How Does the Agricultural Ecosystem Productivity Respond to Climate Fluctuations in the Northern Farming-pastoral Region?

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Abstract Using meteorological data and mathematical statistics analysis, we take Jungar Banner in the northern farming-pastoral region of China for example, to analyze the fluctuations in the precipitation and average temperature in Jungar Banner during the period 1961 – 2009. We calculate the NPP of agricultural ecosystem and climatic yield of the main crops in the region during the period 1961 – 2009, and expound the response of agricultural ecosystem productivity to climate fluctuations in Jungar Banner. Indubitably the climate changes impose great effects on the structure and function of regional ecosystem, and there is a need to take a number of measures to minimize the detrimental effects of climate changes on climatic yield of the main crops.

Key words Agricultural ecosystem productivity, Climatic yield, Climate fluctuations, Northern farming-pastoral region

1 Introduction

Using remote sensing data, GIS tool and statistical analysis, many scholars at home and abroad have carried out extensive studies on the spatial and temporal variations of ecosystem productivity[1–12]. Jungar Banner, located in the northern farming-pastoral region, is an ecologically fragile and environmentally sensitive area. Affected by climate change and human activities, the functions of regional ecosystem will be accordingly changed. Therefore, choosing Jungar Banner as the study area is of strong typicality and it is an ideal case for study. Currently, the researches of Jungar Banner are mainly focused on the physiological and ecological characteristics of plants and soil[13–17], soil erosion or soil and water conservation[18–24], land use change[25–29], etc. Thus, using the data from three meteorological stations and the agricultural production data from Jungar Statistical Yearbook during the period 1961 – 2009, analyzing the response of agricultural ecosystem productivity to climate fluctuations in Jungar Banner, can not only supplement the studies on ecological characteristics of the region, but also provide a theoretical reference for the agricultural production activities and environmental control in Jungar Banner.

2 Materials and methods

2.1 Study site Jungar Banner is a banner of western Inner Mongolia, People's Republic of China, lying on the western bank of the Yellow River and bordering the provinces of Shanxi to the northwest and Shaanxi to the northeast. It is under the administration of Ordos City. Jungar Banner features a temperate semi-arid continental climate, marked by rich energy resources and abundant sunshine. The average annual temperature is 6.2 ℃ – 7.2 ℃, and the average annual precipitation is 379 – 420 mm, concentrated in summers. The average annual evaporation there is very high, and the wind in winter and spring is strong and frequent, with the average annual wind speed of 2 – 3 m/s. The zonal soil in Jungar Banner is chestnut soil, and due to the impact of loess parent material, there is a large area of loess soil. The main types of vegetation include shrub, grass, sandy ground vegetation and low wet land vegetation. Due to climate change, historical deforestation and reclamation since the late Qing Dynasty, the natural forests and grasslands in this banner have been nearly depleted, replaced by artificial vegetation and natural secondary grassland vegetation[30]. It is prone to less precipitation, low temperature and other weather disasters, so the farmers live at the mercy of the elements.

2.2 Statistical analysis In this study, we use the data from three meteorological stations in Jungar Banner and Dongsheng, Hequ nearby and the agricultural production data from Jungar Statistical Yearbook during the period 1961 – 2009, to analyze the agricultural ecosystem productivity, climate productivity and the climatic yield of the main crops.

2.2.1 Analysis method for climate fluctuations. In order to reveal the inherent law of changes in the main climatic factors (precipitation, temperature), we use the data from three meteorological stations and anomaly analysis method, to analyze the inter-annual precipitation fluctuations and inter-annual average temperature fluctuations in Jungar Banner during the period 1961 – 2009. Using the coefficient of variation, we analyze the intra-annual precipitation, average temperature fluctuations during the period 1961 – 2009.

Anomaly is calculated as follows:

$$p = x - y \quad (1)$$

where p is the fluctuation value; x is the actual value of elements;

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y is the sample mean.

Coefficient of variation is calculated as follows:

$$CV = S/\bar{x} \times 100\% \quad (2)$$

where CV is coefficient of variation; S is the sample standard deviation; $\bar{x}$ is the sample mean.

2.2.2 NPP estimation method for agricultural ecosystem. According to the crop growing area and production data in Jungar Statistical Yearbook (1961 – 2009), we estimate NPP (net primary productivity) of agricultural ecosystem. The principle is to convert the statistical agricultural production into vegetation carbon storage, based on the water content of different harvested crops and harvest index. The conversion formula is as follows[31 – 32]:

$$NPP = \sum_{i=1}^{n} \frac{Y_i(1 - MC_i) \times 0.45}{HI_i \times 0.9} / \sum_{i=1}^{n} A_i \quad (3)$$

where Y_i is the yield of crop i in the statistics; MC_i is the water content of harvested crops; HI_i is the harvest index of crop i; A_i is the harvested area of crops.

Using the yield and growing area of 8 major crops planted in Jungar, as well as the water content of harvested crops and harvest index (Table 1), we quantify NPP of agricultural ecosystem in Jungar Banner. Studies have shown that the NPP calculated using this method is significantly correlated with the results calculated using GLO-pEM model[33]. Therefore, this study uses this method to calculate NPP of agricultural ecosystem, and the results are reliable.

2.2.3 Calculation method for climatic yield. To distinguish between the effects of natural and unnatural factors on crop yield, the crop yield is generally decomposed into trend yield, climatic yield and random error. Trend yield, also known as technical production, is the long period output reflecting the productivity level in the historical period. Climatic yield is the fluctuated yield affected by the short-period change factors dominated by climatic factors.

Trend yield often uses "time" as the independent variable for various kinds of linear or non-linear simulation. Climatic yield is calculated as follows[36]:

$$Y_w = Y - Y_t\text{-}e \quad (4)$$

where Y_w is the climatic yield; Y is the actual crop yield; Y_t is the technical production; e is the yield component subject to random factors. e is very small, so the following studies neglect the effects of e.

3 Precipitation and average temperature fluctuations

3.1 Precipitation fluctuations

3.1.1 The inter-annual fluctuations. Using the precipitation data from three meteorological stations and equation (1), we calculate the inter-annual precipitation fluctuations in Jungar Banner during the period 1961 – 2009, as shown in Fig. 1.

Fig. 1 shows that throughout the year and during the growing season, the inter-annual precipitation fluctuations were particularly significant in the 1960s, and relatively moderate after the 1970s. During the period 1961 – 2009, the inter-annual precipitation fluctuations in the whole year and during the growing season showed a high degree of consistency ($r = 0.960$, $P = 0.000 < 0.001$). From each month during the growing season, the inter-annual precipitation fluctuations are also significant, and compared to May, June and September, the inter-annual precipitation fluctuations in July and August become more pronounced.

Table 1 The water content and harvest index of the main crops[34 – 35]

Crops	Water content // %	Harvest index
Wheat	12.5	0.387
Potato	80.0	0.600
corn	13.5	0.433
Broomcorn millet	13.0	0.415
Millet	14.0	0.382
Buckwheat	12.5	0.400
Soybean	12.5	0.436
Oil crops	13.5	0.251

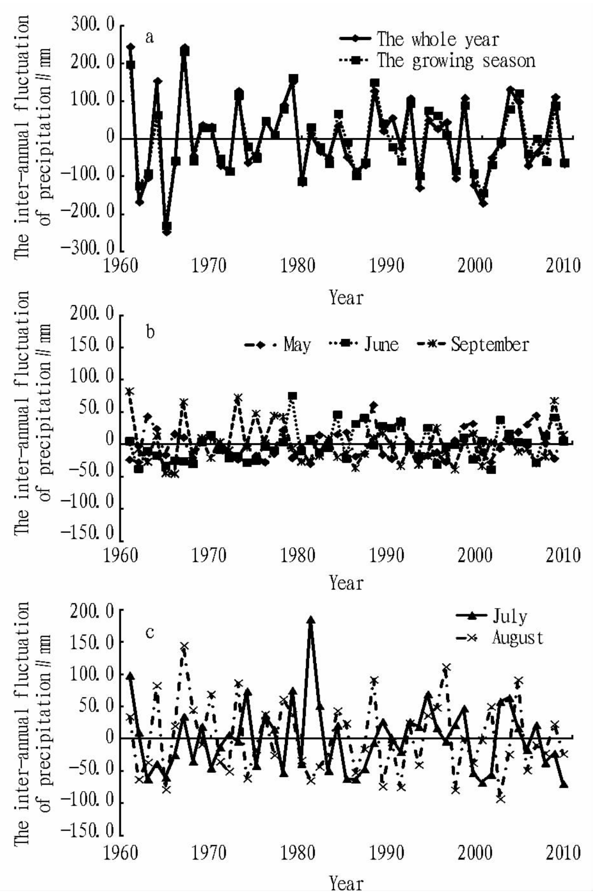

Fig. 1 The inter-annual precipitation fluctuations in Jungar Banner (1961 – 2009)

3.1.2 The intra-annual fluctuations. Due to unique climate in the semiarid northern area, and the intra-annual precipitation fluctuations maybe have important impacts on the climatic yield of crops in Jungar Banner. Using the precipitation data from three meteorological stations and equation (2), we calculate the coefficient of variation of precipitation in the whole year and during the growing season in Jungar Banner during the period 1961 – 2009, to characterize the intra-annual precipitation fluctuations, as shown in Fig. 2.

As can be seen from Fig. 2, during the period 1961 – 2009, the coefficient of variation of precipitation in the whole year and the growing season is 0.87 – 2.15 and 0.27 – 1.44, respectively, indicating that the intra-annual precipitation fluctuations are particularly significant. While the intra-annual precipitation fluctuations during the growing season are significantly lower than the whole year, but highly consistent fluctuations shows between them ($r = 0.859$, $P = 0.000 < 0.001$).

3.2 Average temperature fluctuations The inter-annual average temperature fluctuations in the whole year is not significant and it can not better reflect the effects on the climatic yield of the crops, so this study focuses on the analysis of inter-annual and intra-annual average temperature fluctuations during the growing season. Using the average temperature data from three meteorological stations and equation (1), (2), we calculate the inter-annual fluctuations in average temperature of each month during the growing season, and the coefficient of variation of average temperature between the months during the growing season in Jungar Banner during the period 1961 – 2009, as shown in Fig. 3.

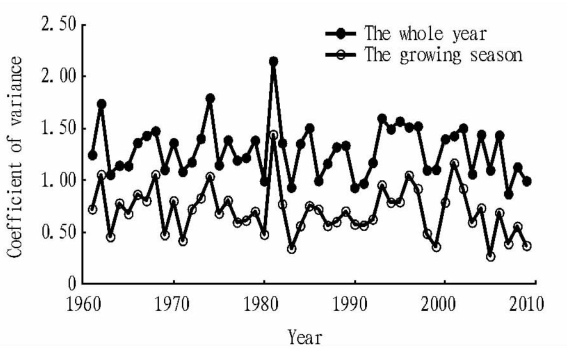

Fig. 2 The intra-annual precipitation fluctuations in Jungar Banner (1961 – 2009)

Fig. 3a, 3b shows that during the period 1961 – 2009, the inter-annual fluctuations in the average temperature were obvious in July, August and September during the growing season; Fig. 3c shows that the coefficient of variation of average temperature fluctuates around 0.17, with maximum of 0.21 in 1997 and minimum of 0.12 in 1969, indicating that the intra-annual average temperature fluctuations during the growing season are also significant.

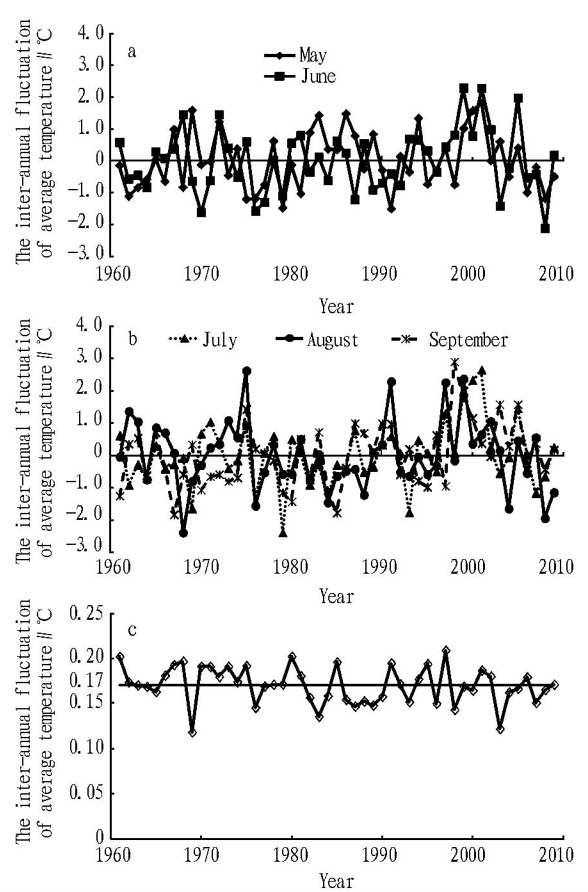

Fig. 3 The average temperature fluctuations during the growing season in Jungar Banner (1961 – 2009; a, b: inter-annual; c: intra-annual)

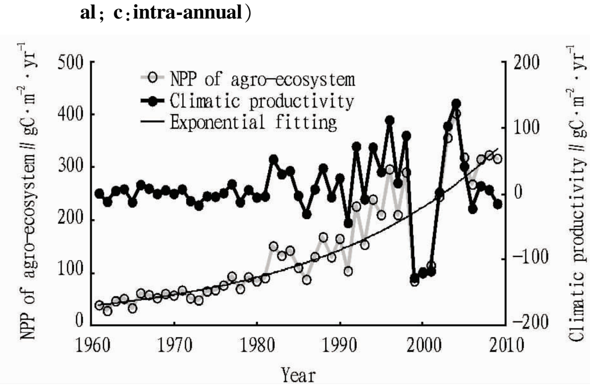

Fig. 4 Changes in NPP and climatic productivity of agro-ecosystem in Jungar Banner (1961 – 2009)

4 The response of agricultural ecosystem productivity to climate fluctuations

4.1 The comprehensive response of NPP of agricultural ecosystem to climate fluctuations Using the agricultural production data in Jungar Statistical Yearbook (1961 – 2009), formula (3) and data in Table 1, we calculate NPP of agricultural ecosystem in Jungar Banner. Using formula (4) and exponential fitting model, we get the technical production, and further get the climate productivity in this region during the period 1961 – 2009, as shown in Fig. 4.

Fig. 4 shows that NPP of agricultural ecosystem in Jungar Banner presents an obvious upward trend in volatility, which can be divided into three stages: (i) during the period 1961 – 1981, the growth was slow; (ii) during the period 1982 – 1998, due to the agricultural policy of household contract responsibility system, enhancement of the level of agricultural science and technology, considerable use of pesticides and chemical fertilizer and other factors, NPP of agricultural ecosystem experienced significant growth; (iii) during the period 1999 – 2001, affected by the extreme drought climate, NPP of agricultural ecosystem was drastically reduced but rebounded after 2002, and due to the impact of national reforestation policies, the growth trend slowed down. This shows that due to the combined effects of society, technology, nature and other factors, NPP of agricultural ecosystem in Jungar Banner was changed significantly, and in some years, the climatic conditions have a decisive impact on it. Results also show that the climate productivity exhibited same fluctuated changes as NPP of agricultural ecosystem, and these changes were more apparent after the 1980s.

The agricultural ecosystem is an artificial controlled system strongly subject to human intervention, and also a biological system with a relatively weak self-regulating mechanism. It is the main bearer of global change[37]. NPP is one of the most important indicators for measuring the production capacity of plants. For the arid and semi-arid regions, the NPP econometric model applied often at home for plant is the natural vegetation NPP model established by Zhou Guangsheng and Zhang Xinshi in accordance with water and heat balance equation and physiological and ecological characteristics of plant[38], which can comprehensively reflect the impact of precipitation, temperature, sunlight, wind and other climatic factors on NPP.

This study uses SPSS13.0 to carry out correlation analysis of climate productivity of agricultural ecosystem and NPP (Fig. 5), and the correlation coefficient is 0.393, significant at the 0.01 level. This indicates that the climate productivity of agricultural ecosystem also shows strong sensitivity to climate fluctuations.

4.2 The response of climatic yield of crops to climate fluctuations

4.2.1 Climatic yield of crops. Climatic yield to some extent reflects the climate productivity of terrestrial artificial ecosystem affected by the climate fluctuations. Using the agricultural production data in Jungar Statistical Yearbook (1961 – 2009), we first calculate the yield of grain and the main crops per unit area, and then use equation (4) to calculate the corresponding climatic yield. In this study, the technical production of grain, millet, broomcorn millet and soybean is calculated using quadratic polynomial; the technical production of wheat, corn and oil crops is calculated using exponential curve; the technical production of potato is calculated using the linear least squares method. The changes in the climatic yield of grain and crops are shown in Fig. 6.

Fig. 6 shows the following results: (i) During the period 1961 – 1981, the actual yield of grain and the main crops fluctuated grew slowly; (ii) During the period 1982 – 1998, due to the agricultural policy of household contract responsibility system, enhancement of the level of agricultural science and technology, considerable use of pesticides and chemical fertilizer and other factors, the actual yield of grain and the main crops was significantly increased; (iii) During the period 1999 – 2001, affected by the extreme drought climate, the actual yield of grain and the main crops was drastically reduced, but rebounded after 2002, and due to the impact of national reforestation policies, the growth trend slowed down; (iv) Compared with the actual yield, there were also fluctuations in the climatic yield, but the trend was not significant.

4.2.2 The relationship between climatic yield and precipitation fluctuations. Using SPSS13.0, we carry out the correlation analysis between the climatic yield of grain, the main crops and inter-annual precipitation fluctuations in different time periods, and the results are shown in Table 2.

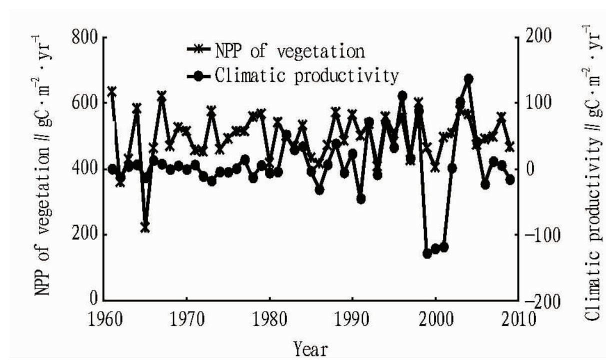

Fig. 5 The fluctuations of NPP, climatic productivity of agro-ecosystem in Jungar Banner (1961 – 2009)

Table 2 Correlation between climatic yield and inter-annual precipitation fluctuations

The inter-annual precipitation fluctuations	Climatic yield							
	Grain	Wheat	Millet	Broomcorn millet	corn	Potato	Soybean	Oil crops
The whole year	0.458**	–	0.380**	0.361*	0.394**	0.375**	0.340*	0.354*
The growing season	0.459**	–	0.313*	0.335*	0.417**	0.381**	0.305*	0.321*
May	–	–	–	–	–	–	–	–
June	–	–	–	–	–	–	–	0.332*
July	0.348*	–	–	–	0.351*	–	–	–
August	0.282*	–	–	–	–	–	–	–
September	–	–	–	–	–	–	–	–

Note: * indicates that the correlation is significant at the 0.05 level; ** indicates that the correlation is significant at the 0.01 level; – indicates that the correlation is no significant.

Table 3 The correlation between climatic yield and intra-annual precipitation fluctuations

The inter-annual precipitation fluctuations	Climatic yield							
	Grain	Wheat	Millet	Broomcorn millet	corn	Potato	Soybean	Oil crops
The whole year	–	–	–0.301*	–	–	–	–	–
The growing season	–	–	–0.324*	–0.288*	–	–	–	–

Note: * indicates that the correlation is significant at the 0.05 level; – indicates that the correlation is no significant.

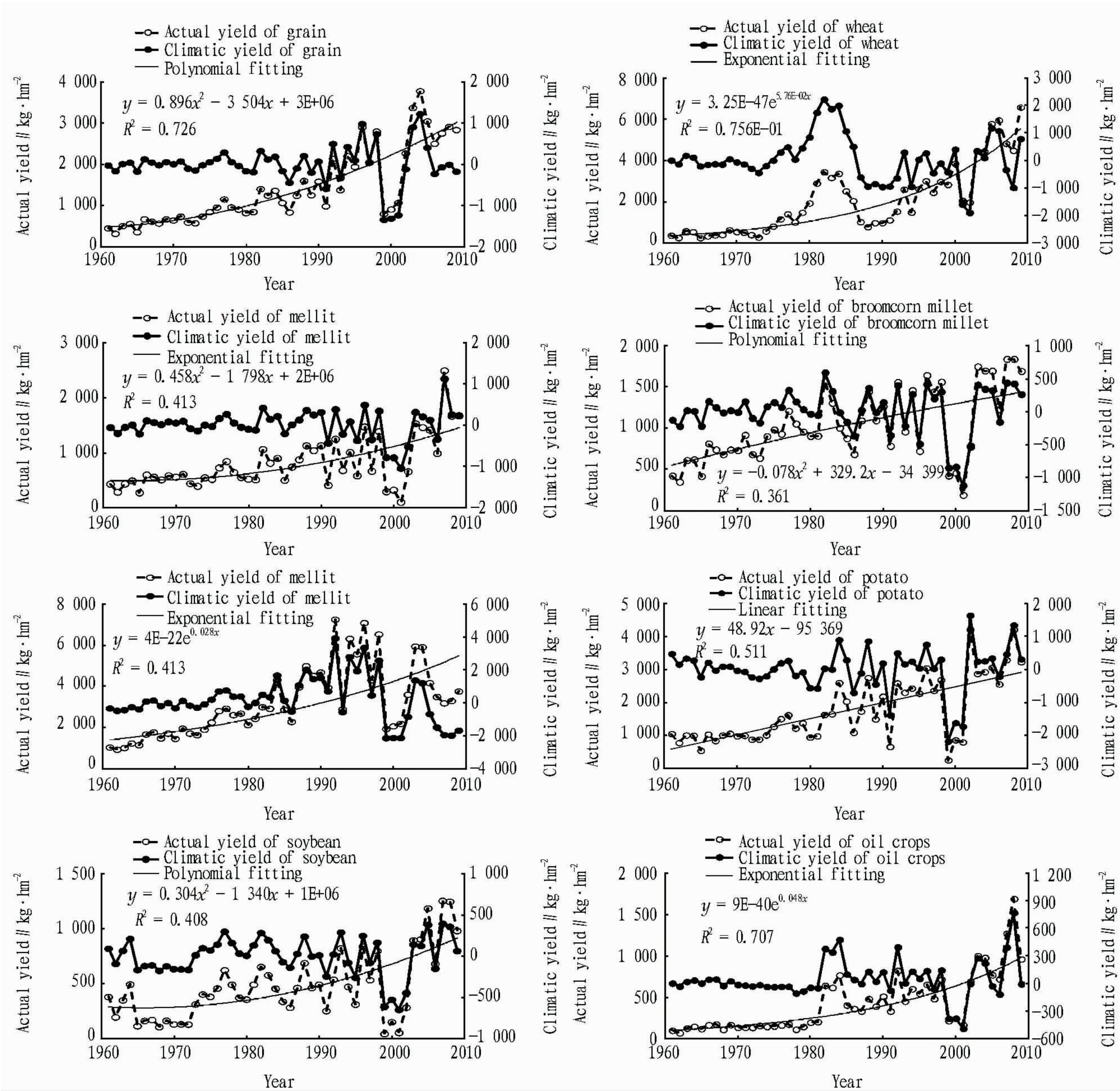

Fig. 6 Changes in the actual yield and climatic yield of grain and the main crops (1961 – 2009)

As can be seen from Table 2, in addition to wheat, there are different positive correlations between the climatic yield of grain, crops and the inter-annual precipitation fluctuations in the whole year and during the growing season, indicating that when the precipitation in the whole year and during the growing season increases, the climatic yield of grain and the main crops will increase accordingly; on the contrary, the climatic yield of grain and the main crops will decrease. Overall, there are significant positive correlations between the climatic yield of grain crops and inter-annual precipitation fluctuations in July and August, indicating that the abundance or deficiency of precipitation in July and August significantly affects the climatic yield of grain; the climatic yield of corn is significantly affected by the inter-annual precipitation fluctuations in July; the climatic yield of oil crops is sensitive to the inter-annual precipitation fluctuations in July. Similarly, using SPSS13.0, we carry out the correlation analysis between the climatic yield of grain, the main crops and the intra-annual precipitation fluctuations in the whole year and during the growing season, and the results are shown in Table 3.

From Table 3, we can find that the climatic yield of millet is significant negative correlated with intra-annual precipitation fluctuations during the whole year, indicating that the greater the coefficient of variation in precipitation during the whole year, the more uneven the intra-annual distribution of precipitation, so it is less conducive to growth and development of millet, and even may reduce the climatic yield; conversely, the climatic yield of millet may increase. Similarly, the climatic yield of millet, broomcorn millet is significant negative correlated with intra-annual precipitation fluctuations during the growing season, indicating that the greater the coefficient of variation in precipitation during the growing season, the more uneven the distribution of precipitation within the growing season, so it is less conducive to growth and development of millet and broomcorn millet, and even may reduce the climatic yield; conversely, the climatic yield of millet and broomcorn millet may increase.

Table 4 The correlation between climatic yield and inter-annual average temperature fluctuations

The inter-annual precipitation fluctuations	Climatic yield							
	Grain	Wheat	Millet	Broomcorn millet	corn	Potato	Soybean	Oil crops
May	–	–	–	–	–	–0.327*	–0.332*	–
June	–0.386**	–	–0.508**	–0.482**	–	–0.382**	–0.432**	–0.501**
July	–0.418**	–	–0.537**	–0.438**	–	–0.529**	–0.542**	–0.545**
August	–0.365**	–	–0.403**	–0.334*	–	–0.425**	–0.361*	–0.441**
September	–	–	–	–	–	–	–	–

Note: * indicates that the correlation is significant at the 0.05 level; ** indicates that the correlation is significant at the 0.01 level; – indicates that the correlation is no significant.

Table 5 The correlation between climatic yield and intra-annual average temperature fluctuations

The inter-annual precipitation fluctuations	Climatic yield							
	Grain	Wheat	Millet	Broomcorn millet	corn	Potato	Soybean	Oil crops
The growing season	–	–	–0.442**	–0.293*	–	–	–0.361*	–0.351*

Note: * indicates that the correlation is significant at the 0.05 level; ** indicates that the correlation is significant at the 0.01 level; – indicates that the correlation is no significant.

4.2.3 The relationship between climatic yield and average temperature fluctuations Using SPSS13.0, we carry out the correlation analysis between the climatic yield of grain, the main crops and the inter-annual average temperature fluctuations in May, June, July, August and September, respectively, and the results are shown in Table 4.

Table 4 shows that on the whole, there is a significant negative correlation between the climatic yield of grain, the main crops and inter-annual average temperature fluctuations, indicating that if the inter-annual average temperature fluctuations during the growing season are greater, beyond the optimum temperature for the crops in different growth stages, it will be not conducive to crop growth, and the climatic yield of crops may reduce; if the inter-annual average temperature fluctuations during the growing season are smaller, there will be smaller impact on the crop growth and development, and the stability in climatic yield of crops will be stronger. The inter-annual average temperature fluctuations in May have a significant impact on the climatic yield of potato and soybean; the inter-annual average temperature fluctuations in June, July and August have a significant impact on the climatic yield of crops (except wheat and corn). Similarly, using SPSS13.0, we carry out the correlation analysis between the climatic yield of grain, the main crops and the intra-annual average temperature fluctuations during the growing season, and the results are shown in Table 5.

As can be seen from Table 5, the intra-annual average temperature fluctuations during the growing season significantly affect the climatic yield of millet, broomcorn millet, soybean and oil crops; if such fluctuations are larger, beyond the optimum temperature and tolerance limits of crops at different growth stages, it will be not conducive to crop growth, and the climatic yield of crops will reduce; conversely, the climatic yield of crops may increase.

5 Conclusions and recommendations

The agricultural ecosystem in the northern farming-pastoral region is a complex giant ecology-economy-society system, and agricultural ecosystem productivity is affected by natural conditions, national policies and technological level. The climate change has a significant impact on the functions of ecosystem in the farming-pastoral region[39-42]. In this study, we take Jungar Banner in the farming-pastoral region as a typical case to analyze the response of agricultural ecosystem productivity to the climate fluctuations. And conclusions are as follows:

(i) The inter-annual and intra-annual precipitation fluctuations are both particularly significant in Jungar Banner; the inter-annual and intra-annual average temperature fluctuations are also significant in July, August and September. The inter-annual precipitation fluctuations in the whole year and during the growing season are both particularly significant and highly consistent, and the inter-annual precipitation fluctuations are also significant each month during the growing season, particularly evident in July and August; the intra-annual precipitation fluctuations in the whole year and during the growing season are also particularly significant. The fluctuated changes in the precipitation and average temperature in the northern farming-pastoral region, coupled with the climate warming and drying trend, will be bound to have significant effects on the growth and development, variety maturity, planting area, yield and quality of food crops in the regional agricultural ecosystem[43].

(ii) The agricultural ecosystem productivity in Jungar Banner showed a prominent upward trend in volatility, which could be roughly divided into three stages: (a) During the period 1961 – 1981, the growth was slow; (b) During the period 1982 – 1998, affected by the agricultural policy of household contract responsibility system, enhancement of the level of agricultural science and technology, considerable use of pesticides and chemical fertilizer and other factors, NPP of agricultural ecosystem experienced significant growth; (c) during the period 1999 – 2001, affected by the extreme drought climate, NPP of agricultural ecosystem reduced drastically but rebounded after 2002, and due to the impact of national reforestation policies, the growth trend slowed down.

(iii) There are different positive correlation between the climatic yield of millet, broomcorn millet, corn, potato, soybean and oil crops, and the inter-annual precipitation fluctuations in the whole year and during the growing season. Especially in July and August, the inter-annual precipitation fluctuations obviously affect the climatic yield of grain. The climatic yield of corn is significantly affected by the inter-annual precipitation fluctuations in July; the climatic yield of oil crops is sensitive to the inter-annual precipitation fluctuations in June. In terms of the whole year, there is a significant negative correlation between the climatic yield of millet and the intra-annual precipitation fluctuations; in terms of the growing season, there is a significant negative correlation between the climatic yield of millet, broomcorn millet, and the intra-annual precipitation fluctuations. Therefore, whether in the whole year or during the growing season, the ill-timed precipitation will significantly affect the climatic yield of millet. Meanwhile, the increase in light and heat resources is bound to increase the crop field evapotranspiration, and the possibility of reduced precipitation may increase the drought risk in Loess Plateau[44]. Based on the characteristics of precipitation fluctuations in this region, it is necessary to strengthen the research on the field furrow water harvesting, mulching, drought-resistant agents, drought-resistant varieties and water-saving technologies[45], as well as the SPAC system theory, to develop water-gathering eco-agriculture[46], improve water and fertilizer and heat conditions, maintain the dynamic balance of soil organic matter, reduce drought risk, and enhance the stability of agricultural ecosystem.

(iv) The inter-annual average temperature fluctuations in May have a significant negative impact on the climatic yield of potato and soybean. For the potato, in the late period of tuber formation, 17 – 18 ℃ is the most appropriate; for the soybean, the number of days from emergence to flowering is swayed by temperature, and if below 17 ℃, the flowering will be greatly delayed. During the period 1961 – 2009, the average temperature in May was about 17℃ in Jungar Banner, so the inter-annual average temperature fluctuations in May have a significant impact on the climatic yield of potato and soybean. In addition to wheat and corn, there is a significant negative correlation between the climatic yield of millet, broomcorn millet, potato, soybean and oil crops and the inter-annual average temperature fluctuations in June, July and August; the intra-annual average temperature fluctuations during the growing season have a significant negative impact on the climatic yield of millet, broomcorn millet, soybean, oil crops and other crops. The average temperature fluctuations during the growing season in Jungar Banner and climatic warming may bring agrometeorological disasters. Therefore, based on the climate characteristics of rain and heat in the same period, coupled with the trend of rising temperatures in Jungar Banner, we can on one hand choose to introduce some crop species with a long growth period[47], and on the other hand take effective protective tillage practices.

(v) As the ecological factors, precipitation, temperature, sunshine, wind and other weather elements all affect the agricultural ecosystem productivity, and as natural capital, they participate in the nutrient cycling and energy flow of agricultural ecosystem. The fluctuated climatic characteristics in Jungar Banner, coupled with other natural driving forces and human activities, are bound to have an important impact on the structure and function of the region's fragile ecosystem, and exacerbate the land degradation. Thus, in the process of building the ecological environment in Jungar Banner, it is necessary to maintain and consolidate the soil and water conservation projects, vigorously promote and implement the biological measures based on growing thermophilic and drought-resistant crops, rely on science and technology to improve agriculture, and minimize the adverse effects of climate fluctuations on the agricultural ecosystem productivity.

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