol League, with the value of 27,641 kg·hm^{-2}. The second-highest value (17,601~22,600 kg·hm^{-2}) was located the eastern part of Ordos city and most of Baotou city, most of Hohhot, northern Ulanqab, central and northern Xilin Gol League and most of its eastern areas. The lowest value was located in Ejina Banner of Alxa League, being only 2594 kg·hm^{-2} (Figure 5). High temperatures and low rainfall amounts are the probable reasons for the lowest potentials of potato climatic production.

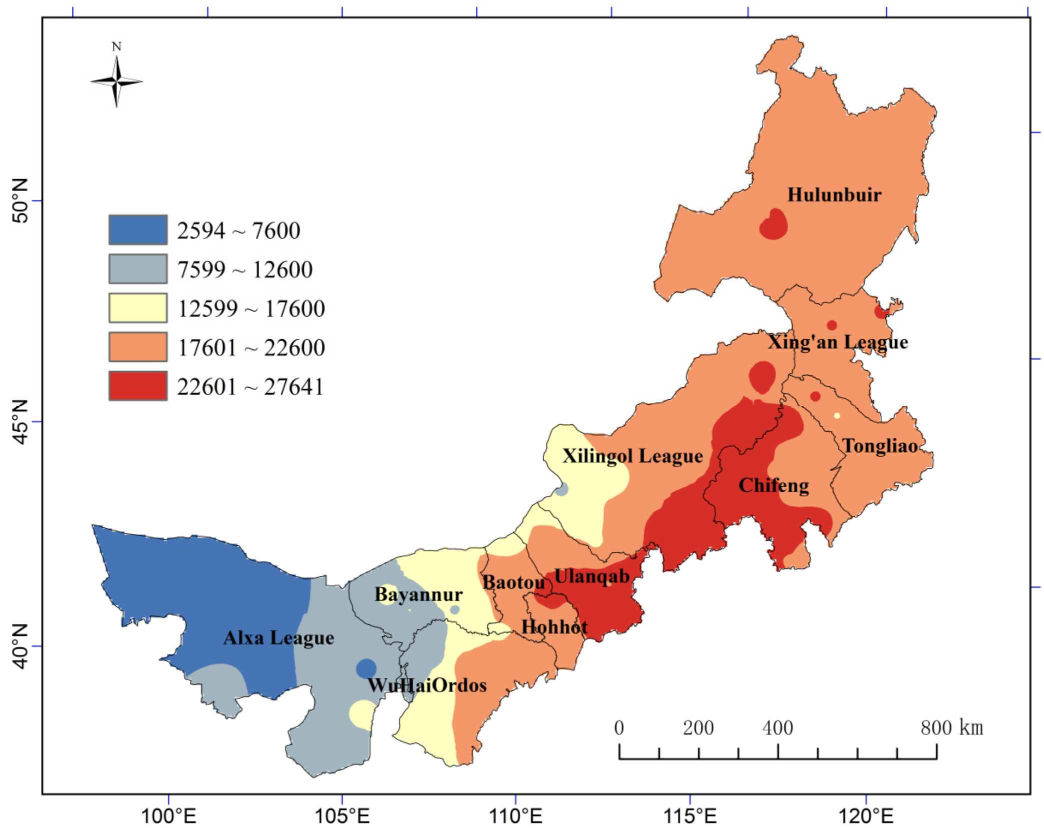

Figure 5. The spatial distribution of the climatic production potential of potatoes in Inner Mongolia, China (kg·hm^{-2}).

The annual meteorological yields and climatic production potentials of potato over the past 57 years in Wuchuan County of Hohhot city were relatively consistent, with a very significant positive correlation (0.5131 at 0.1% significance). These potato climatic production potentials are based on the results of the step-by-step revision correction method, and can better reflect the changing trends of the potato meteorological yields (Figure 6). The average annual potato yield in Wuchuan County was about 2163 kg·hm^{-2}, with 5.4% of the maximum climatic production potential and 14.2% of the minimum climatic production potential. The average application level of the potato climatic production potential in Wuchuan County was only 7.6%.

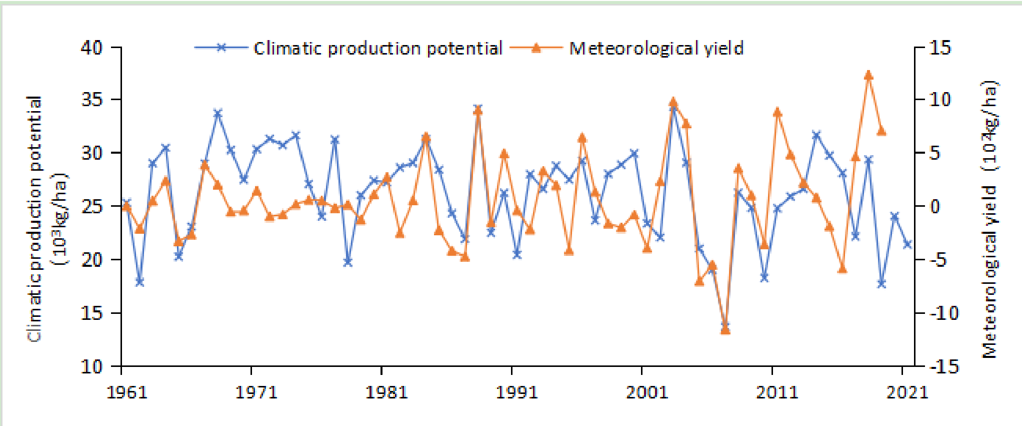

Figure 6. The relationship between the climatic production potentials and meteorological yields of potato in Wuchuan, Inner Mongolia, China, from 1961 to 2020.

3.3. Influence of Changes in the Main Meteorological Elements on the Potato Climate Production Potential

3.3.1. The Effect of Radiation Changes on the Potato Climatic Production Potential

Over the past 58 years, the total solar radiation in Inner Mongolia has fluctuated and decreased at a rate of 39.3 MJ·m^{-2} (10 a)$^{-1}$ ($p > 0.05$) [29]; this decreasing trend was obvious in some areas ($p < 0.05$). Over the past 61 years, the number of sunshine hours during the potato growth period in Inner Mongolia fluctuated at a rate of 18.1 h·(10 a)$^{-1}$ ($p < 0.001$) (Figure 7). Potato is a light-loving crop, and reductions in radiation and light are detrimental to its growth. Figure 8 shows that the influences of radiation changes on the climatic production potential of potato during the growth period in most of Inner Mongolia had negative effects, indicating that radiation reductions were not conducive to improving the climatic production potential of potato during the growth period. The areas experiencing negative effects are mainly distributed in the central and northeastern parts of Ordos city, southern part of Baotou city, most of Hohhot city, central and eastern parts of Ulanqab city, central and southern parts of Xilingol League, southeastern part of Chifeng city, most of Tongliao city, the southeastern part of Xing'an League, and the southeastern part of Hulunbuir city. Ulanqab city, the Chayouhou Banner in Lanchabu city and the Arong Banner in Hulunbuir city experienced the greatest impacts. The areas experiencing positive effects were relatively rare and were mainly distributed in the southwest and east parts of Xilingol League, the south part of Chifeng city and the central and eastern, central and northern Xing'an League and northwestern Hulunbuir city. However, the above-mentioned radiation changes in most of the regions had little effects on the climatic production potential of potato during the growth period, and the values were mostly between −20 MJ·m^{-2}·a^{-1} and 20 MJ·m^{-2}·a^{-1}.

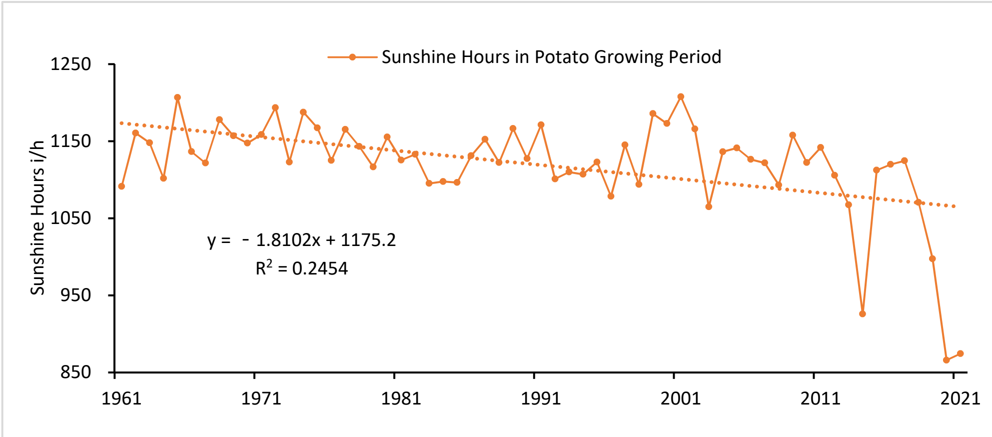

Figure 7. Changes in sunshine hours during the potato growing period in Inner Mongolia, China (h).

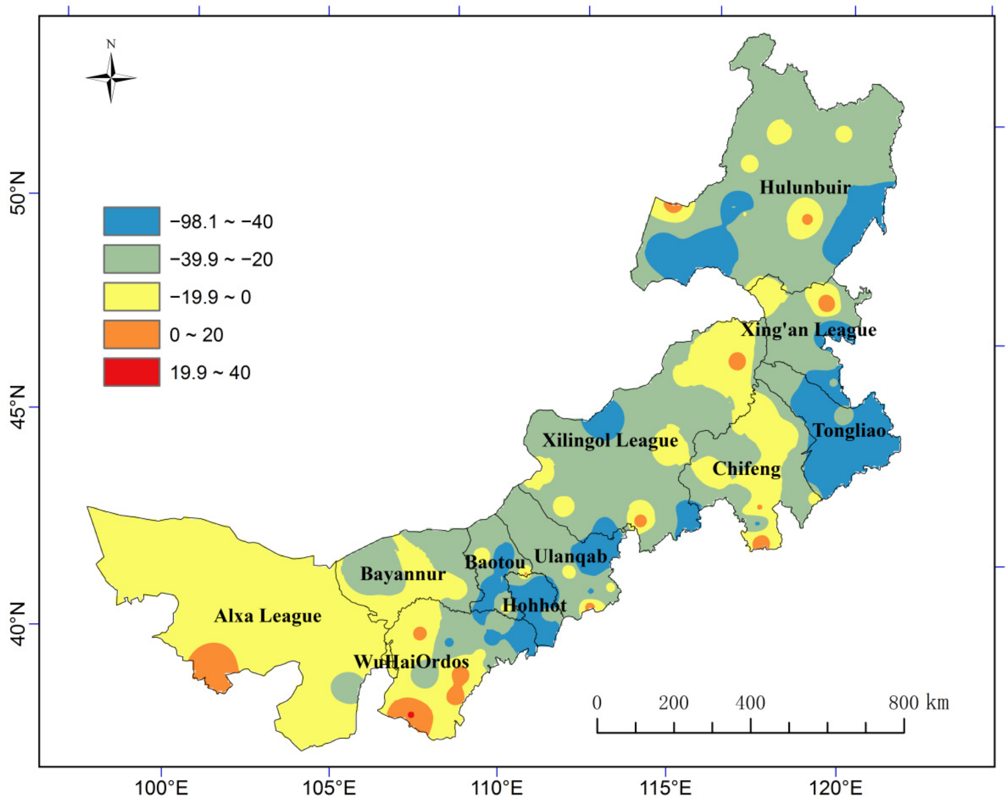

Figure 8. Impacts of radiation changes on the climatic production potential of potato in Inner Mongolia, China (kg·hm^{-2}·a^{-1}).

3.3.2. Effects of Temperature Changes on the Potato Climatic Production Potential

Over the past 61 years, the average temperatures during the potato growing season in Inner Mongolia have exhibited a significant upward trend as a whole ($p < 0.001$), with a climatic trend rate of 0.3 °C·(10 a)$^{-1}$. The temperatures increased significantly in most areas (94% of meteorological stations ($p < 0.01$) (Figure 9). Potato is a crop that prefers cool and cool conditions, and increased temperatures are not conducive to the growth and development of potato. Figure 10 shows that the impacts of the temperature changes on the potato climatic production potential were mostly negative, indicating that the temperature increases during the potato growth period in Inner Mongolia were not conducive to improving the climatic production potential. Negative effects were seen in the central and western parts of Inner Mongolia and in the southeast, while the negative effects were most obvious in the Northwest Territories, which were −102~−20 kg·hm^{-2}·a^{-1}. The greatest negative effects were found in Bayannaoer city, the north and southwest parts of Ordos city, the southwest part of Baotou city, and the central and western parts of Hohhot city. The positive effects were concentrated only in the central and northern parts of Hulunbuir city and the northwestern part of Xing'an League, with an impact range of 20~40 kg·hm^{-2}·a^{-1}; the influence range in the central and northern parts of Hulunbuir city was greater than 30 kg·hm^{-2}·a^{-1}.

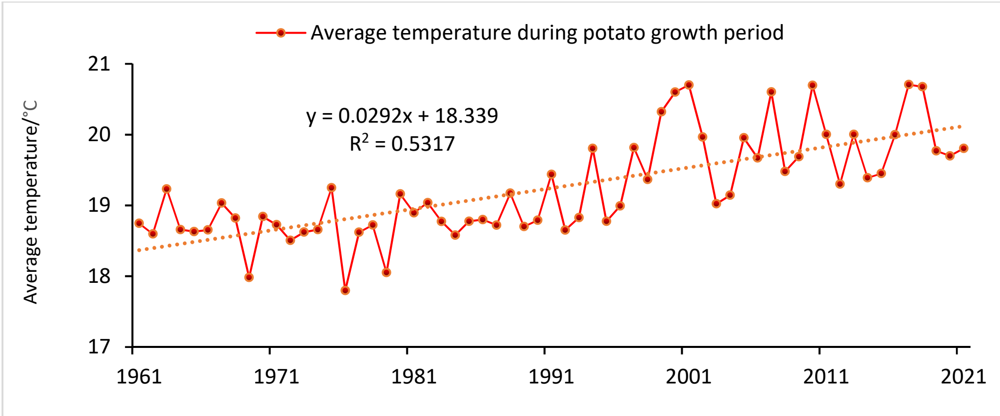

Figure 9. Variations in average temperature during the potato growth period in Inner Mongolia, China (°C).

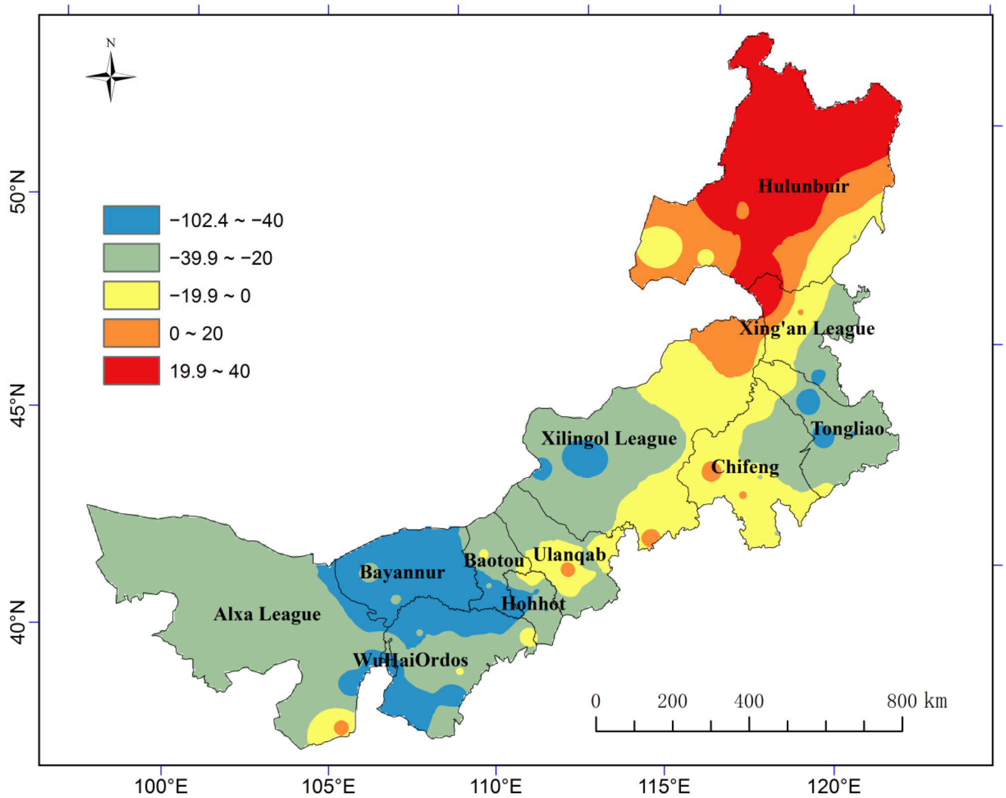

Figure 10. Impacts of temperature changes on the climatic production potential of potato in Inner Mongolia, China (kg·hm^{-2}·a^{-1}).

3.3.3. The Impact of Precipitation Changes on the Climatic Production Potential

Over the past 61 years, the precipitation levels during the potato growing season in Inner Mongolia has decreased at a rate of 0.7 mm·(10a)$^{-1}$ ($p > 0.1$), and the change trend was not significant in most areas (Figure 11). Figure 12 showed that most of western Inner

Mongolia, Hohhot, western Chifeng and eastern Xing'an League experienced positive effects on the climatic production potential of potato during the growth period of the precipitation changes, with an impact range of 20~40 kg·hm^{-2}·a^{-1}, in which the positive effects in the central and eastern parts of Ordos city and most of Baotou city were large and were greater than 30 kg·hm^{-2}·a^{-1}. The central and eastern regions experienced mostly negative effects, with an impact range of −102~ −20 kg·hm^{-2}·a^{-1}; the southeast part of Chifeng city, the southwest part of Tongliao city and the northwest part of Hulunbuir city experienced greater negative impacts, which were less than −50 kg·hm^{-2}·a^{-1}.It is worth mentioning that the change in precipitation in most areas of Wulanchabu city, which is the main potato-producing area in Inner Mongolia, had a negative impact on potato climatic production potential.

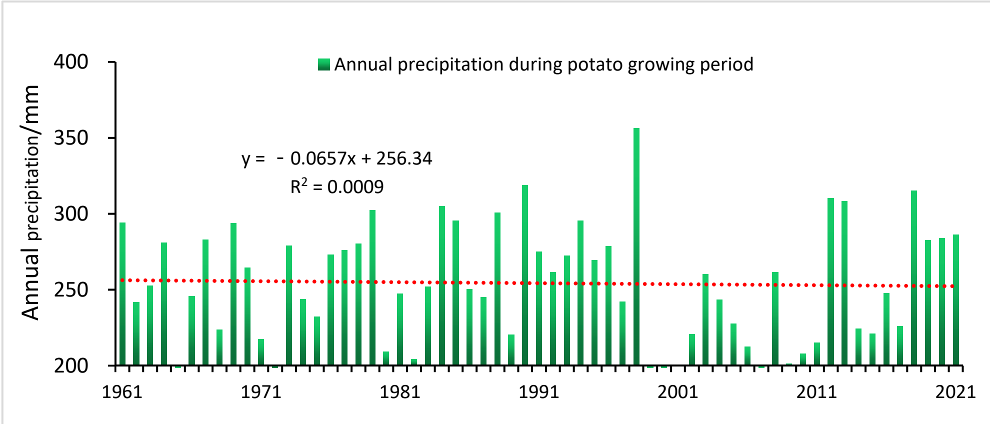

Figure 11. Variations in annual precipitation during the potato growth period in Inner Mongolia, China (mm).

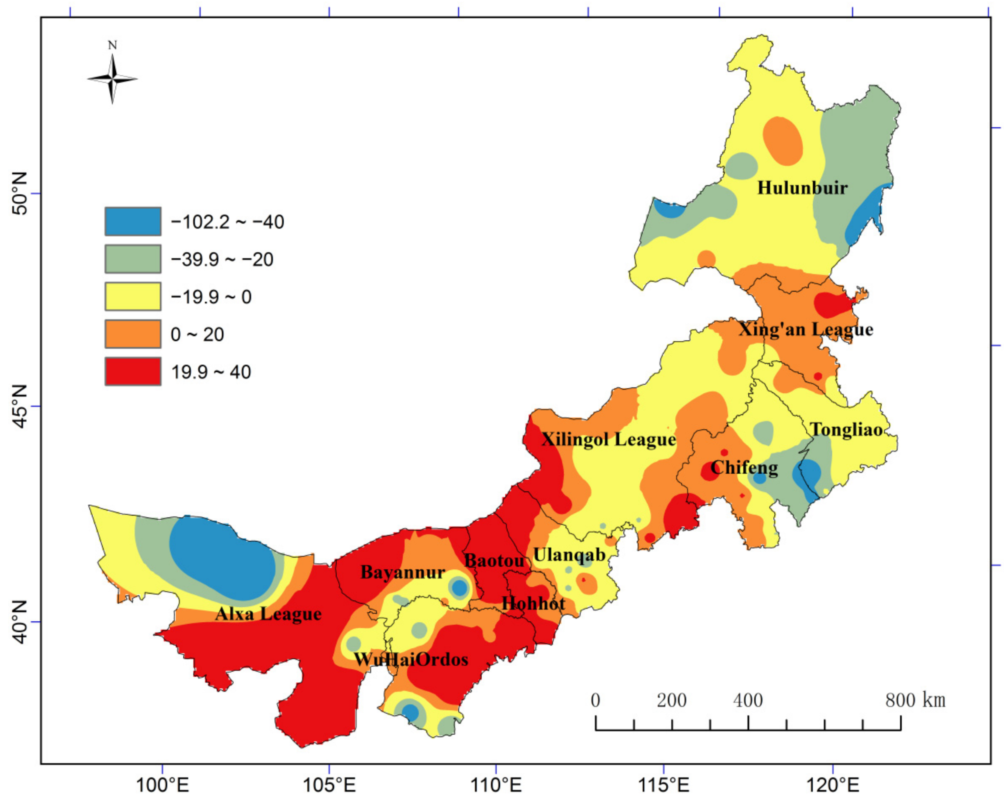

Figure 12. Impact of precipitation changes on the climatic production potential of potato in Inner Mongolia, China (kg·hm^{-2}·a^{-1}).

4. Discussion

Light, temperature and water are important drivers of climatic production potential [30,31]. Analyzing the impact of climate factors on potato climatic production potential will help people take better measures to adapt to climate change, so as to ensure the high-quality development of the potato industry. In general, the impact of climate change on potato climatic production potential in Inner Mongolia has both advantages and disadvantages, but the disadvantages outweigh the advantages. In particular, in Wulanchabu city, the main potato-producing area in the Inner Mongolia Autonomous Region, the impact of climate change on potato climatic production potential is relatively adverse. Compared with the average value of potato climatic production potential in Shanxi Province (13,428 kg$\cdot$hm^{-2}), the average value of potato climatic production potential in Inner Mongolia (19,318 kg$\cdot$hm^{-2}) in this study was higher. Although the average precipitation during the growing period in Shanxi Province is slightly higher than that in Inner Mongolia, the high average temperature leads to a lower climatic production potential of potato in Shanxi Province than that in Inner Mongolia. The impact of light, temperature and water changes on potato climatic production potential in Shanxi Province is also more negative; particularly, the impact of radiation and temperature changes in most areas is negative, similar to the impact of climate change on the potato climatic production potential in Inner Mongolia. The impact of precipitation change on the potato climatic production potential in Shanxi Province is positive in the north and negative in the south [28,32]. However, we found that the distribution of impacts of precipitation change on potato production potential in Inner Mongolia was more complex, spanning the main southern agricultural areas from southwest to northeast as follows: positive effect—negative effect—positive effect—negative effect—positive effect—negative effect. The average application level of the potato climatic production potential in Wuchuan County was only 7.6%, lower than the application level of the potato climatic production potential in Jixi County of Ningxia [20]. This shows that the potato yield in Wuchuan County is bound to have room for improvement. We need to pursue advantages, avoid disadvantages and make effective use of climate factors.

In order to adapt to the current climate change trend and its adverse impacts, it is necessary to vigorously promote water-saving irrigation technology and biofilm technology in agricultural areas to improve water use efficiency. In particular, most of the central and western parts of Inner Mongolia are mainly rain-fed agriculture. In Ordos, Baotou, Hohhot and other central and western regions, it is necessary to adjust the sowing date of potatoes so that the yield can occur in the critical period to avoid high temperatures and obtain high yield. The potato production in the eastern agricultural area needs to improve field management in order to improve the utilization rate of light energy and obtain high yield.

In this study, the step-by-step correction method was adopted, and the physical meaning of the model was clear. However, there are still shortcomings that need to be resolved. Because of the incompleteness and discontinuity of the data, we used the data of the average growth period of potato from agrometeorological observation stations for many years. In general, studying only the main variety of local potato, i.e., the mid-late maturing variety, without considering the early maturing variety of potato will lead to differences in climatic resources during the growing period of potato, resulting in certain differences in the calculation results of potato climatic production potential. In Inner Mongolia, water condition was the main limiting factor of potato climatic production potential. This is consistent with the previous study on various crops which found that the same precipitation was far greater than the crop water demand, or even impacted the potato climatic production potential in case of flood disaster, so there were inevitably some omissions in the calculation results [33]. The parameter determination in the step-by-step correction method was empirical, and only reflected the overall variety characteristics of current crops. With the continuous development of breeding and cultivation techniques, the parameters of better varieties might be different in the future, which is likely to lead to changes in the calculation results of potato climatic production potential [8,33]. As the precipitation in local agricultural areas was relatively low [20,34,35], the adverse impact from calculating the water correction coefficient was not considered in this study. In addition, the climatic production potential of potato was the maximum yield under ideal conditions. The actual yield of potato is affected by many factors, such as climate, soil, social economy and so on. Therefore, in the future, multiple methods can be used for comprehensive analysis to conduct in-depth comparative research on climatic production potential and actual yield, so as to explore the differences and responses between the two [35–37].

5. Conclusions

We investigated the effects of climate change on the climatic production potential of potatoes since 1961 in Inner Mongolia using the step-by-step correction method. From 1961 to 2021, the average climatic production potential of potato in Inner Mongolia decreased from the central south to the surrounding areas. Under the direct influence of local climatic factors, the average climatic production potential of potato showed a downward trend year by year, especially after 2000. The changes in three climatic factors, light, temperature and water, had different effects on the climatic production potential of potato. The impact of radiation change on the climatic production potential of potato was mainly negative, especially in the main potato-producing area of Wulanchabu. Temperature change had both advantages and disadvantages. In the cold climate region of Northeast China, the temperature change had a favorable impact on the climatic production potential of potato. Other areas were mainly adversely affected, and most areas of Ulanqab city were adversely affected by temperature changes. The change in rainfall had a favorable impact on the climatic production potential of potato west of Hohhot and in the southern and central area of Xilin Gol League. However, the change in rainfall had a negative impact on the climatic production potential of potato in most other areas.

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