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Impacts of Recent Climate Change on Potato Yields at a Provincial Scale in Northwest China

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Abstract: Understanding the effects of climate change on potato yield is vital for food security in northwest China. Based on the long-term data of yields and meteorology, this study analysed the impacts of recent climate change on potato yields at a provincial scale in northwest China. The first difference method was used to disentangle the contributions of climate change from the changes in potato yield in two consecutive years. The moving average method was used to decouple the climate-induced yield of potato. The results showed that the yield and planting area of potato from the period 1982 to 2015 increased markedly, with inter-annual fluctuations. The temperature increased significantly during the potato growing period in northwest China, while other climatic factors did not change significantly. Specifically, the changing trends in climatic factors varied among different provinces. The key meteorological factors limiting potato yield were temperature, precipitation and diurnal temperature range, varying in the different provinces. Potato yields in Gansu, Shaanxi, Ningxia and Xinjiang decreased by 127, 289, 199 and 339 kg ha⁻¹, respectively, for every 1 °C increase in daily maximum temperature. The potato yield in Xinjiang decreased by 583 kg ha⁻¹ for every 1 °C increase in daily minimum temperature. For every 100 mm increase in precipitation, the potato yields in Gansu, Qinghai and Ningxia increased by 250, 375 and 182 kg ha⁻¹, respectively. Combining the first difference method and the moving average method, precipitation was the dominant climatic factor affecting potato yield in rain-fed areas (Gansu, Qinghai and Ningxia). For areas with irrigation (Xinjiang) or relatively high rainfall (Shaanxi), maximum temperature was the deciding climatic factor affecting potato yield. Appropriate adaptation to climate change in the different regions will help to ensure potato production in northwest China.

Keywords: long-term data; climatic factor; first difference method; moving average; climate–yield relationship

1. Introduction

As one of the most serious environmental problems facing humans to date, global climate change has attracted substantial attention [1]. The 2014 Intergovernmental Panel on Climate Change (IPCC) report notes that global warming has been accelerating since 1951, with the average global temperature rising by 0.12 °C per decade [2]. Climate change has significant impacts on open agro-ecosystems, especially on agricultural production, crop growth and yield formation in ecologically fragile areas, such as arid and semi-arid lands [3–5]. Understanding the impact of climate change on crop yields is required to ensure global food security [6].

The potato (*Solanum tuberosum* L.) is the world's fourth largest edible crop after wheat, rice and maize [7,8]. As the world's largest potato producer, China produced 94.9 million tons of potatoes in 2015, accounting for approximately 25.2% of the world's potato production [8]. Potatoes

are more tolerant to drought and barren conditions, but less tolerant to high temperature and humidity conditions; therefore, potatoes are suitable for growing in warm or cold climates [9]. The temperature difference between day and night in northwest China is very large, and the distribution of rainfall and heat is synchronous with the growing and expanding stages of the potato tuber, which is very suitable for potato growth. Northwest China, most of which is arid and semi-arid land, is a major potato producing area in China. In 2015, the planting area and total yield of potatoes in this region accounted for 22.6% and 20.5% of the whole country, respectively [10]. However, this region is ecologically fragile, and agricultural production is vulnerable to climate change [11]. Since 1960, northwest China has experienced significant climate change, the annual average temperature has significantly increased, and precipitation has fluctuated greatly between years, which have aggravated the degree of drought in some parts of the region [12,13]. Therefore, studying the effects of climate change on potato yields is of great significance for improving and stabilizing the potato production in the region.

Two methods can be used to explore the effects of climate change on crop yields: crop models and statistical analyses [14]. Crop models simulate crop growth and development and predict crop yields using meteorological, soil, field management, and cultivar parameters, among others [15,16]. Crop models can simulate the growth stages of crops and quantify the physiological and ecological processes [17,18]. However, crop models require many parameters, and uncertainty in the parameters often leads to uncertainty in the simulation results [19]. Another common method is to use historical data for statistical analyses to study climate–yield relationships [20]. Unlike crop models, statistical analysis methods do not require calibration and validation of parameters. Moreover, the reliability of a climate–yield regression equation can be judged directly by a statistical test [21]. However, the statistical analysis method also has some shortcomings: statistical models are often unable to consider all the factors that cause changes in yields, and the corollary of the statistical model is not sufficiently robust [14].

The impacts of climate change on potato in northwest China in recent decades have attracted concerns. Xiao et al. [22] analysed the impact of climate change on potato water use efficiency (WUE) in the semiarid area of Guyuan in China, using temperature rise and precipitation simulation testing. They found that when temperature increased by $> 1.5\text{ }^{\circ}\text{C}$ and precipitation was $< 310.0\text{ mm}$, the potato WUE tended to decline. Xiao et al. [23] investigated the effects of climate change on the WUE of potato in the northwest semiarid region by statistically analyzing yield, soil moisture, rainfall and temperature data in the last 50 years. The results showed that, due to climate warming and to a drop in rainfall in the last 50 years, the WUE of potato significantly increased. Wang et al. [9] showed that postponing sowing time is a good practice for potato production to adapt to climate warming in Dingxi on the Loess Plateau. Zhang et al. [21] indicated that a marked warming–drying trend significantly decreased potato yield in Wuchuan from the period 1980 to 2009. In addition, structural adjustment of the cropping system (e.g., a shift from wheat to potato as the predominant crop) and planting date adaptation (e.g., a delay in crop planting date) can offset the impact of the warming–drying trend. However, these studies of statistical analyses or field experiments conducted in a single site were often limited to local conditions and could not evaluate the climate–yield relationship in macro-scale areas. Understanding the effects of climate change on potato yield is essential to improve the ability to adapt to climate change in the future.

The objectives of our study are to: (1) analyse the trends in climatic factors during the potato growing period in northwest China; (2) decouple the contributions of climate change to potato yield in the last three decades; (3) identify the key climatic factors affecting potato yields; and (4) examine the relationships between climatic factors and potato yield at a provincial scale.

2. Materials and Methods

2.1. Study Area

Northwest China is located between latitudes 31° and 48° N and longitudes 73° and 111° E with an area of $310.7 \times 10^4 \text{ km}^2$, accounting for 32.8% of China's land area. Northwest China consists of five provinces: Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang (Figure 1). This region is located in the centre of Eurasia. The climate is a typical arid and semi-arid continental climate, which is characterized by low and irregular precipitation and higher evaporation. The annual average air temperature is from -2 to $14 \text{ }^\circ\text{C}$, the annual average precipitation is 50–800 mm, gradually decreasing from the southeast to the northwest, and the annual average evaporation is 1400–3200 mm [13]. Northwest China is a major potato producing area in China. Potatoes in northwest China are usually sown from late April to early May and harvested from late September to early October. Potatoes in Xinjiang are mostly irrigated, and the other four provinces are mostly rain-fed. The potato growing areas in Xinjiang are mainly distributed along the northern and southern slopes of the Altai, Kunlun and Tianshan Mountains. Potato planting areas in Qinghai are mainly distributed in the eastern part of the region. Potato growing areas in Gansu are mainly distributed in the central part of the region. Ningxia potato planting areas are mainly distributed in the southern mountains of the region. Shaanxi potato planting areas are mainly distributed in the northern and southern parts of the region.

2.2. Data

The meteorological data were obtained from the China Meteorological Data Service Center (<http://data.cma.cn/>) based on the following criteria: (1) the meteorological station is located in the potato growing area of northwest China, (2) the number of days of missing measured data at each station does not exceed 20 days, and (3) the duration of the data is over 35 years. Daily climate data including maximum air temperature (T_{\max}), minimum air temperature (T_{\min}), average air temperature (T_{ave}), precipitation (Prec) and sunshine hours (S) were obtained from 72 meteorological stations (18 in Gansu, 12 in Shaanxi, 6 in Qinghai, 5 in Ningxia and 31 in Xinjiang) in northwest China between 1982 and 2015. The distribution of the meteorological stations is shown in Figure 1. Diurnal temperature ranges (DTR) were obtained by calculating the difference between T_{\max} and T_{\min} . As the data obtained from the meteorological observing station were only sunshine hours, it was necessary to calculate the solar radiation (R_s) by using the Food and Agriculture Organization (FAO) formula [24]

$$d_r = 1 + 0.033 \left(\frac{2\pi}{365} J \right) \quad (1)$$

$$\delta = 0.409 \sin \left(\frac{2\pi}{365} J - 1.39 \right) \quad (2)$$

$$\omega_s = \arccos[-\tan(\varphi) \tan(\delta)] \quad (3)$$

$$N = \frac{24}{\pi} \omega_s \quad (4)$$

$$R_a = \frac{24 \times 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (5)$$

$$R_s = \left(a + b \frac{n}{N} \right) R_a, \quad (6)$$

d_r is the relative distance between the sun and earth; J is the number of the days in the year between 1 (1 January) and 365 or 366 (31 December); δ is the solar declination angle (Rad); ω_s is the sunset hour angle (Rad); φ is the latitude of the meteorological station (Rad); N is the maximum possible duration of sunshine or daylight hours (h); R_a is the extraterrestrial solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$); G_{sc} is the solar constant ($=0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}$); a ($=0.25$) and b ($=0.50$) are the coefficients recommended by the FAO; n is the duration of sunshine hours according to the meteorological station (h).

Before the analysis, the meteorological data underwent a quality assurance procedure [25]. The long-term statistical data of the potato (1982–2015), including the total yield and sowing area of each province in northwest China, were obtained from the National Bureau of Statistics of China (<http://data.stats.gov.cn/>).

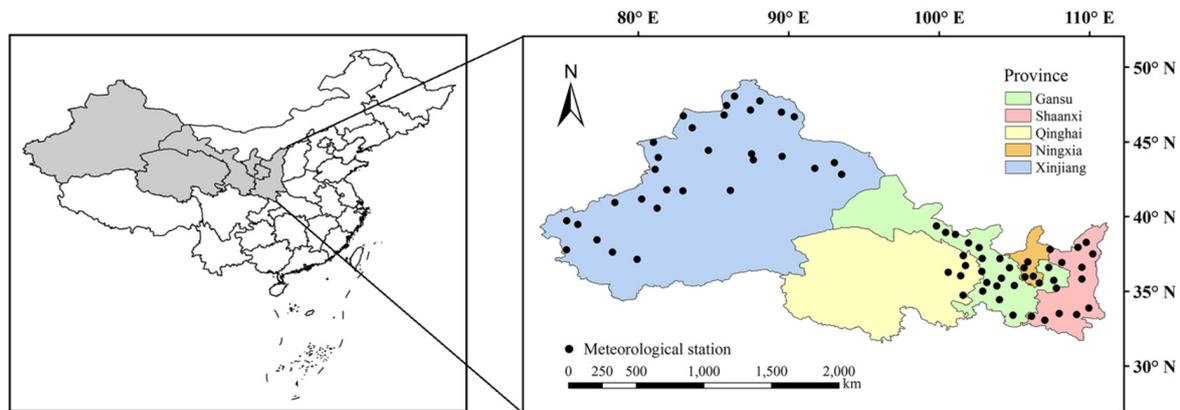


Figure 1. The spatial distribution of each meteorological station in northwest China.

2.3. Research Methods

To understand the variations in the different climate factors during the potato growing period in northwest China, the linear change trends of the study period (1982–2015) were analysed.

2.3.1. Method of First Difference

Due to technological differences, it is difficult to identify the contribution of climate change directly from original yield data; therefore, it is necessary to detrend the yield data. The first difference method is a commonly used method to decouple the nonlinear trend in yield. This method was used to evaluate the impact of climate change and effectively remove the influence of slow change factors on variables [20,26,27]. Previous study showed that both the first difference method and linear detrend statistical method had almost the same effect of eliminating the influence of technological progress on the yield [28]. The first difference values of the potato yield and climate factors in each province were calculated as follows

$$\Delta Y = Y_t - Y_{t-1}, \quad (7)$$

$$\Delta X = X_t - X_{t-1}, \quad (8)$$

where ΔY is the potato yield variation in two consecutive years (value of first difference of potato yield); Y_t and Y_{t-1} represent the potato yield in t and $t - 1$ years, respectively; ΔX is the variation in single climate variables during potato growth in two consecutive years; X_t and X_{t-1} represent the values of single climate variables in t and $t - 1$ years, respectively.

Second, the linear regression equation between the change in yield and the change in climate factors was established as follows

$$\Delta Y = \alpha \Delta X_j + \varepsilon, \quad (9)$$

where ΔY is the potato yield variation in two consecutive years; ΔX_j is the variation in single climate variables (T_{ave} , T_{max} , T_{min} , DTR, Prec, S and R_s) during potato growth in two consecutive years; α is the regression coefficient; ε is a constant of the single factor regression equation.

Climate-induced yield changes are usually the result of a combination of different climate factors. Multiple linear regression was applied to calculate the response of potato yield to climate change as follows

$$\Delta Y = \beta_1 \Delta X_1 + \beta_2 \Delta X_2 + \dots + \beta_k \Delta X_k + \omega, \quad (10)$$

where ΔY is the climate-induced potato yield variation in two consecutive years; ΔX_k is the change in the climate factor (ΔT_{ave} , ΔT_{max} , ΔT_{min} , ΔDTR , $\Delta Prec$, ΔS and ΔR_s); β_k is the regression coefficient of the climate factor; and ω is the constant term of regression equation.

2.3.2. Method of Moving Average to Decouple the Climate-Induced Potato Yield

In general, crop yields can be expressed as the sum of management, climate contributions, and random error at any year [29,30]. The crop yield induced by crop management (including technological changes and any other non-climatic factors) mainly depends on the development level of productivity (science and technology). The crop yield induced by climate, also known as fluctuating yield, mainly reflects the short-term yield fluctuation caused by changes in climate factors.

$$Y = Y_m + Y_c + \epsilon \quad (11)$$

where Y is the crop yield; Y_m is the crop yield induced by management; Y_c is the crop yield induced by climate; ϵ is the random error.

The method of moving average resembles a low-pass filter. After processing, the period sequence will be weakened to reflect the long-term change trends. The sequence of moving average was established as follows

$$Y_j = \frac{1}{k} \sum_{i=1}^k Y_{i+j-1}, j = 1, 2, \dots, n - k + 1, \quad (12)$$

where Y_j is the moving average value at the (j)th year, namely the crop management induced yield at the (j)th year; k is the moving average time step, in this study, $k = 5$; Y_{i+j-1} is the yield at the ($i + j - 1$)th year; n is the sample number.

Pearson's correlation was used to identify the climatic factors that have a significant correlation with the climate induced crop yield. The stepwise regression method was used to establish a multiple linear regression equation of the climate induced potato yield and dominant climatic factors, which can not only ensure that all independent variables pass the significance test, but also overcome multicollinearity between independent variables. The multiple linear regression was described as follows

$$Y_c = \gamma_0 + \gamma_1 X_1 + \gamma_2 X_2 + \dots + \gamma_k X_k \quad (13)$$

where Y_c is the climate-induced potato yield; γ_0 is the regression constant; γ_k is the partial regression coefficient; X is the different climatic factor.

2.4. Statistical Analysis

Linear regression was used to quantify the relationship between potato yield and climatic factors. The relationship between potato yield change and a single climatic factor was calculated by Pearson's correlation analysis [31]. Multiple linear regression was used to quantify the comprehensive relationship between potato yield variation and multiple climatic factors [32]. Statistical analyses were performed using SPSS statistical software (Version 20.0 for Windows, SPSS, USA) [33], and figures were drawn with SigmaPlot (Version 10.0 for Windows, Systat Software) [34]. The tests of correlation coefficients and linear regression by SPSS software were set at two levels with significance ($\alpha = 0.05$) and remarkable significance ($\alpha = 0.01$).

3. Results

3.1. Changes in Potato Yields and Planting Areas in Northwest China

From the period 1982 to 2015, the potato yield increased significantly from 1246 kg ha⁻¹ to 3116 kg ha⁻¹, with an average increase of 54.3 kg ha⁻¹ per year ($P < 0.01$) in northwest China (Figure 2). The potato planting area increased markedly from 545.7×10^3 ha to 1249.6×10^3 ha at a rate of 26.87 ×

10³ ha per year ($P < 0.01$) (Table 2). Gansu had the largest planting area and the fastest increasing rate (16.19×10^3 ha per year) (Figure 3a and Table 1). The potato yield varied greatly among the different provinces. Xinjiang had the highest potato yield and the fastest increasing rate (Figure 3b and Table 1).

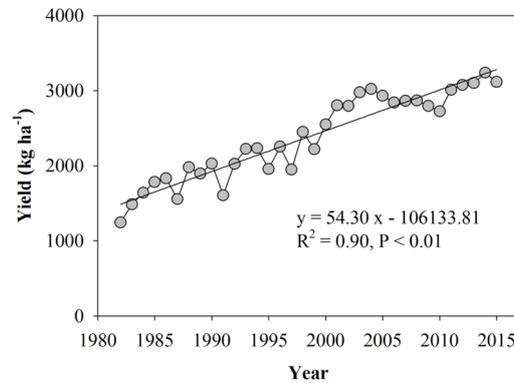


Figure 2. Changes in potato yields from 1982 to 2015 in northwest China.

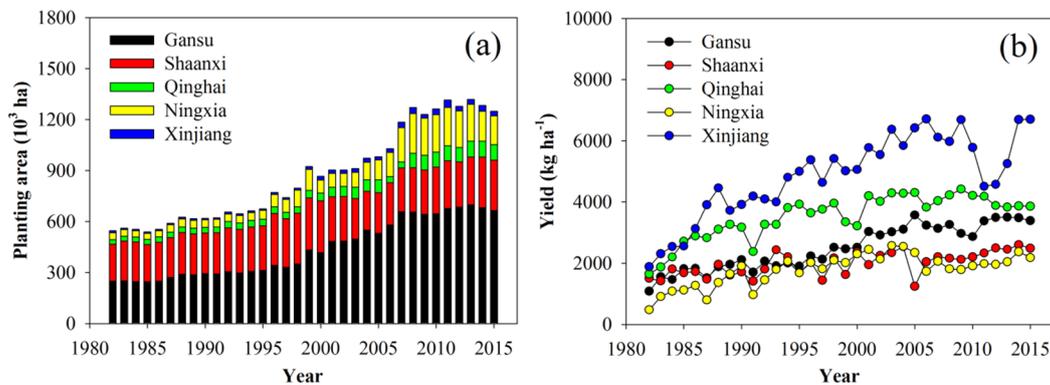


Figure 3. Changes in potato yields and planting areas from 1982 to 2015 in different provinces of northwest China.

Table 1. Change trends of potato yield and planting area for each province and overall northwest China from 1982 to 2015.

Region	Change Trends of Potato Yield	Change Trends of Planting Area
Gansu	$y = 69.09x - 135,568.37, R^2 = 0.90, P < 0.01$	$y = 16.19x - 31,925.44, R^2 = 0.93, P < 0.01$
Shaanxi	$y = 26.62x - 51,221.67, R^2 = 0.47, P < 0.01$	$y = 1.47x - 2685.22, R^2 = 0.32, P < 0.01$
Qinghai	$y = 59.67x - 115,725.95, R^2 = 0.67, P < 0.01$	$y = 2.07x - 4084.67, R^2 = 0.77, P < 0.01$
Ningxia	$y = 38.61x - 75,378.34, R^2 = 0.54, P < 0.01$	$y = 6.24x - 12,371.59, R^2 = 0.79, P < 0.01$
Xinjiang	$y = 113.38x - 221,744.13, R^2 = 0.71, P < 0.01$	$y = 0.89x - 1756.29, R^2 = 0.76, P < 0.01$
Overall	$y = 54.30x - 106,133.81, R^2 = 0.90, P < 0.01$	$y = 26.87x - 52,823.21, R^2 = 0.94, P < 0.01$

3.2. Changes in Climate Factors during the Potato Growing Period

Fit lines were implemented to reflect the trends of climatic factors from 1982 to 2015 (Figure 4). According to the slope of the linear response curve in Figure 4a, T_{ave} , T_{max} , and T_{min} increased significantly at rates of 0.42, 0.43, and 0.51 per decade, respectively ($P < 0.01$). The diurnal temperature ranged between 12.0 and 13.5 °C, which showed a downward trend (-0.093 °C per decade), but the change was not significant (Figure 4b). Prec, S and R_s showed increasing trends (3.4 mm, 0.015 h and 5.8 MJ m⁻² per decade, respectively), but the changes were not significant (Figure 4c–e).

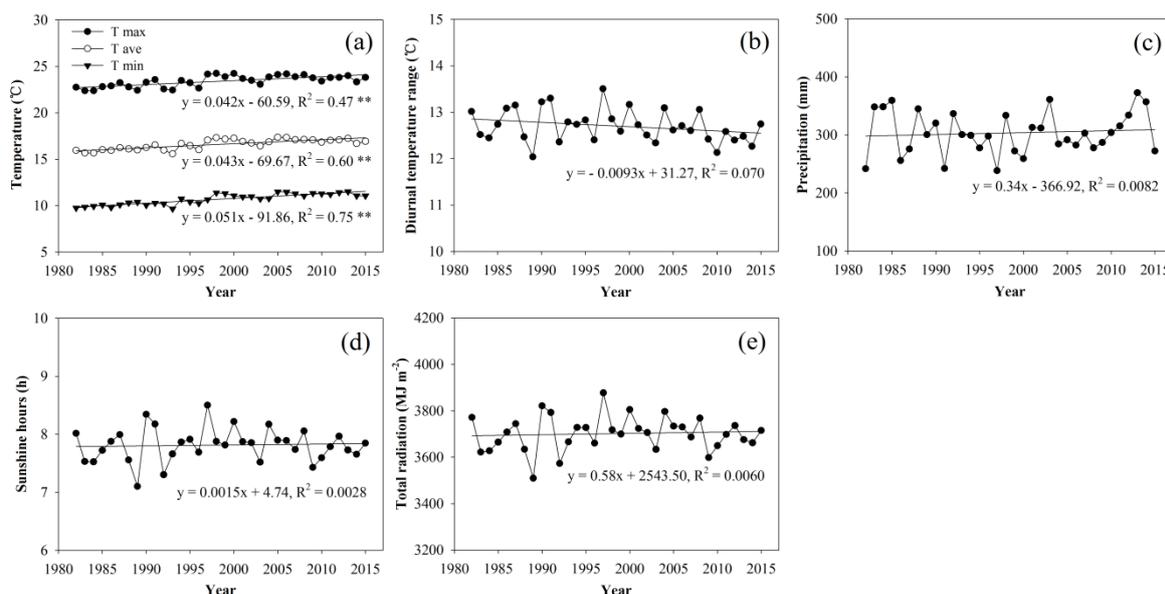


Figure 4. Changes in climatic variables during the potato growing seasons from 1982 to 2015 in northwest China: (a) temperature; (b) diurnal temperature range; (c) precipitation; (d) sunshine hours and (e) total radiation.

In different provinces, the climatic factors that affected potato yield changed by varying degrees during the growing period (Table 2). The T_{ave} , T_{max} and T_{min} of the five provinces increased significantly in northwest China ($P < 0.01$). In Gansu, Ningxia and Xinjiang, the T_{min} increased more than the T_{max} , so the DTR showed a decreasing trend. The DTR of Xinjiang significantly decreased by $0.16\text{ }^{\circ}\text{C}$ per decade ($P < 0.01$). The change in Prec in each province was not significant. The S in Qinghai significantly decreased ($P < 0.01$), while the S in Xinjiang markedly increased at the rate of 0.12 h per decade ($P < 0.01$). The R_s in Qinghai showed a significant downward trend (-33.42 MJ m^2 per decade) ($P < 0.05$). However, in Xinjiang, the R_s showed a significant increasing trend (31.41 MJ m^2 per decade) ($P < 0.05$).

Table 2. Trends in climate variables during the potato growing season from the period 1982 to 2015 in different provinces of northwest China.

Climatic Factor	Gansu	Shaanxi	Qinghai	Ningxia	Xinjiang
T_{ave} ($^{\circ}\text{C decade}^{-1}$)	0.519 **	0.332 **	0.490 **	0.414 **	0.445 **
T_{max} ($^{\circ}\text{C decade}^{-1}$)	0.491 **	0.351 **	0.511 **	0.365 **	0.383 **
T_{min} ($^{\circ}\text{C decade}^{-1}$)	0.560 **	0.323 **	0.476 **	0.456 **	0.531 **
DTR ($^{\circ}\text{C decade}^{-1}$)	-0.071	0.032	0.031	-0.080	-0.160 **
Prec (mm decade ⁻¹)	0.088	6.836	5.895	-0.851	4.807
S (h decade ⁻¹)	0.035	0.125	-0.139 **	-0.060	0.115 **
R_s ($\text{MJ m}^{-2} \text{ decade}^{-1}$)	15.905	42.712	-33.416 *	-4.821	31.409 *

Notes: ** indicates significance at $P < 0.01$. * indicates significance at $P < 0.05$. T_{ave} : average temperature; T_{max} : maximum temperature; T_{min} : minimum temperature; DTR: diurnal temperature range; Prec: precipitation; S: sunshine hours; R_s : total radiation.

3.3. Establishing Relationships between First-Difference Yield and Climatic Factors

At the provincial scale, the first-difference potato yields were sensitive to the changes in air temperature and precipitation but not the changes in diurnal temperature ranges, sunshine hours and total radiation.

Specifically, there were significant negative correlations between the changes in potato yield and the changes in T_{max} in Gansu ($P < 0.05$), Shaanxi ($P < 0.01$), Ningxia ($P < 0.05$) and Xinjiang

($P < 0.01$) (Figure 5). The potato yields of the above four provinces decreased by 127, 289, 199 and 339 kg ha⁻¹, respectively, when the T_{max} increased by 1 °C. In addition, the change in potato yield in Xinjiang was negatively correlated with the change in T_{min} ($P < 0.01$). For every 1 °C increase in T_{min} , the potato yield in Xinjiang significantly decreased by 583 kg ha⁻¹ (Figure 6). In Gansu, Ningxia and Qinghai, there were significant positive correlations between the changes in potato yield and Prec during the potato growing period ($P < 0.01$). For every 100 mm increase in Prec, the potato yields in Gansu, Qinghai and Ningxia significantly increased by 250, 375 and 182 kg ha⁻¹, respectively (Figure 7). The results indicated that temperature and precipitation were the dominant climatic factors affecting potato yield in northwest China.

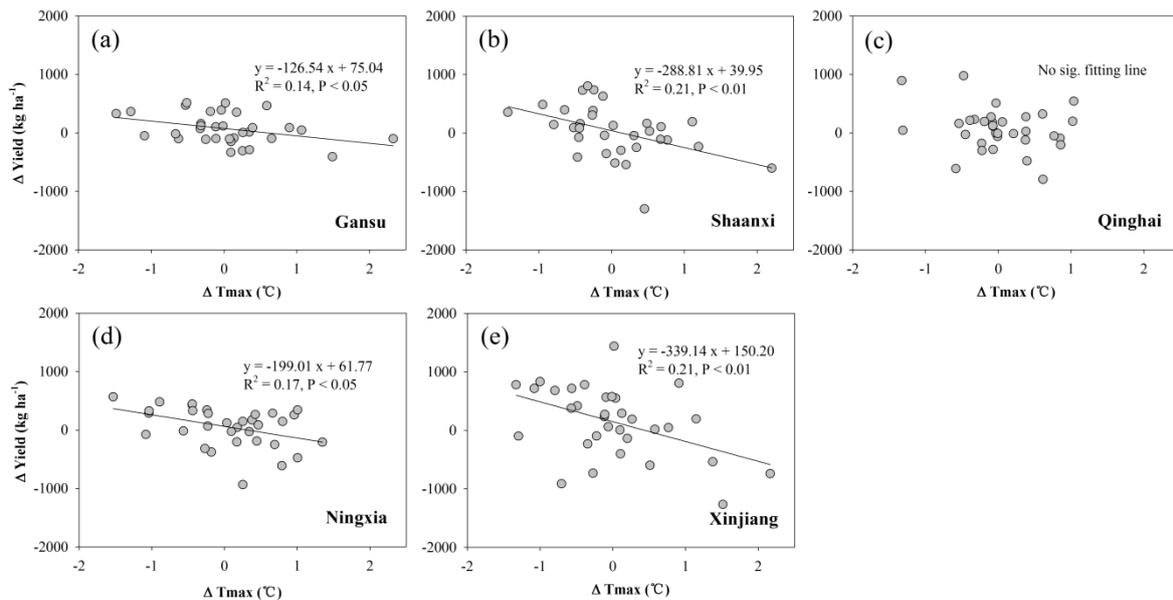


Figure 5. Relationships between changes in the daily maximum temperature and potato yield in different provinces of northwest China.

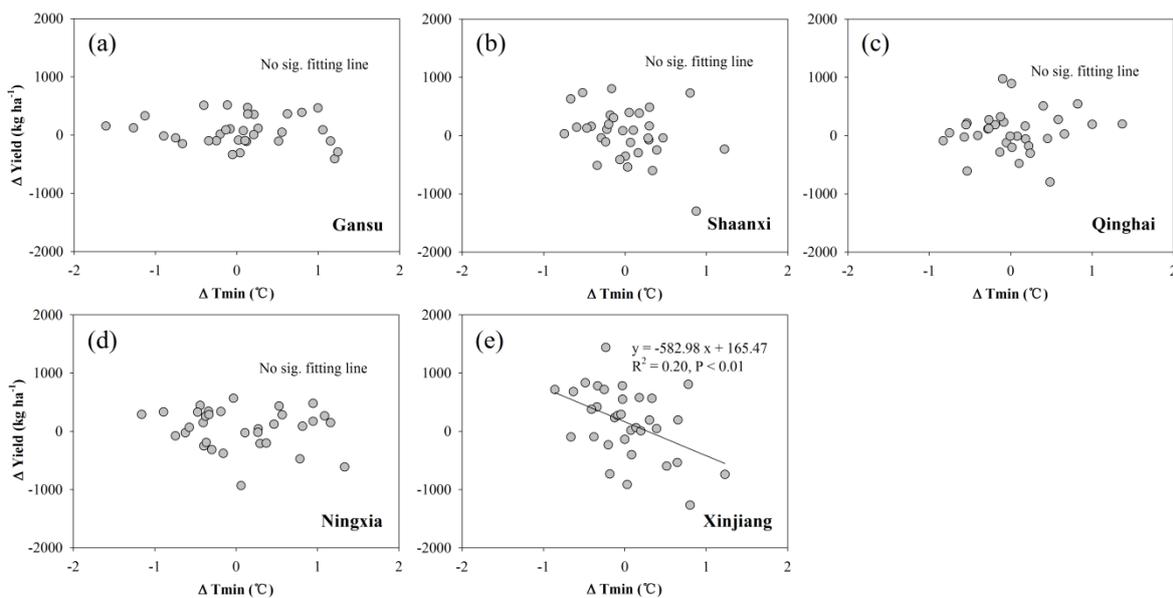


Figure 6. Relationships between changes in the daily minimum temperature and potato yield in different provinces of northwest China.

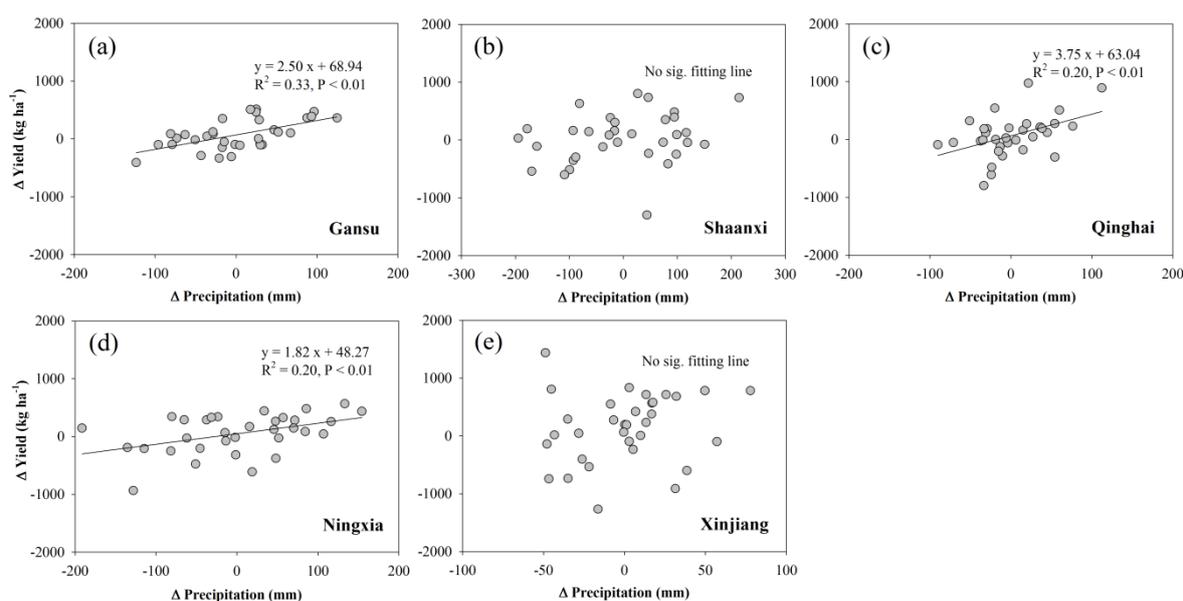


Figure 7. Relationships between changes in the precipitation and potato yield in different provinces of northwest China.

By using multiple linear regression, regression models describing the combined effects of different climate factors on the first difference values of the potato yield in various provinces were established (Table 3). The key climate factors affecting the potato yields in Gansu ($P < 0.01$) and Ningxia ($P < 0.05$) were Prec and T_{max} . However, the potato yields in the other three provinces were influenced by a single climatic factor, which was T_{max} in Shaanxi ($P < 0.01$) and Xinjiang ($P < 0.01$) and Prec in Qinghai ($P < 0.01$). The results indicated that precipitation was the dominant climatic factor affecting potato yield in rain-fed areas (Gansu, Qinghai and Ningxia) due to the relatively low local rainfall and uneven seasonal distribution. Potato is a shallow-rooted, cool-season crop, and lower night temperatures are favourable for the accumulation of dry matter and carbohydrates in the tubers. Although precipitation is relatively abundant, the higher T_{max} is the limiting factor in Shaanxi. Potatoes in Xinjiang are mostly irrigated, and water condition is not a sensitive factor, thus the T_{max} is a local limitation.

Table 3. Multiple linear regression models established in different provinces of northwest China.

Province	Regression Model
Gansu	$\Delta Y = 2.38 \Delta \text{Prec} - 15.67 \Delta T_{max} + 69.62, R^2 = 0.33, P < 0.01$
Shaanxi	$\Delta Y = -288.81 \Delta T_{max} + 39.95, R^2 = 0.21, P < 0.01$
Qinghai	$\Delta Y = 3.75 \Delta \text{Prec} + 63.04, R^2 = 0.20, P < 0.01$
Ningxia	$\Delta Y = 1.36 \Delta \text{Prec} - 133.05 \Delta T_{max} + 55.88, R^2 = 0.26, P < 0.05$
Xinjiang	$\Delta Y = -339.14 \Delta T_{max} + 150.20, R^2 = 0.21, P < 0.01$

Notes: ΔY : the first difference values of the potato yield; ΔPrec : change in precipitation; ΔT_{max} : change in maximum temperature.

3.4. Establishing Relationships between Climate-Induced Potato Yield and Climatic Variables

Changes in the observed yield of potato (statistical yield), decoupled management-induced yield and climate-induced yield, using the moving average method, are shown in Figure 8. With the development of agricultural science and technology, the potato yields in northwest China increased prominently, with inter-annual fluctuations and regional differences. After using the moving average method, the change trend was consistent between the decoupled management-induced yield and the observed yield. There were fluctuations in climate-induced yield in different provinces.

If the fluctuations are above zero, this indicates that the impact of meteorological conditions on potato yield is positive, otherwise the effect is negative.

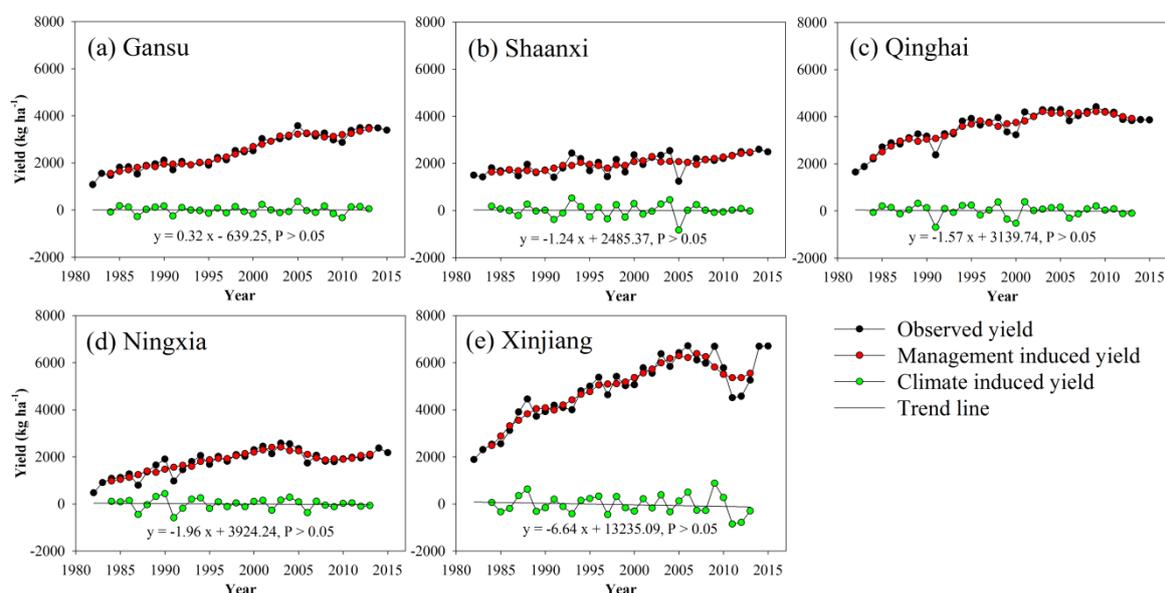


Figure 8. Changes in potato observed yield, management-induced yield and climate-induced yield in different provinces of northwest China.

Table 4 shows the correlation coefficients between climate-induced yield of potato in different provinces of northwest China. After using moving average separation, in Gansu ($P < 0.05$), Qinghai ($P < 0.01$) and Ningxia ($P < 0.05$), the climate-induced yields of potato had significant positive correlations with the Prec of growing season. In Shaanxi ($P < 0.05$) and Xinjiang ($P < 0.05$), the climate-induced yields of potato had significant negative correlations with the T_{max} . In addition, the climate-induced potato yields had significant negative correlations with the T_{ave} in Shaanxi ($P < 0.05$) and the DTR in Qinghai ($P < 0.05$).

Table 4. Correlation coefficients between climate-induced potato yield and key climatic variables.

Climatic Variables	Correlation Coefficient				
	Gansu	Shaanxi	Qinghai	Ningxia	Xinjiang
T_{ave} ($^{\circ}C$ decade $^{-1}$)	0.015	-0.452 *	-0.107	-0.147	-0.355
T_{max} ($^{\circ}C$ decade $^{-1}$)	-0.031	-0.463 *	-0.207	-0.182	-0.374 *
T_{min} ($^{\circ}C$ decade $^{-1}$)	0.062	-0.255	0.033	-0.042	-0.277
DTR ($^{\circ}C$ decade $^{-1}$)	-0.140	-0.349	-0.374 *	-0.188	-0.215
Prec (mm decade $^{-1}$)	0.387 *	0.336	0.532 **	0.369 *	0.156
S (h decade $^{-1}$)	-0.075	-0.332	-0.215	-0.223	-0.256
R_s ($MJ\ m^{-2}$ decade $^{-1}$)	-0.080	-0.342	-0.209	-0.218	-0.226

Notes: ** indicates significance at $P < 0.01$. * indicates significance at $P < 0.05$. T_{ave} : average temperature; T_{max} : maximum temperature; T_{min} : minimum temperature; DTR: diurnal temperature range; Prec: precipitation; S: sunshine hours; R_s : total radiation.

The regression models describing the relationships between climatic variables and climate-induced yield of potato were established in northwest China (Table 5). In Gansu and Ningxia, the climate-induced yield of potato was mainly decided by the Prec. In Shaanxi, the climate-induced potato yield was mainly decided by two climatic variables, including the T_{ave} and the T_{max} . In Qinghai, the climate-induced potato yield was also decided by two climatic variables, namely the Prec and the DTR. In Xinjiang, the climate-induced potato yield was decided by the T_{max} . Overall, precipitation and maximum temperature were the key climatic limiting factors for climate-induced potato yield in northwest China.

Table 5. Regression models established in different provinces of northwest China.

Province	Regression Model
Gansu	$Y_c = 1.399 \text{ Prec} - 448.041, R^2 = 0.15, P < 0.05$
Shaanxi	$Y_c = -64.741 T_{ave} - 129.354 T_{max} + 4589.871, R^2 = 0.22, P < 0.05$
Qinghai	$Y_c = 4.123 \text{ Prec} + 14.088 \text{ DTR} - 1447.137, R^2 = 0.28, P < 0.05$
Ningxia	$Y_c = 1.323 \text{ Prec} - 404.417, R^2 = 0.14, P < 0.05$
Xinjiang	$Y_c = -202.769 T_{max} + 5102.801, R^2 = 0.14, P < 0.05$

Notes: Y_c : the climate-induced yield of potato; T_{ave} : average air temperature; T_{max} : maximum air temperature; Prec: precipitation; DTR: diurnal temperature range.

4. Discussion

4.1. Reasons for the Increase in Potato Yields in Northwest China

From the period 1982 to 2015, the potato yield in northwest China increased significantly, and the change trend was consistent with the decoupled management-induced yield (Figure 8). The results indicated that the main factors contributing to the yield increase were improvements in the crop managements, including the optimization of potato varieties and cultivation techniques. Recently, medium-late mature varieties with a strong growth potential and good stress resistance were widely used in potato farming in northwest China. The main cultivars were Kexin No. 1 in Xinjiang and Shaanxi; Qingshu No. 168 and Qingshu No. 9 in Ningxia; Leshu No. 1, Qingshu No. 2 and Xiazhai No. 65 in Qinghai; and Longshu No. 3 and Zhuangshu No. 3 in Gansu [10]. In addition, a project to breed and popularize virus-free potato varieties was carried out in northwest China, and the pace of popularizing improved potato varieties obviously accelerated [35]. Since the 1980s, plastic film mulching technology has been widely used in northwest China. The use of farmland film in northwest China increased from 44.4×10^3 tons in 1991 to 385.2×10^3 tons in 2015 [10]. Film mulching can effectively improve the moisture and temperature of topsoil, inhibit weed growth, and promote potato yield [11]. In recent years, ridge-furrow planting patterns have been widely used in northwest China. Ridge-furrow planting technology allows precipitation to be effectively collected and improves the rainfall utilization efficiency of potatoes [36]. Combining alternate ridges and furrows and plastic film mulching, a planting pattern called full mulching on double ridges and furrows (DRFFM) can effectively improve the utilization of trace rainfall amounts, promote the germination of seedlings, increase the emergence rate, and significantly improve the yield and WUE of potatoes [37].

4.2. Effects of Different Climatic Factors on Potato Yields

Potatoes are sensitive and vulnerable to meteorological conditions, and climatic factors can greatly influence the growth and development of potatoes. The main climatic factors affecting potato yields are air temperature, rainfall and light [38].

Air temperatures can greatly affect potato germination, emergence, canopy development, tuber bulking and growth period length. Potatoes are suitable for growing in areas with average air temperatures of approximately 15–18 °C, and low night temperatures are beneficial to dry matter and carbohydrate accumulation in tubers [39]. The results of this study showed that the average air temperature during the potato growing period was 15.6–17.4 °C in northwest China from 1982 to 2015, which was very beneficial for potato growth. Above the optimum range, an increase in air temperature will hinder the growth of roots and stolons, delay the formation of tubers and starch accumulation, and eventually lead to a decrease in yield [40]. In terms of interannual changes in temperatures, an increase in temperature during the growth period leads to a decrease in potato yields [41]. In this study, after using both the first-difference method and moving average method, there were significant negative correlations between the changes in potato yield and the changes in maximum temperature in Shaanxi and Xinjiang. In the hottest month of the potato growing period, the daily maximum air temperatures exceeded 25 or even 30 °C. Potato growth was inhibited by high-temperature stress,

and an increase in daytime temperature could accelerate potato maturation and shorten the potato growth period. In addition, by using the first difference method, the change in potato yield in Xinjiang was negatively correlated with the change in the daily minimum air temperature. Unsuitable night temperatures hinder tuber formation, enhance respiration and accelerate the consumption of assimilates such as starch [42,43]. In areas with a similar climate, Zhang et al. [21] showed that changes in air temperature was an important driving factor that affected potato yields in northern China.

As a crop with shallow roots, the potato is sensitive to water deficits. Water deficiencies will reduce the number of leaves, leaf area, availability and utilization of light energy, yield and quality of tubers [44]. In the arid and semi-arid regions of northwest China, the arable land is mostly rain-fed farmland, and rainfall is the main water source for potato cultivation in this region. However, because of low precipitation and higher evaporation, water deficits often limit crop yields in this region [13]. In this study, there was no significant correlation between the yield change in potatoes and the change in precipitation in Shaanxi and Xinjiang. The precipitation in Shaanxi was relatively high, and the drip irrigation technique was mostly used in Xinjiang, so the effect of rainfall in these two provinces was not obvious. The potato yields in Gansu, Ningxia and Qinghai were positively correlated with precipitation during the growing period. Potatoes in the three provinces are mainly rain-fed cultivated, and the local rainfall is relatively low and seasonally unevenly distributed, therefore, precipitation is the dominant climatic factor affecting potato yield. For every 100 mm increase in precipitation, the potato yields in Gansu, Qinghai and Ningxia significantly increased by 250, 375 and 182 kg ha⁻¹, respectively. Similarly, Zhang et al. [21] showed that in Wuchuan of Inner Mongolia, which is located in the northern agro-pastoral ecotone of China, the potato yield increased by 489 kg ha⁻¹ for every 100 mm increase in precipitation.

From 1982 to 2015, solar radiation during the potato growing period was between 3500 and 3900 MJ m⁻², and the diurnal temperature range was between 12.0 and 13.5 °C, which could satisfy potato growth. After using moving average separation, the climate-induced potato yields had a significant negative correlation with the diurnal temperature range in Qinghai. The result indicated that the large diurnal temperature range caused by high altitude is not conducive to the increase in potato yield.

4.3. Study Limitations

The long-term effects of climate change on potato yields are complex and uncertain. Due to data limitations, the effects of greenhouse gases such as CO₂ in the atmosphere on potato yields were not considered in this study. Previous studies have shown that an increase in CO₂ concentrations can increase potato production [45]. In addition, the effects of extreme climatic events (including droughts, heat waves, rainstorms and hails, etc.) on potato yields were not considered in this study [46]. Despite the shortcomings of this study, the effects of climate factors such as temperature, precipitation and other climatic factors on potato yields were quantitatively reflected to a certain extent. Further verification and in-depth analysis with continuous improvement of crop development and phenology data are needed in the future.

4.4. Adaptation Measures to Climate Change

To cope with climate change, effective measures should be taken in potato cultivation. In northwest China, due to rising temperatures, late-maturing varieties with a long growth period and good drought resistance should be selected for cultivation and planting [47]. In addition, the sowing time of potatoes should be adjusted according to the specific conditions in different regions [48]. Future climate warming will not only shorten the length of the crop growth period and reduce crop-chilling injury but also expand the crop planting area to higher latitudes. The spatial expansion of potato cultivation should be adjusted according to temperature, precipitation and cultivar characteristics. The construction of agricultural water conservancy infrastructure should be strengthened and the irrigation system should be improved. Water-saving agricultural planting technology and promote irrigation technology (such as sprinkler irrigation, drip irrigation and pipeline irrigation) should be developed. Water-saving

measures such as plastic film mulching and rainfall harvesting techniques should be used to improve the WUE of potato cultivation [49]. The soil quality, especially the content of organic matter, decreased continuously because of unsustainable fertilization and tillage measures in the past. Straw return, organic manure and conservation tillage should be used to improve soil quality so that local agriculture can be sustainable [50–52]. Develop forecasting and early-warning systems to enhance the ability to predict extreme weather and climate events, thereby reducing the harm of weather disasters to agricultural production and improving the stability of food production. Develop facility agriculture (plastic greenhouses, temperature controlled greenhouses, etc.) to improve the ability to resist natural disasters.

5. Conclusions

This study explored the effect of long-term climate change on potato yields in northwest China. Overall, from 1982 to 2015, the temperature increased significantly during the potato growing period in northwest China, while other climatic factors did not change significantly. Specifically, the changing trend of climatic factors varied among different provinces. Both the sunshine hours and the solar radiation increased significantly in Xinjiang, while these two factors decreased markedly in Qinghai. In addition, the diurnal temperature range showed a significant decreasing trend in Xinjiang. Based on the combined results of the first different method and the moving average method, the potato yields of rain-fed areas (Gansu, Qinghai and Ningxia) were determined by precipitation. In areas with irrigation (Xinjiang) or relatively high rainfall (Shaanxi), potato yields were decided by maximum temperature. According to specific local conditions, effective adaptations to climate change will help ensure the stability of potato production in northwest China.

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