



Sensitivities of Wheat and Maize Productivity in Kazakhstan to Future Climate Change Scenarios

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Abstract

Crop productivity is sensitive to climate change, especially in arid Central Asia, where few studies have been conducted on how crop productivity responds to global climate change. Based on the history of yield trends of major crops in Kazakhstan, this study proposed a quantitative method to estimate the sensitivity of relative crop yields to agro-technique development and temperature rise in Kazakhstan. Taking wheat and maize as typical crops, this research attempted to assess the potential impact of future global climate change scenarios on crop yields in 14 agricultural areas of Kazakhstan, based on the interaction between agro-technique development and climate change. The effects of future agro-technique development were assumed to be consistent with historical trends, which were expressed in a second-order polynomial form and adjusted by the disparity between actual yields and predicted yields. The parameters representing technology development were determined by the special report of the Intergovernmental Panel on Climate Change (IPCC) on emission scenarios and the future temperature was predicted by the global climate change model, IPSL-CM5A-LR Model (ICLM). In this study, 2060 and 2100 were selected as assessment years. The results showed that crop yields will continue to increase until 2060 under future climate change scenarios, but the estimates of yield changes after 2060 are subject to great uncertainty in the longer term. By 2100, the impact of temperature rise on crop productivity will be greater in the southern and eastern areas than that in the central and western areas. Crop productivity will be improved with the combined impact of temperature and technology under Representative Concentration Pathway 2.6 (RCP2.6), Representative Concentration Pathway 4.5 (RCP4.5) and Representative Concentration Pathway 6.0 (RCP6.0) by 2060. However, compared with 2060, the relative yields of the two crops will be improved under RCP2.6, RCP4.5 and RCP6.0 scenarios by 2100. By contrast, the results under Representative Concentration Pathway 8.5 (RCP8.5) are not uniform: the yield of wheat will decrease by 7.4%, while that of maize will increase by 23.86% compared with 2060. The contribution rate of agricultural technology to improving maize yield is higher than that to wheat yield and maize is less sensitive to temperature than wheat in terms of yield. The wheat yield increases the most in the RCP4.5 scenario and the maize yield increases most in the RCP6.0 scenario. Considering that the wheat yield counts for more than 70% of crop production in Kazakhstan, it is suggested that emissions are controlled to reach the RCP4.5 standard and maximize the agricultural yields.

Keywords Climate change · Crop yield · Relative change · Sensitivity · Future scenarios

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Introduction

Global climate change is having a great impact on the development of human society, especially on global agricultural production. It has attracted great international attention in recent years. The global annual average surface temperature has increased by 0.85 °C between 1880 and 2012, based on the detection of carbon dioxide (CO₂) emission and the feedback results of various popular global change models (IPCC, 2013). Meanwhile, fluctuations in global food prices and crop yields initiated by the high sensitivity of crops to climate change will to some extent affect decision-making in all sectors of the economy, especially in the agricultural sector (Downing & Parry, 1999; Knox & Wade, 2012). Therefore, there is an urgent need to develop balanced and sustainable strategies to address food security (Jha & Srinivasan, 2015).

Climate change causes fluctuations in crop yields. For example, climate change can increase yields by providing a suitable environment for crops to grow in the right phenology. By contrast, it can also lead to more severe agricultural production conditions (Fischer et al., 2005). In general, crops ensure yield by adjusting their physical characteristics to climate change (Manderscheid & Weigel, 2007; Rosenzweig & Parry, 1994). However, the limited self-regulation capacity of crops is simply unable to cope with frequent extreme events such as floods and droughts caused by warming effects (Chiotti & Johnston, 1995), leading to a reduction in crop yields. Hatfield et al. (2011) found that increased emissions of CO₂ would increase crop yields in the future. Other scholars (Knox et al., 2012; Osborne et al., 2009; Tjahjono et al., 2019) used the global climate model to assess the impact of climate change on crop yields in Africa and South Asia and analyzed crop production potential in different areas. The results showed that climatic factors harmed the production potential of wheat, maize, and millet, but had no obvious effect on cassava and sugarcane. In addition, in the study of regional crop yield estimation, regional habitat differences (soil, topography, potential evapotranspiration, precipitation, temperature, etc.) also affected crop yield. The habitats were inevitably affected by climate change, so climate change was still the main factor leading to crop yield uncertainty in small regions (Smit et al., 1989). In contrast, the implementation of agricultural technology could mitigate the negative effects of climate change to some extent (Kongchum et al., 2007). For example, crop yields could be increased through measures to improve agricultural techniques, such as controlling pests, establishing seeds in centres of genetic diversity reserves, and reducing soil erosion (Svetlana et al., 1999). Therefore, the dual factors of climate change and agricultural technology

need to be taken into account when predicting future crop yields. In central Asia, the problem of food security is becoming increasingly prominent, and the sensitivity of accurately predicting crop production potential provides a theoretical basis for the promulgation of agricultural policies to adjust agricultural structure in a timely manner and to optimise agricultural production efficiency.

Kazakhstan is among the five Central Asian countries with the largest cultivated area, which is the most important food-producing area in Central Asia (Aksoy & Beghin, 2005). A large part of the grasslands has been converted to farmland due to the special geographical location and the dividend policy guidance during 1954–1964, which helped Kazakhstan to become the third-largest agricultural production area in the former Soviet Union (Pomfret, 1995). However, after Kazakhstan's independence in 1991, the agricultural sector suffered immensely, which set back the economy of the country. To return to pre-independence levels, the government introduced a series of policies to encourage agricultural production to meet food self-sufficiency. Although the area of cultivated land was expanded and supported by agricultural investment, the further increase of crop yields still faced great challenges (Herath, 1998; Pimentel et al., 1992). At present, scholars are conducting many studies on crop yield and food self-sufficiency in Kazakhstan, focusing on land productivity and crop productivity. Due to the factors of population size and natural resources, the evaluation results of productivity potential in various ecological environments are quite different from the actual results. For example, the main crop has shown a certain amount of growth, but the growth conditions are worsening, which will affect crop yields in the future (Istvan Feher et al., 2017). From a biophysical (crop growth) perspective, the economic incentives and competition from other crops become the major factors limiting crop growth potential under different scenarios (Swinnen et al., 2017). However, the production potential of crops in Kazakhstan and the balance of food demand have not yet reached a consistent conclusion because of different estimation methods (Azevedo et al., 2003). Studies on the sensitivity of regional climate change and agricultural technology development to crop production potential in Kazakhstan are still lacking. Therefore, an accurate assessment of the sensitivity of Kazakhstan's food production to future scenarios would contribute to supplement corresponding research gaps to help to improve the agricultural policies.

Many datasets have been established in existing studies, but the lack of a continuation of historical trends and the agro-technique (including crop management and breeding) of crop potential development has led to inadequate and inaccurate databases related to the various components of the crop production system (Tubiello & Ewert, 2002). Therefore, to explore the future crop production potential and regionalisation in Kazakhstan, this paper attempts to

develop quantitative, spatially-explicit and alternative scenarios to quantify the sensitivity of wheat and maize productivity across agricultural areas under the change of future temperature and technology development. Based on historical crop yield data, we assume other influencing factors (such as precipitation, human impact, species change, etc.) to change according to historical trends. In the estimation, the influence of other factors on crops was not calculated separately from the historical trend. Four scenarios, RCP2.6, RCP4.5, RCP6.0 and RCP8.5, were used to explore the sensitivity of crop production potential in Kazakhstan to climate change and agro-techniques. The purpose of this study was to reveal the regional variation characteristics of food crops in Kazakhstan based on different agrotechnique development scenarios and quantify the relationship between food crop production potential, climate change, and agro-technique development.

Study Area, Data and Methodology

Study Area

Kazakhstan, as one of the most important countries along the route of the Silk Road, is adjacent to China, Russia, Uzbekistan, Turkmenistan, and Kyrgyzstan. It is also the largest country in Central Asia, connecting Asia and Europe, with a land area of about $2.72 \times 10^6 \text{ km}^2$, ranking ninth in size in the world (Fig. 1). Most of Kazakhstan is made up of plains and lowland, such as the lowlands of Turan and the Caspian coastal lowlands in the south-west; the middle and east belong to the Kazakhskiy Melkosopochnik region and the eastern edge is mountainous. The south-west comprises mostly desert and semi-desert, while the natural environment in the north is relatively humid, similar to that in Russia. In general, the topography is high in the south-east and low in the north-west. Kazakhstan has a continental climate, with an average annual precipitation of 300–500 mm in the north, 100 mm in the desert and 1000–2000 mm in the mountainous areas.

Kazakhstan has a small population and the economy is supported mainly by heavy industry, agriculture, and animal

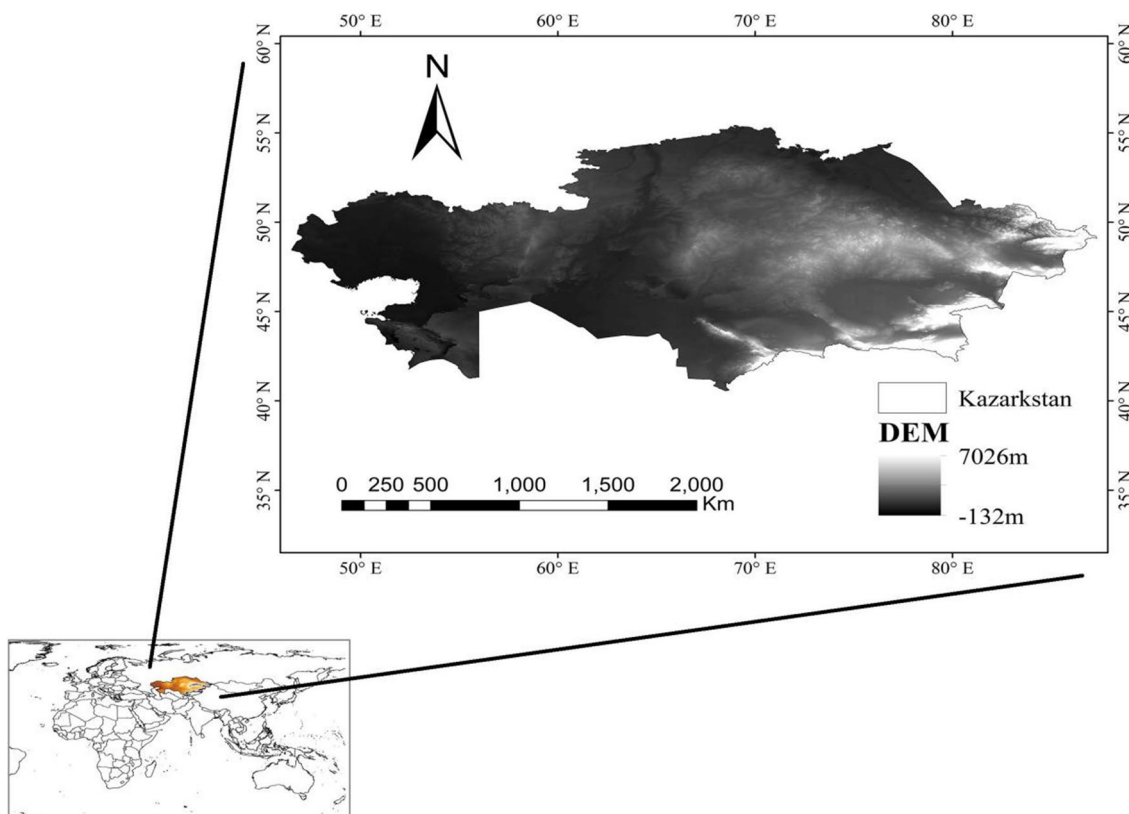


Fig. 1 Schematic map of the study area (the lower left picture is central Asia)

husbandry. Among them, the main crop types are wheat, maize, barley, oats, and rye. Most of the grain-producing areas are concentrated in the northern part of Kostanai, northern Kazakhstan, and Akmolain. While Kazakhstan has large tracts of arable land to ensure food supplies for its people, climate change could make agricultural development unstable. Therefore, how to use the limited labour force to improve agricultural productivity as efficiently as possible has become an important issue for the agricultural sector of Kazakhstan.

Data

Historical data for the crop yields selected for this study came from the Kazakhstan Statistics Agency, which contains the annual agricultural data of 14 prefectures, including the annual yield and planting distribution of wheat, rice, corn, sugar beet and other crops, as well as the planting areas of various crops in Kazakhstan. The data has been officially recognised by Kazakhstan, so it could be used to represent past agricultural development trends. This study took two representative food crops, wheat and maize, as target crops. Since agricultural development suffered heavily after 1992, historical yields could not be represented. Therefore, the average annual yield data of the Kazakhstan Statistics Agency from 1997 to 2016 were selected as historical data in this study. This study used data from 14 prefectures of Kazakhstan as the statistical areas, and the data of the cultivated land area, crop type, and crop yield were counted using the geostatistical method. The average annual yield of crops fluctuated greatly from 1997 to 2016 (Fig. 2, data source: Kazakhstan Statistics Agency).

Figure 2 shows that with the agricultural development of Kazakhstan, the yield of the two crops rises with great fluctuation. Overall, Kazakhstan’s wheat yield per hectare (ha) is less than that of maize, and the gap is widening. At the same time, maize’s yield per ha is growing faster than wheat’s. Kazakhstan’s Gross Domestic Product (GDP) increased rapidly during this time period and it became one of the fastest-growing countries at that time (China, Kazakhstan and India). Agricultural output accounted for about 7% of GDP due to the promulgation of the Agri-Food Program (AFP) of the World Bank. However, it was affected by the global economic crisis in 2008, and crop production fell seriously due to market tightening and other factors. Annual output in 2008 was comparable to that in 2001. Economic, agro-technique and other factors have an impact on crop yields in Kazakhstan. The historical development trend of crop yield provides the basis and reference for predicting future crop production potential.

The methodological flowchart of this study is shown in Fig. 3, which was applied for estimating crop productivity.

Methods

Analysis of Historical Yield Trends

$$Y_{e[r,c,ty]} = f_{[r,c,ty]} * t_y + b_{[r,c]} \tag{1}$$

$$Y_{R,a[r,c,ty]} = Y_{[r,c,ty]} / Y_{[r,c,ty-1]} - 1 \tag{2}$$

$Y_{e[r,c,ty]}$ is the estimated yield at a particular year ty . The annual rate of yield change is represented by $f_{[r,c,ty]}$ and $b_{[r,c]}$ is an empirical parameter. $Y_{R,a[r,c,ty]}$ represents the annual

Fig. 2 Trend of wheat and maize yields in Kazakhstan from 1997 to 2016

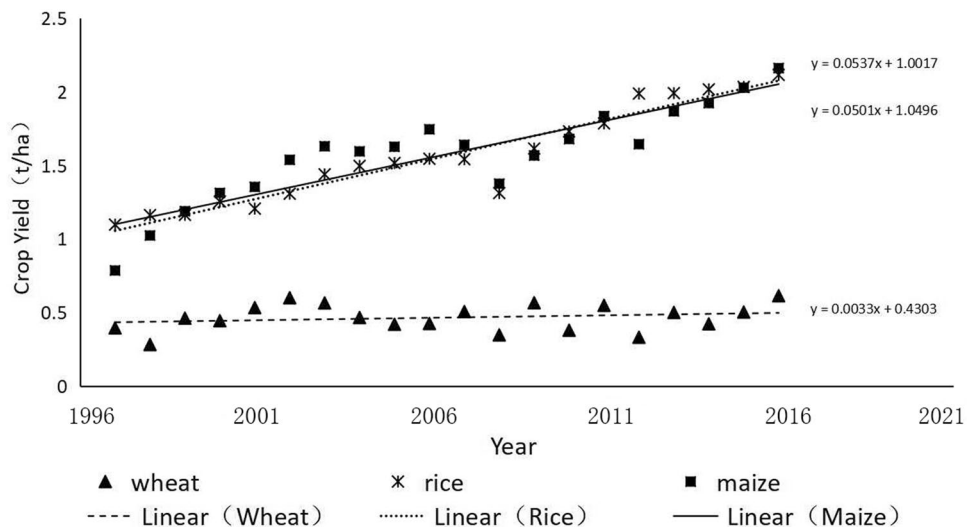
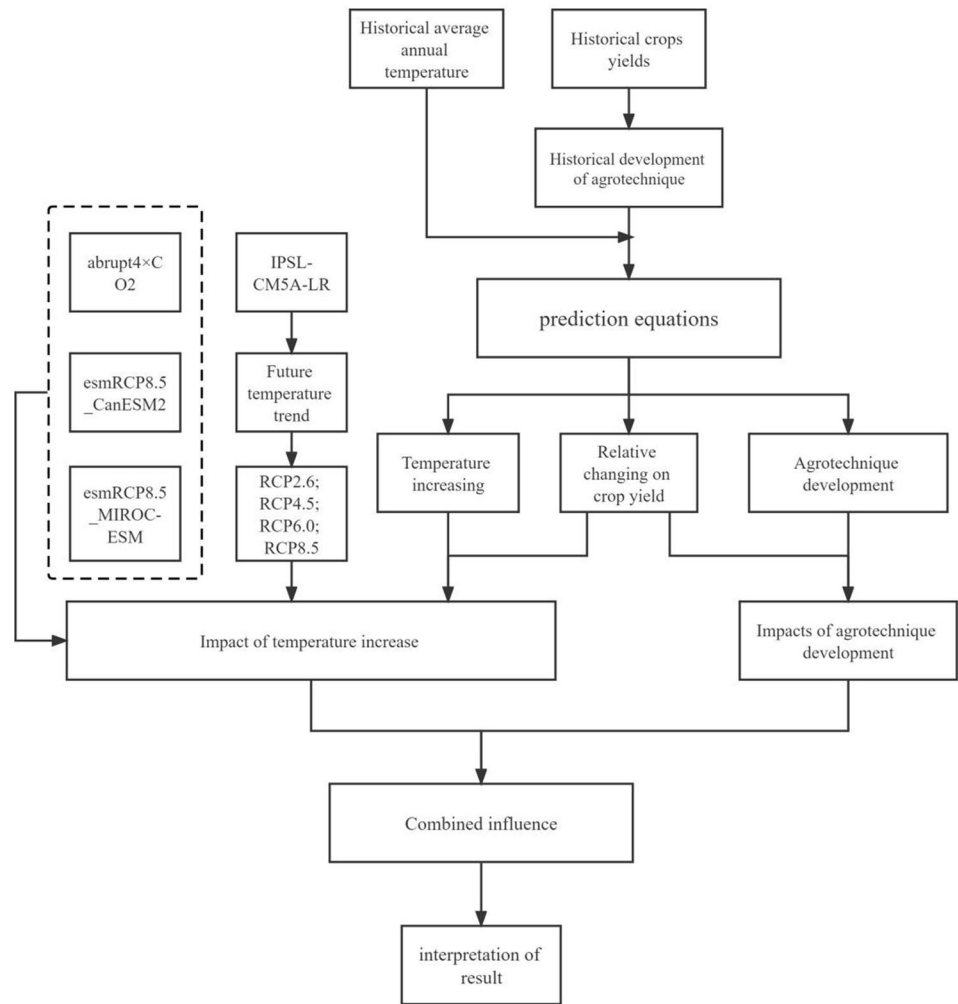


Fig. 3 Flowchart of the study



relative yield change rate of crop *c* at the year *ty*. $Y_{[r,c,ty]}$ and $Y_{[r,c,ty-1]}$ represent the crop yields at time *ty* and *ty-1* is calculated from the fitted regression lines through observed yields, respectively.

Future Relative Change in Crop Yield

$$Y_{[r,c,t]} = A_{[r,c]} * \lim_{n \rightarrow \infty} \prod_{i=1}^n f(X_{[r,c,i,t]}), \tag{3}$$

Many factors affect crop growth and yield but, in general, it is impossible to determine all the influencing factors. A part of the influencing factors which cannot be

observed can be considered as becoming the cause of the error between the actual yield and the theoretical yield. In studies related to agriculture, some scholars have found that there are interactions between various influencing factors. In terms of nitrogen and water effects, crop yield changes with a change in the nitrogen content in water (Dichio et al., 2007). On a larger spatial scale, such as a regional, national, or even global scale, the influence generated by such interaction over long periods of time was often obscured by other major factors. In the long run, the most important factors affecting crop yields include technology development, fertiliser use and climate change (Rounsevell et al., 2005

$$\frac{Y_{[r,c,t]}}{Y_{[r,c,t0]}} = \frac{f(T_{ech[r,c,t]})}{f(T_{ech[r,c,t0]})} * \frac{f(C_{[r,c,t]})}{f(C_{[r,c,t0]})} \tag{4}$$

$Y_{[r,c,t]}/Y_{[r,c,t0]}$ represents the future relative change in crop yield, as affected by the change in technology development. $f(T_{ech[r,c,t]})/f(T_{ech[r,c,t0]})$ stands for future technology development and $f(C_{[r,c,t]})/f(C_{[r,c,t0]})$ donates climate change that affects crop yield, respectively.

Effect of Future Agro-Technique Development on Crop Yield Growth

Ewert et al. (2005) divided agricultural technology development measures into two parts: crop management and breeding. Crop management is a way to optimise crops’ resistance to physiological stress, pests, and diseases, which is referred to cultivate new crop varieties with higher potential yield, by improving farmers’ knowledge about machinery, fertilisation, pest control, weeding and other agricultural knowledge. Because technological development changes with time and can accumulate, the influence of future technological development on crop yield must consider the historical trend of crop yield changes. Ewert transformed the change rate of annual crop output caused by technology development for the historical change rate of relative production (Ewert et al., 2005

$$\frac{f(T_{ech[r,c,ts]})}{f(T_{ech[r,c,t0]})} = 1 + \int_{t0}^{t=ts} \left(\frac{(Y_{R,a[r,c,t0]} * f(Tech, P_{R[r,c,ts]}) * f(Tech, G_{R[r,c,ts]}))}{P_{p[r,c,t0]}} \right) dt \tag{5}$$

$f(Tech, P_{R[r,c,ts]})f(Tech, G_{R[r,c,ts]})$ are the components to account for changes in the potential yield and changes in relative yield, respectively, which are used to adjust and simulate the historical relative yield change at the base year $t0$ ($Y_{R,a[r,c,t0]}$, which is calculated by Eq. (2). $P_{p[r,c,t0]}$ is the differentials of present actual crop yields to potential yields. This approach pushes historical yield trends into the future simply, focusing on relative rather than absolute yield changes. Its advantage is that the average yield changes between different crops and areas can be compared to avoid unnecessary complexity.

Effects of Increasing Temperature

The potential change directly caused by global climate change is rising temperature (IPCC, 2007). If no further efforts are made to reduce emissions, anthropogenic greenhouse gas emissions will continue to increase in the future. The CO₂ concentration will exceed 450 parts per million (ppm) by 2030 and 750 ppm by 2100. The average global surface temperature will increase by 3.7–4.8 °C compared to pre-industrialization (IPCC, 2013). Currently, the interaction between interception radiation and canopy conductivity, measured by the water content and temperature of crops, will affect the photosynthesis and yield of crops. The understanding of the comprehensive effect of temperature on crop growth and yield is currently very limited (Connor et al., 1999). Crop yield will change according to varieties when the temperature rises above a threshold, which often affects the key development stage of some crops and cause serious crop yield loss (IPCC, 2013). Therefore, temperature has an important impact on the growth of crops. Schlenker and Robert (2006

$$\frac{f(T_{emp[r,c,t]})}{f(T_{emp[r,c,t0]})} = 1 + \sum_{j=0}^n c_{j[r,c]} * \Delta T_{emp[r,c,t]}^j \tag{6}$$

$\Delta T_{emp[r,c,t]}$ donates future temperature change compared to the current level.

Climate Change Scenarios

In this study, IPSL-CM5A-LR model (ICLM) simulation results (Institut Pierre-Simon Laplace-Earth System Model for the 5th IPCC Report, Low Resolution) were selected to predict the temperature information from 2017 to 2100. The IPCC fifth assessment report (AR5) relied heavily on the Coupled Model Intercomparison Project Phase 5 (CMIP5), a collaborative climate modelling process coordinated by the World Climate Research Programme (WCRP) (IPCC, 2013). According to the differences in CO₂ concentration, radiation cycle, and land-sea distribution, CMIP5 used 61 models from 14 climate model centres to simulate future climate. Four RCP scenarios were selected based on the total forced path and level of radiation by the end of the century. RCP was chosen to represent a wide range of climate outcomes, each of which might come from different combinations of economic, technological, demographic, policy, and institutional futures (IPCC, 2013). This study chose four groups of data of RCP2.6, RCP4.5, RCP6.0 and RCP8.5 as input data to future climate change simulation,

at the same time increased abruptly $4\times\text{CO}_2$ (ABC), esmRCP8.5_CanESM2 (ESMC) and esmRCP8.5_MIROC-ESM (ESMME) data as control groups. Relative to pre-industrial 1750, RCP2.6, RCP4.5, RCP6.0, and RCP8.5 represented total radiation forcing of 2.6w/m^2 , 4.5w/m^2 , 6.0w/m^2 , and 8.5w/m^2 at the end of the century, respectively. The other three kinds of forecast data in this research are respectively expressed as follows: (1) ABC, compared with pre-industrial conditions, which is four times of atmospheric CO_2 applying in an instant and remaining fixed; (2) ESCM, the predicted value of the Canadian Earth System Model under the RCP8.5 scenario, whose results are influenced by the co-influence of the atmospheres—the oceans circulation model, the land-vegetation model and the carbon cycle of land–ocean interaction (Chylek et al., 2011); (3) EsmRCP8.5_MIROC—the ESM, in the RCP8.5 situation, the environmental model put forward by the ocean and earth science and technology department of Japan, atmospheric and oceanic research institute (Tokyo University) and the national institute. Based on the Model for Interdisciplinary Research on Climate (MIROC), it further includes atmospheric chemical composition (CHASER), nutrient-plankton-zooplankton-debris (NPZD) marine ecosystem composition and terrestrial ecosystem composition of 10 dynamic global vegetation models (SEIB-DGVM) (Watanabe et al., 2011).

Parameterisation

According to the administrative divisions of Kazakhstan, a total of 14 prefectures were used as agricultural areas for research: Almaty, Aqmola, Aktyubinsk, Atyrau, East Kazakhstan, Mangghystau, North Kazakhstan, Pavlodar, Qaraghandy, Qostanay, Qyzylorda, South Kazakhstan, West Kazakhstan, and Zhambyl, which are shown in Fig. 4. In the future consider using the zones and for this study display the ecological zones. This study uses 2016 as the base year. Table 1 shows the information of the base year. Wheat and maize were the main cultivated crops in Kazakhstan, accounting for 76.29% of the total crop yield in 2016, of which the wheat and maize yields accounted for 72.62% and 3.67% respectively. Wheat was the main export crop of Kazakhstan and the acreage was larger than 80% of the total planting area, which is mainly found in north-central Kazakhstan, including Aqmola, North Kazakhstan, Qostanay, Pavlodar, and Qaraghandy. Meanwhile, maize was planted in scattered areas, due to regional climate, environment, and social economy. Of the 14 prefectures, Atyrau and Mangghystau were no longer growing wheat by 2016; and only Zhambyl, South Kazakhstan, Qyzylorda, East Kazakhstan and Almaty areas grew maize.

Before independence, Kazakhstan's agriculture had maintained a stable and rapid development due to an abundant labour force, subsidies from the former Soviet Union, and a wide market. It was the 'breadbasket' of the former Soviet Union (Pomfret, 1995). Affected by the collapse of the Soviet Union in 1992, Kazakhstan's agriculture declined. To improve the situation, the Kazakh government made sweeping reforms, including the areas of farming and animal husbandry. At the same time, Kazakhstan's economy began to grow due to the rise of the oil industry. The GDP grew quickly after 2000, which provided the foundation for agricultural capital demand. The government increased investment in agriculture after the promulgation of the National AFP in 2003, and agricultural development gradually improved (Bank World, 2005).

Fig. 4 Overview of the state of Kazakhstan

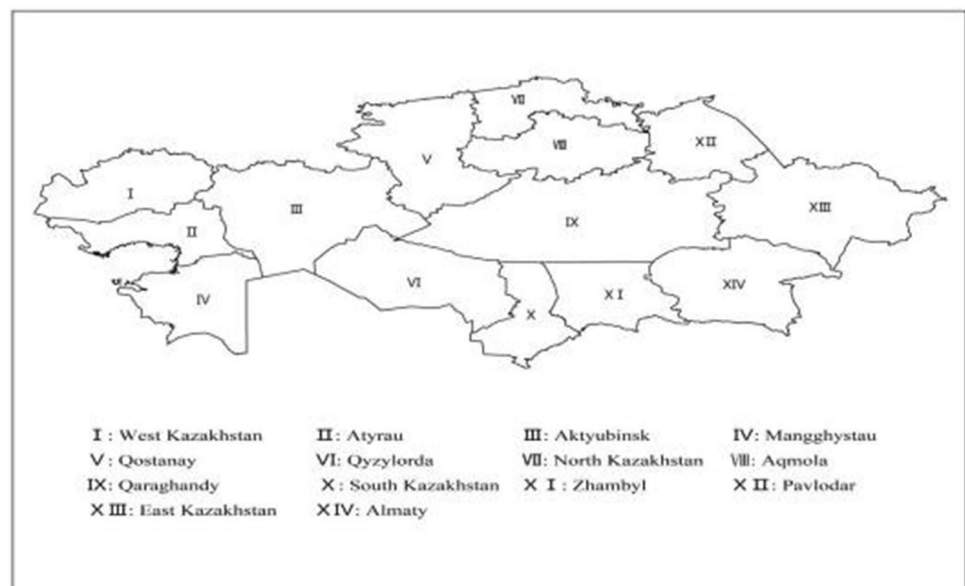


Table 1 Basic information about Kazakhstan agriculture in the base year

	Wheat	Maize	All crops
Gross yield (thsd tons)	14,984.1	757.1	20,632.7
Percentage of total crop yield	72.62%	3.67%	100%
Relative yield change (from 2015)	9%	3.23%	10.50%
Crop area (thsd ha)	12,435.4	133.2	15,401.4
Percentage of total crop area	80.74%	0.86%	100%
Crop area relative change (from 2015)	5.12%	-3.69%	2.80%
Crop yield per unit area (ton per ha)	1.20496	5.68393	1.33966
Agricultural areas	Aqmola, Aktyubinsk, East Kazakhstan, North Kazakhstan, Pavlodar, Qaraghandy, Qostanay, Qyzylorda, South Kazakhstan, West Kazakhstan, Zhambyl	Almaty, East Kazakhstan, Qyzylorda, South Kazakhstan, Zhambyl	Aqmola, Aktyubinsk, Atyrau, East Kazakhstan, North Kazakhstan, Pavlodar, Qaraghandy, Qostanay, Qyzylorda, South Kazakhstan, West Kazakhstan, Zhambyl

The analysis of the historical trend of crop yield from 1997 to 2016 is based on the data provided by the Kazakhstan Statistics Agency, and the crop yield from 2017 to 2100 is simulated. The years 2060 and 2100 were selected as the key years to analyse the future crop production potential. The ICLM simulated the future temperature of Kazakhstan under four different concentration paths. Scholars have conducted many studies on the factors affecting crop yield at present. Crop yield and temperature showed a non-linear relationship under different temperature conditions. Rosenzweig (1993) found that, under the direct influence of CO₂

$$\frac{f(T_{emp[r,c,t]})}{f(T_{emp[r,c,t0]})} = 1 + \begin{bmatrix} -0.0329 \\ -0.0211 \end{bmatrix} * \Delta T_{emp[r,t]}^2 + \begin{bmatrix} 0.1283 \\ 0.0812 \end{bmatrix} * \Delta T_{emp[r,t]} + \begin{bmatrix} 1E - 6 \\ 7E - 17 \end{bmatrix} \quad (7)$$

Results and Discussion

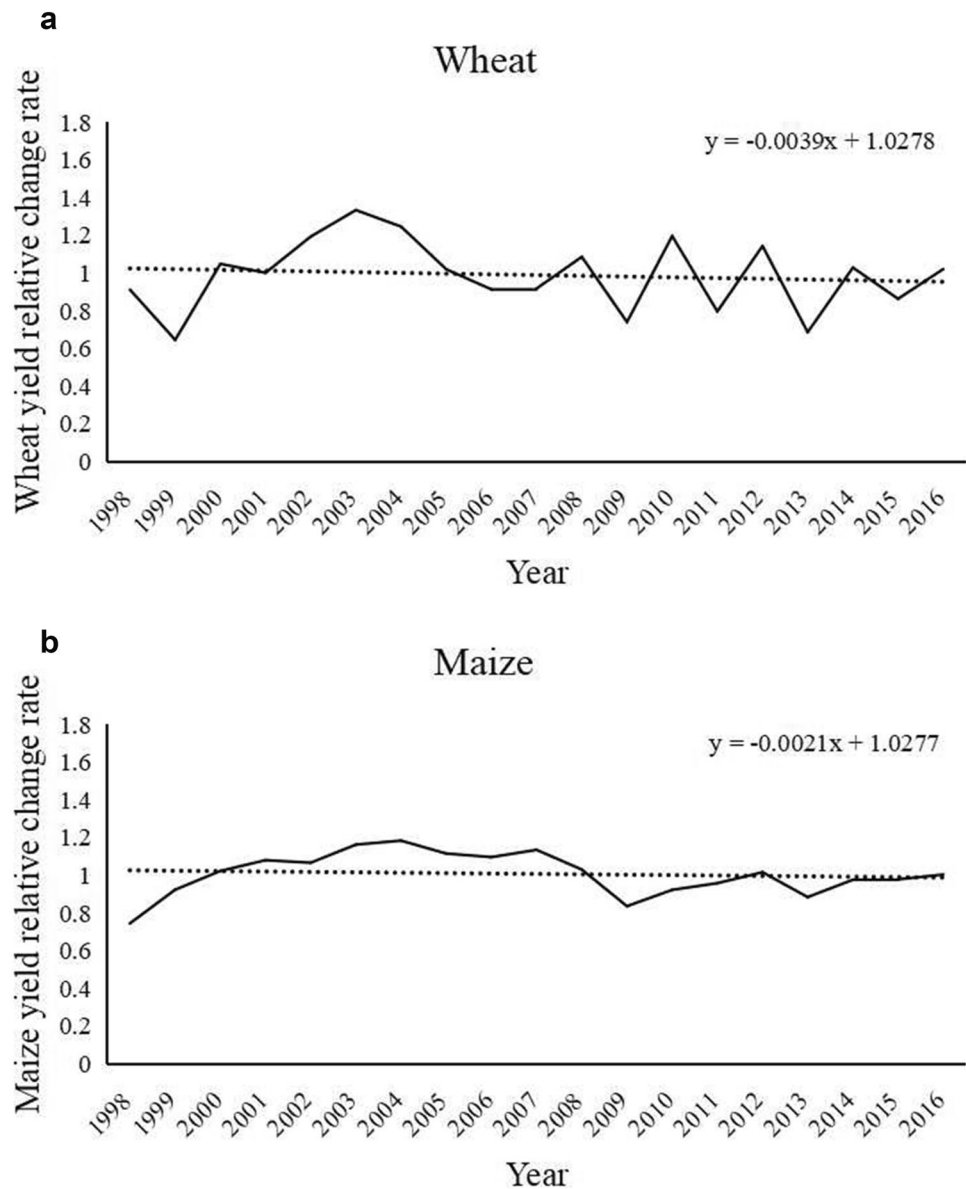
Impacts of Agro-Technique Development on Crop Yield

When forecasting the future crop yield, it is necessary to consider the historical yield and future trends in combination with other factors. Figure 5 shows the change rate and the historical trend of the two crops' yields. The yield relative change rate of wheat in 1997–2016 was tending to 1. The overall trend was declining, and the wheat yield change rate was unstable from 2010 to 2016. The wheat yield was highest in 2004 and lowest in 1999, which were 3.5% higher and 0.65% lower than that in the base year 2016 for future estimation, respectively. However, the maize yield changed

more gently. It increased from 1997 and reached its highest level in 2004, then declined to its lowest level in 2010, which was an increase of 2% and a decrease of 0.55% from the base year 2016, respectively, and it showed a gentle upward trend after 2010. The results demonstrate that these two crop yields in Kazakhstan had not been significantly improved, implying that Kazakhstan's agro-technique development and management policy were not sufficiently developed and practised.

The simulated results of wheat and maize yields in 2017–2100 under four scenarios indicate that the responses of crop yield changes vary under different concentration paths (Fig. 6). On the whole, the relative yield change rate of the two crops is about 1, and with the decrease of concentration path, the relative yield change of crops is stable. Under the RCP8.5 scenario, the change rate fluctuates greatly and shows an obvious downward trend. Particularly after 2064, it shows a precipitous decline and both crops reach a low level in 2076. However, under the RCP2.6 scenario, the relative change rate of the two crops is the most stable. Figure 6 shows that, according to the historical trend of crop yield, both maize and wheat reach the lowest yield under the influence of the development of agricultural technology under the ESMME by the end of the century. Figure 6 shows the prediction result of yield relative change rate based on historical data. Under the ESMME, the yield relative change rate of maize and wheat will decline sharply after 2065 under the influence of agro-technique development. By the end of the century, the yield relative change rates of both crops will be much lower than that in other scenarios.

The relative change rate in crop yield from 1997 to 2016 in different agricultural areas is shown in Fig. 7. Wheat yield continued to increase in all agricultural areas except Atyrau and Mangghystau. The fluctuation of wheat yield in Aktyubinsk was the largest, and reached its peak in 1999, an

Fig. 5 Relative yield change rates from 1997–2016

increase of more than three times compared with the previous year. After a flat period from 2000 to 2006, there was a phenomenon of fluctuation in alternate years in Aktyubinsk. The fluctuating trend also indicated that the development of wheat farming in Kazakhstan was slow, and the maximum production potential in each agricultural area was not achieved, which caused some difficulties for the prediction of agricultural output value.

The relative change rate of maize yield in Kazakhstan's agricultural areas was relatively stable except in East Kazakhstan, where the maize yield fluctuated greatly, with the maximum decrease during 2007–2008, then increased quickly during 2009–2010. The two relative changes differed by more than 300%. The large fluctuation of yield not only led to the instability of agricultural production

and the export trade (Reimer & Li, 2009) but also affected the forecast results of Kazakhstan's agricultural production potential.

By comparing the relative change rate of both crops' yields in each agricultural area with that in the whole country, it was found that the trend of crop yield in the main agricultural areas was consistent with that in the whole country. Therefore, the trend of crop yield in the main agricultural areas was the key to predicting the trend of crop yield change in the whole country.

Concentration paths corresponded to different emission standards, which affected future climate change and crop yield changes. It was assumed that the agro-technique achieved sustainable development and promoted an increase in potential crop yields from the base year. Figure 8 shows

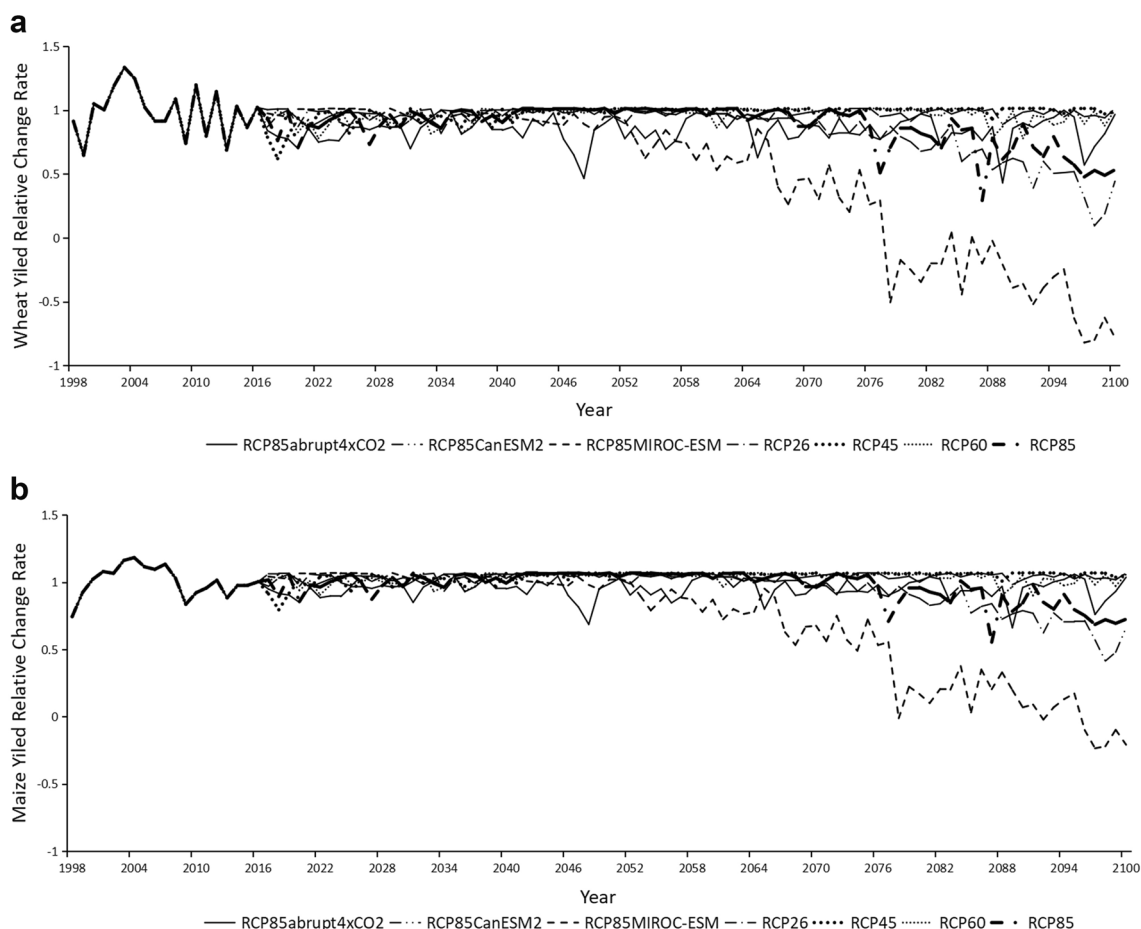


Fig. 6 Relative yield change rates of the two crops

that the yield growth rate of the two crops would continue to be slow at the end of this century under scenario RCP8.5 due to rapid warming. Particularly after 2075, the relative change rate of the yield of the two crops declines rapidly and reach the lowest level in 2087, while the yield of maize will account for 0.55 of the previous year and that of wheat is 0.3. Compared with RCP8.5, the predicted result under scenario RCP6.0 is relatively stable, and the relative change rate of yield of the two crops fluctuates only in the two periods of 2016–2028 and 2087–2100. The lowest relative change rate is 0.75 for wheat and 0.9 for maize. Under scenarios RCP2.6 and RCP4.5, the relative change rates of the yields of the two crops fluctuate very little and the yields of wheat and maize increase steadily. Compared with the base year 2016, the wheat yield increases by 82.49% and 82.62%, and the maize yield by 88.36% and 88.41% by the end of this century under RCP2.6 and RCP4.5, respectively.

According to Formula (5), the relationship between the development of agro-technique and crop yield was positively correlated without considering the influence of climate factors (Fig. 9). In Kazakhstan, the contribution to wheat yield

by agro-technique development was lower than that to maize yield. Compared with the base year 2016, the contribution of agro-technique development to maize yield reaches 255.85% by the end of this century, and the development of the agro-technique further improves maize yield. For wheat, although the contribution of the agro-technique is lower than that of maize, wheat yield continues to increase by 138.23% by the end of this century due to the improvement of the agro-technique, which undoubtedly promotes the improvement of crop yield. Therefore, the improvement of the agro-technique plays an important role in the prediction of crop yield, and the agro-technique becomes an indispensable factor in the study of crop productivity potential. Thus, the study of crop yield potential should consider not only the climate factor, but also the development factor of agro-technique.

Impacts of Temperature on Crop Yield

Crop yield is closely related to ambient temperature. The relationship between temperature rise and crop yield is non-linear, therefore the effect of a temperature rise on crop

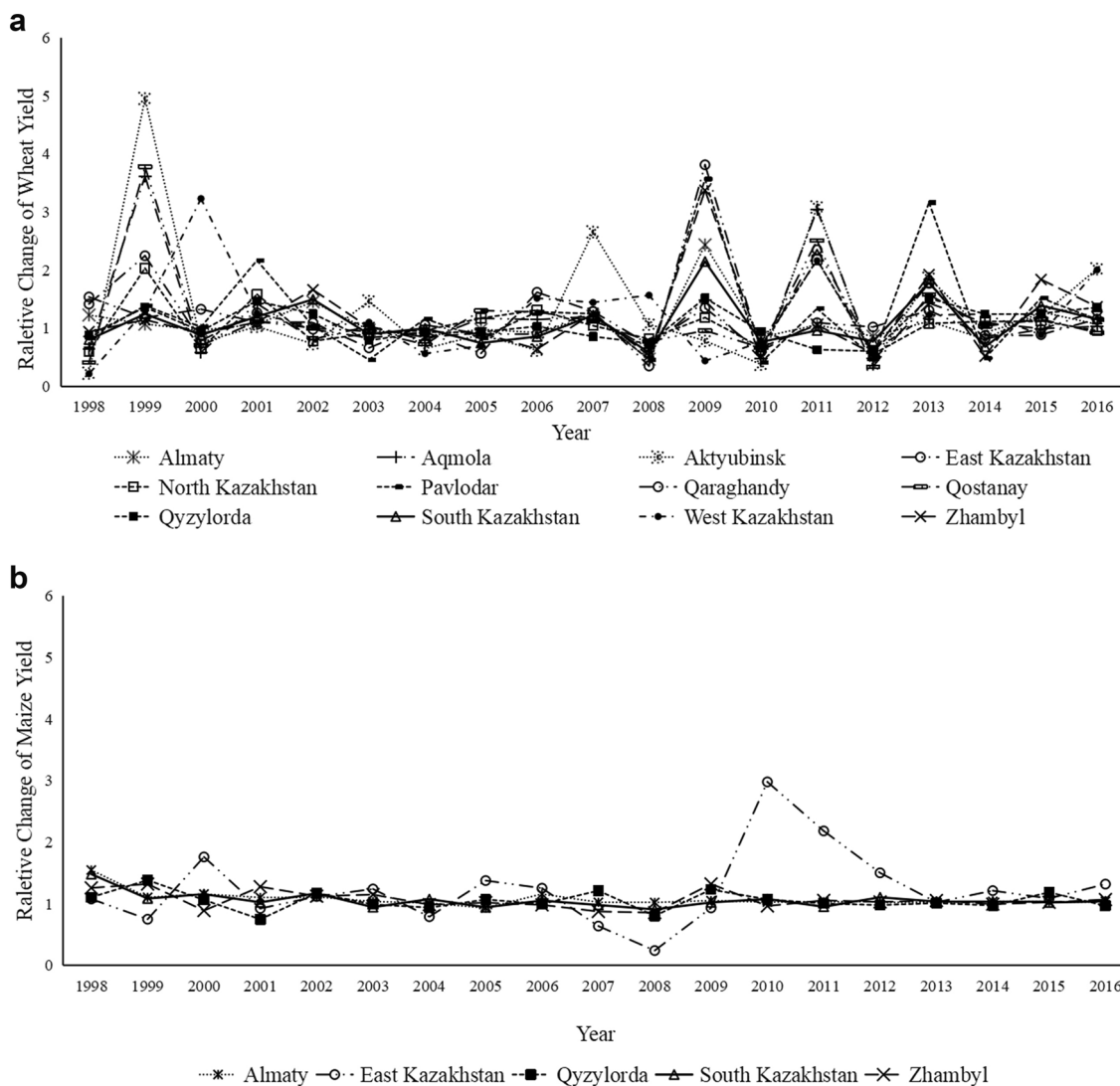


Fig. 7 Relative change in yield of the two crops in each agricultural area

yield under different concentration paths is uncertain. In this study, the ICLM is used to simulate temperature from 2016 to 2100, and the ESMME, EMSC, and ABC models are used as comparisons to explore the temperature difference in 2060, 2100, and the base year in agricultural areas (Figs. 10 and 11). The temperature in 2100 increases significantly compared with 2060, and the ESMME shows the largest increase. In scenarios RCP2.6, RCP4.5, RCP6.0, and RCP8.5, the overall temperature also increases in a step-by-step manner with the increase in concentration path. Under the RCP8.5 scenario, the average temperature of each agricultural area increases by about 4 °C from 2060 to 2100.

Table 2 shows the cumulative relative yield increase of the two crops in 2060 and 2100. It can be seen that, with the increase of concentration path, wheat yield increases slowly. Wheat in Kazakhstan is more sensitive to temperature changes. When the temperature goes over a certain

range, the wheat yield decreases gradually. Compared with 2016, under the ideal emission condition of RCP2.6, the temperature increases slowly, and the wheat yield increases by 0.47 times in 2060. Although the sensitivity of wheat yield to temperature results in a decrease in the relative change rate of wheat yield with 0.35 in 2100 compared to 2060, it continues to increase by 0.12 compared to 2016. Wheat yield in 2100 is lower than that in 2060 under all seven scenarios, and temperature restricts the wheat yield. By 2100, with the increase of emission concentration, wheat yield decreases sharply, especially under the ESMME. Thus, reducing emissions to control climate change is crucial to increasing wheat yield.

The situation of maize is different from that of wheat. By 2060, maize yield increases in all scenarios. Under the RCP2.6 scenario, maize yield increases 1.67 times, while in all the other three scenarios it increases about 1.1 times. By

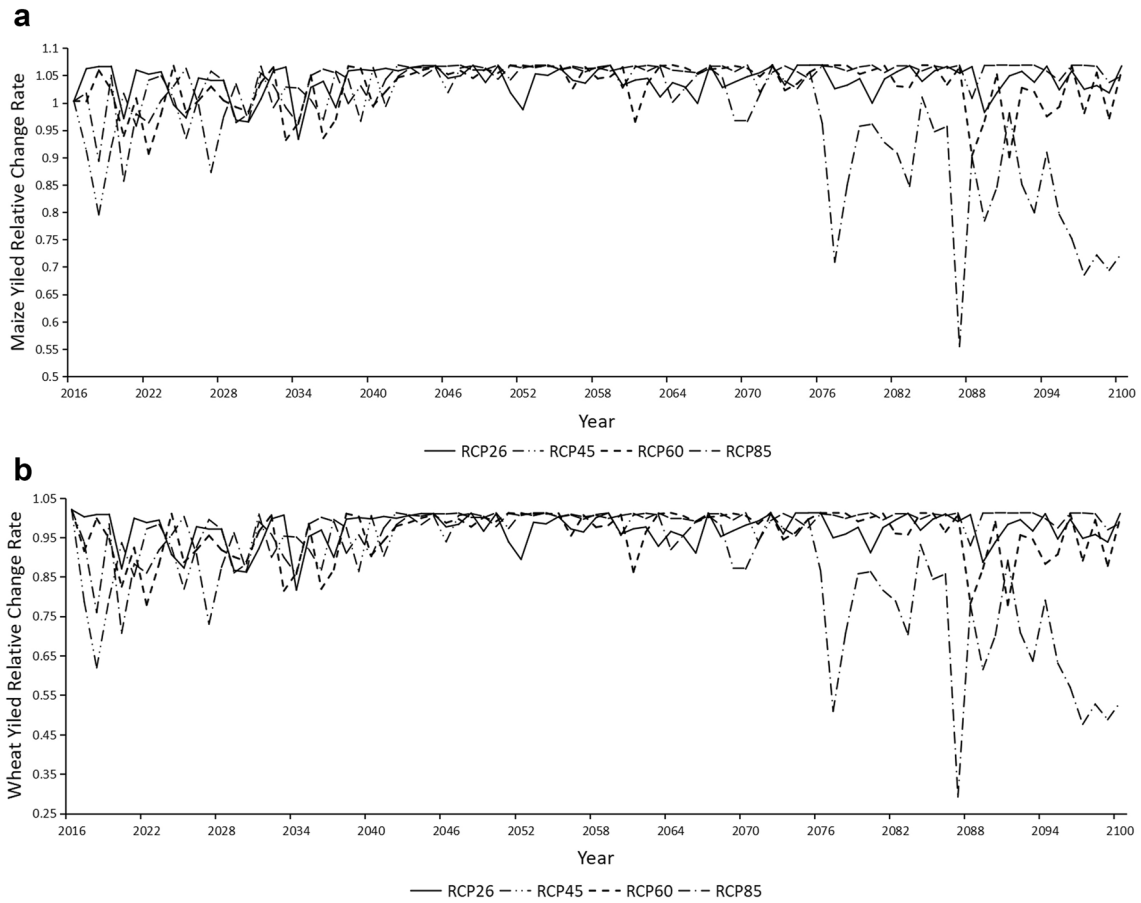


Fig. 8 Prediction of two crop yield changes under different concentration paths

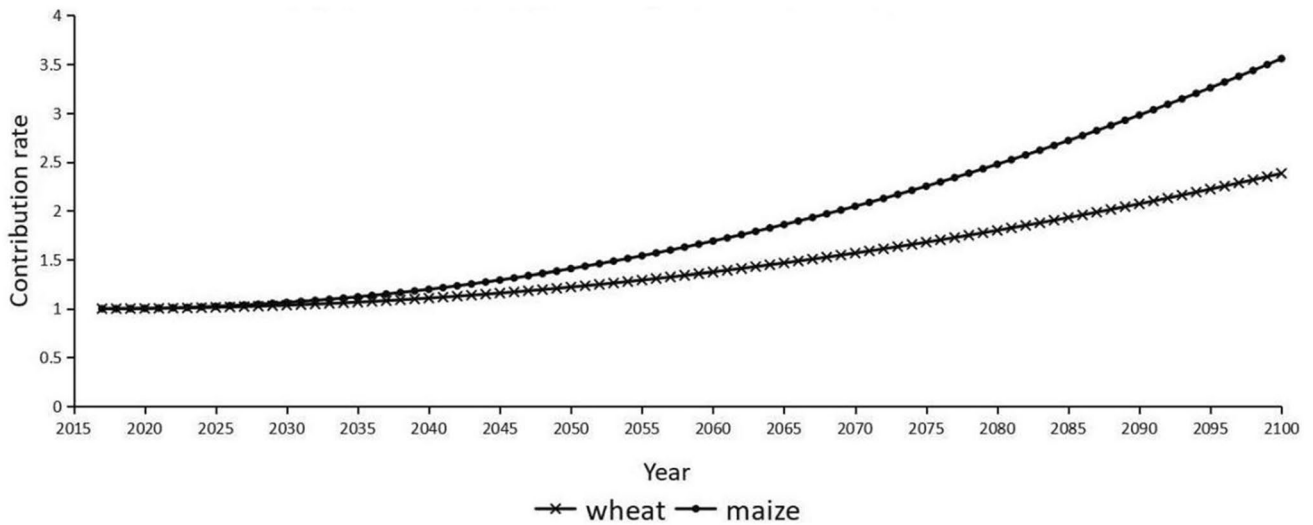


Fig. 9 Contribution of agro-technique improvement to the crop yield

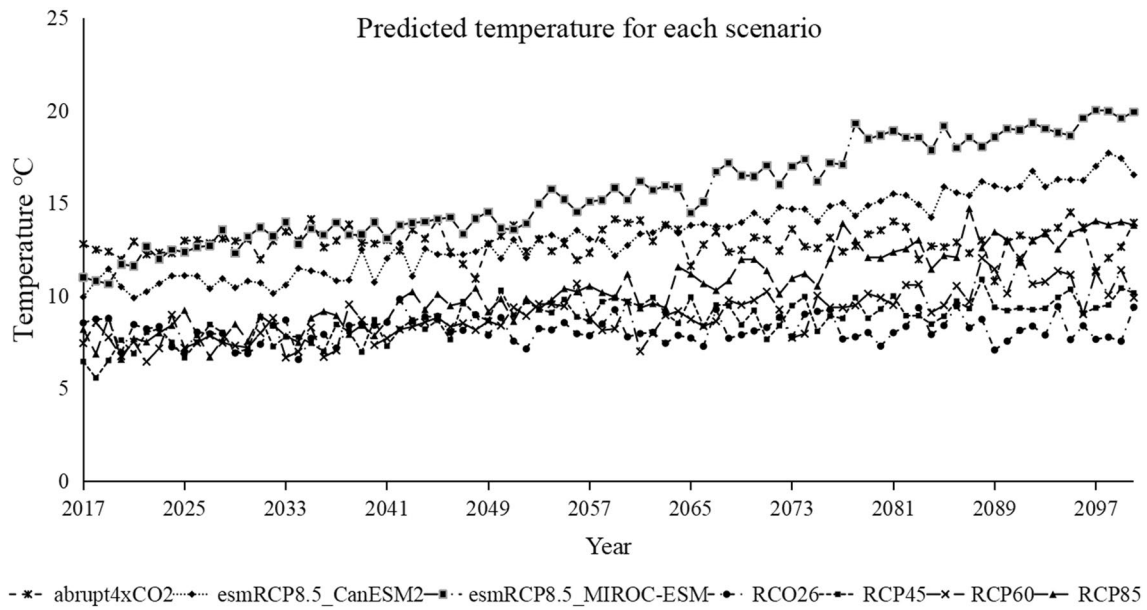


Fig. 10 Temperature of each scenario

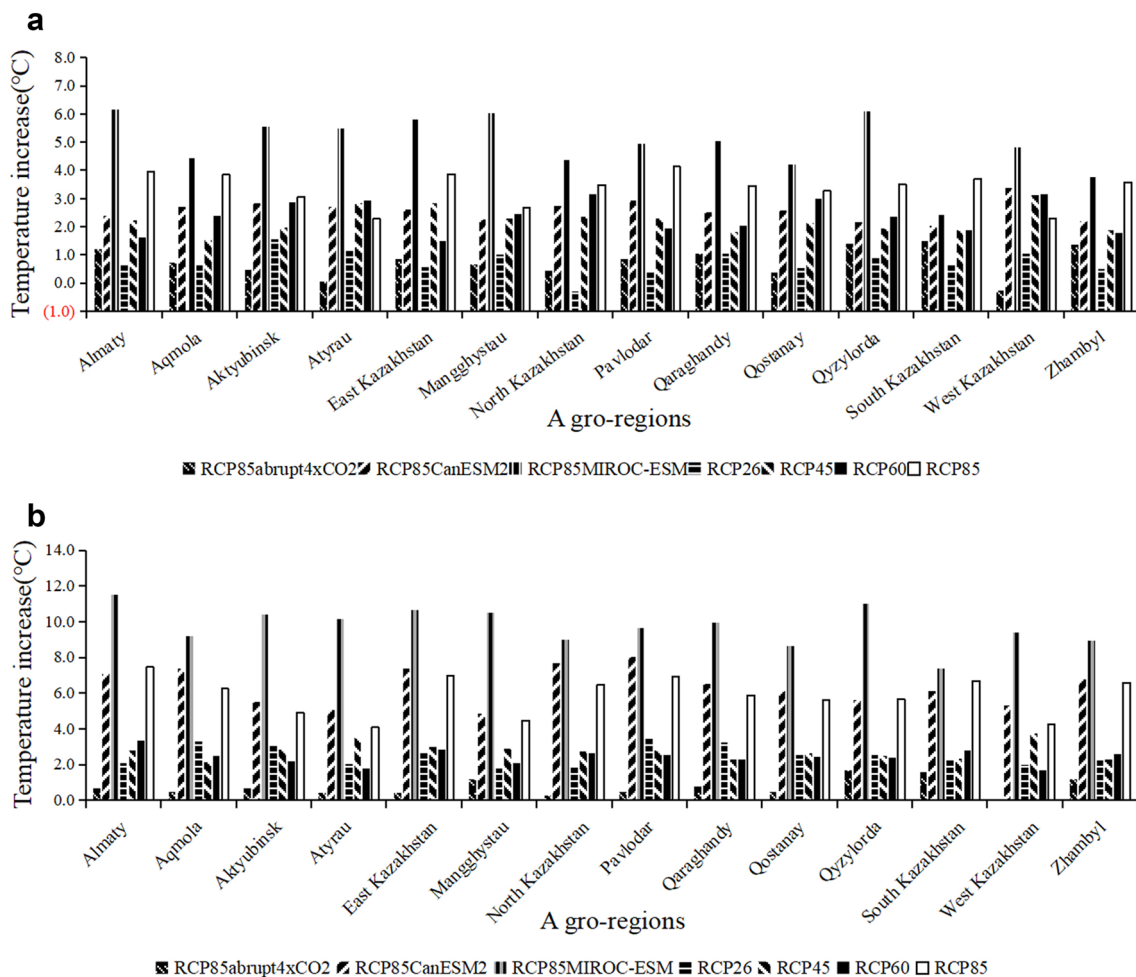


Fig. 11 Temperatures in agricultural areas under different scenarios in 2060 and 2100

Table 2 The cumulative relative yields of the two crops in 2060 and 2100

Year	RCP2.6	RCP4.5	RCP6.0	RCP8.5	abrupt4xCO ₂	esmRCP8.5_ CanESM2	esmRCP8.5_ MIROC-ESM
Wheat							
2060	0.47	0.15	0.26	0.16	0.06	0.42	0.88
2100	0.12	0.07	0.08	0.01	0.00	0.02	0.00
Maize							
2060	1.67	1.03	1.16	1.15	-2.42	1.81	-0.07
2100	3.36	3.41	2.56	-2.29	-4.36	-4.07	0.00

2100, maize yield increases in all scenarios except RCP8.5, especially in RCP4.5, which increases nearly 3.41-fold from 2016 to 2100. Therefore, maintaining the RCP4.5 or RCP2.6 emission standards will maximise the increase of maize yield. The current emission standard is close to RCP8.5 (IPCC, 2013), and the yields of both crops under this concentration path are lower by the end of the century than those in 2060. Under the ESMME, maize yield still does not increase by the end of the century, which is the same as wheat. Therefore, controlling greenhouse gas emissions to meet the RCP4.5 or even RCP2.6 emission scenarios will maximize the crop yield.

Figure 12 shows crop productivity potential in 2060 and 2100 influenced only by temperature increase. The trends of the relative change of crop yield from 2060 to 2100 in each agricultural area is consistent with the overall trend of Kazakhstan. On the whole, crop yield in Kazakhstan gradually declines from east to west in 2100. Under scenario RCP8.5, the change rate of both crops' yields decline the most in the Almaty agricultural area, with a decline of more than 85% for wheat and more than 50% for maize by 2100. The crops' yields decline the least in Qyzylorda.

Under scenario RCP2.6, there are eight agricultural areas where the relative change of crop yield increases, among which Zhambyl is the largest, with an increase of 4.25%. However, central and eastern Kazakhstan areas have an average decline of 2.66%. Under scenarios RCP4.5 and RCP6.0, the temperature increase is relatively moderate. By 2100, the relative change of crop yield decreases in all agricultural areas. Under scenario RCP6.0, the relative yield of maize tends to decrease, but the relative yield of wheat continues to increase. Both crops' yields tend to be saturated at the same time, and the yield no longer increases rapidly without considering the development of agricultural technology.

Combined Impact of Agro-Technique Development and Temperature Increase

Figure 13 shows the relative change of both crops' yields in various agricultural areas under the combined impact of agricultural technology development and temperature rise.

Crop yields increase in all concentration paths by 2060 due to the interaction between agro-technique development and temperature changes. Technological developments can mitigate the negative effects of rising temperatures on crop production, but excessive increases in temperature lead to uncertainty in crop yield after 2060. In short, the crops' yields increase with the development of the agro-technique by 2100 under the scenarios RCP2.6, RCP4.5 and RCP6.0. Among them, North Kazakhstan, Zhambyl, and Almaty have the biggest changes in the relative change of two crops yield in RCP2.6, which increase by 93.7%, 116.15% and 3.25% respectively. However, under the RCP8.5 scenario, the relative change of the two crop yields is different. The relative change rate of maize yield in all agricultural areas increases by 2100, except for Almaty. Qyzylorda has the largest increase in maize production, up to 61.2%. As for wheat, the relative change of wheat yield increases in the west-central areas of Kazakhstan, with the largest increase of 50.8% in the Atyrau area. The eastern areas show a significant decrease, with the largest decrease of 78.2% in Almaty. Under scenarios RCP2.6, RCP4.5, and RCP6.0, the likelihood is that both crops' yields continue to increase after 2060. However, wheat yields will be lower under scenario RCP8.5 after 2060. Particularly in eastern Kazakhstan, the negative effects of rising temperatures offset the gains of agricultural technology.

Summarizing the yields of the two crops is as follows:

Wheat: All four scenarios have positive impacts on wheat yield in Kazakhstan by 2060. The national average wheat yield increases by 49.73%. Under scenario RCP2.6, the temperature rise is slow and the increase rate of wheat yield in 2060 is limited. The leading factor for the increase of wheat yield is the progress of agro-technique. The relative change rate of wheat yield significantly increases under scenarios RCP4.5 and RCP6.0. The relative change rates of wheat yield are 2.76% and 2.34% higher than that in RCP2.6 by the end of this century, due to the comprehensive effect of temperature rise and agricultural technology progress. When temperature exceeds a certain range, crop growth will be stunted, which cancels out gains from the improved agro-technique. Excessive emissions lead to rapid temperature rise under the RCP8.5 scenario, which results in a sharp

Fig. 12 Simulation results in 2060 and 2100 by the influence of climate change

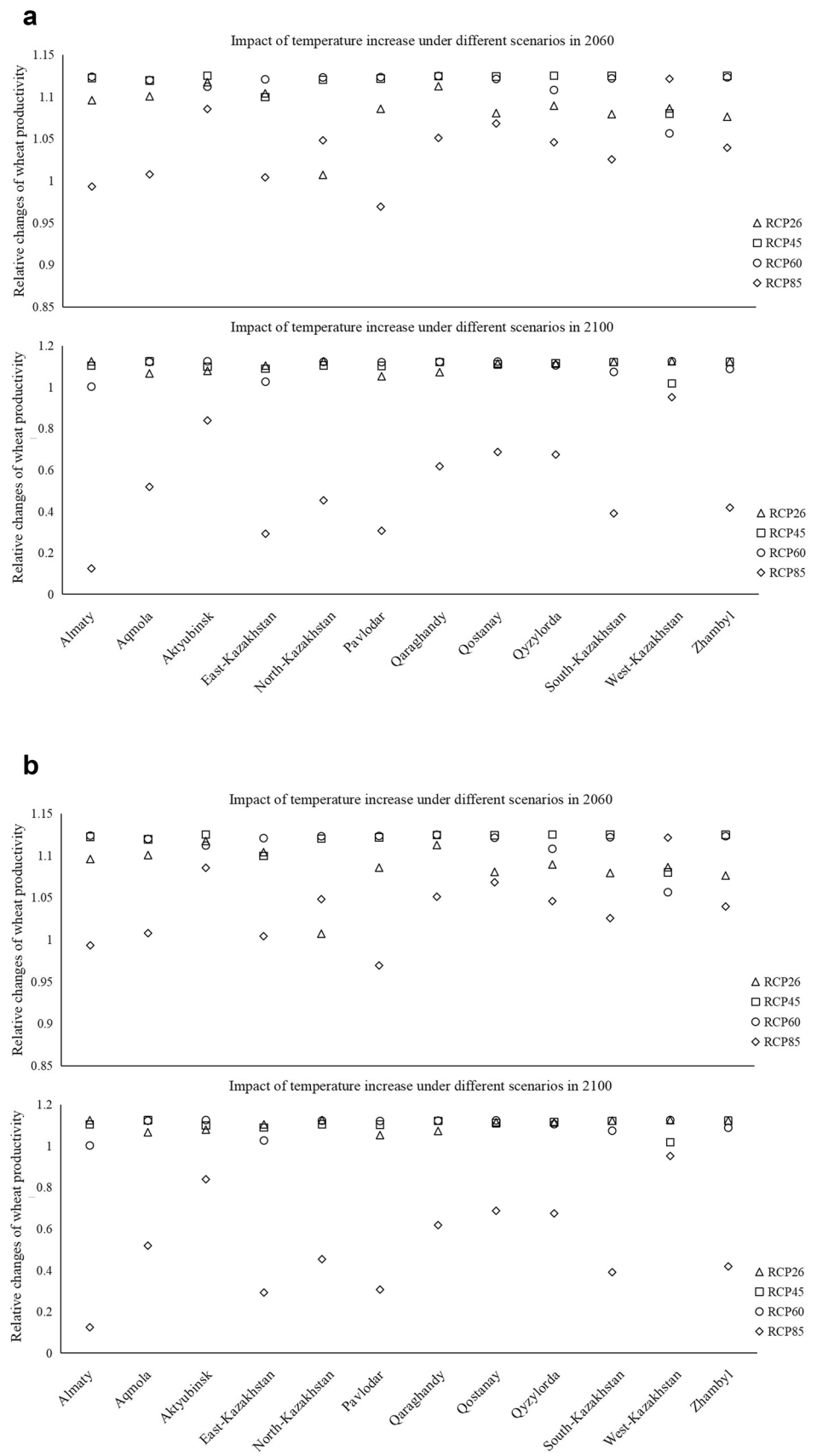
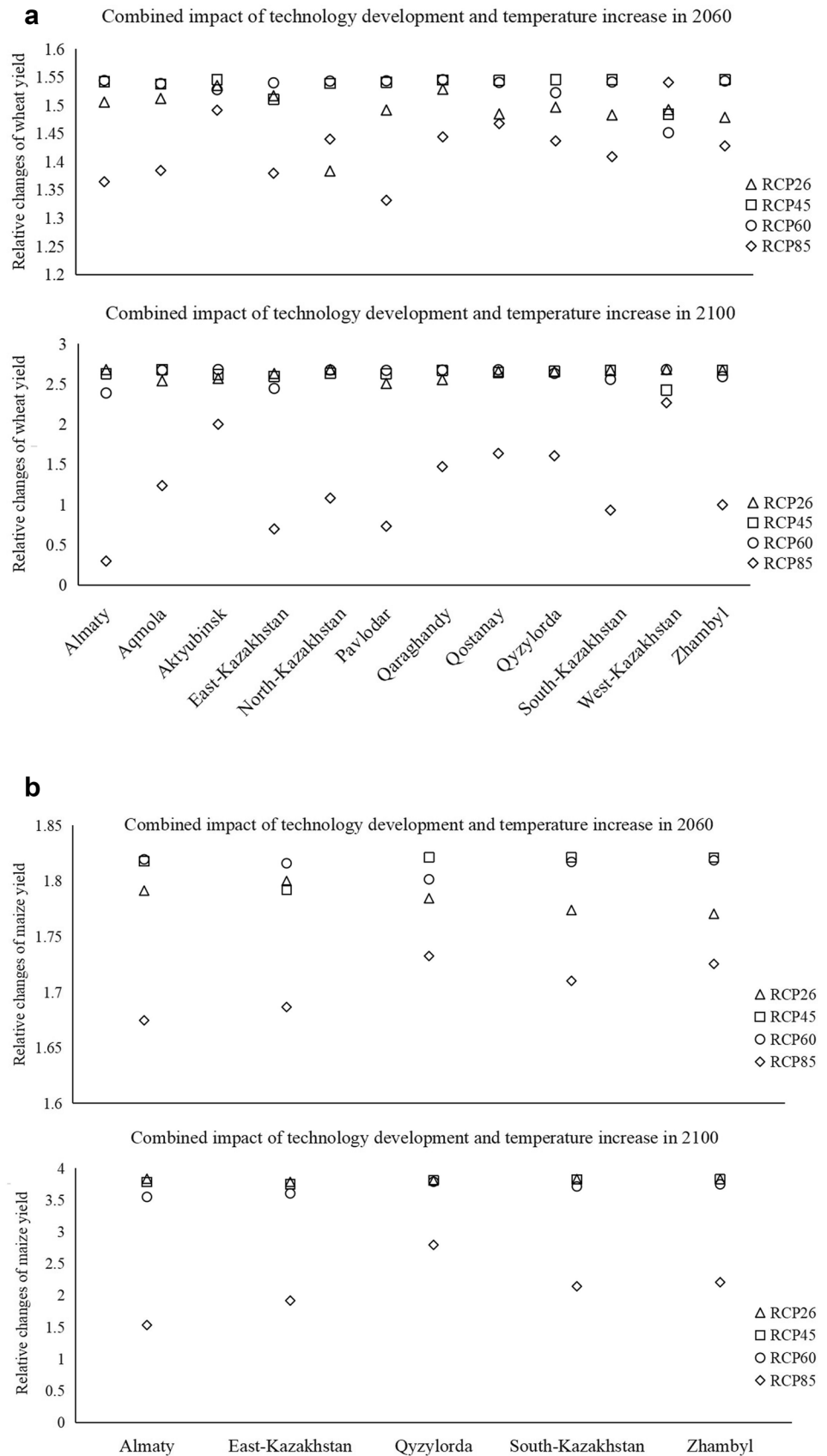


Fig. 13 Relative changes of crop yield under the influence of climate change and agro-technique improvement in 2060 and 2100



decline in wheat yield to only 43.5% of the base year by 2100. To investigate the specific effect of temperature on wheat, this study compared the relative changes of wheat yield under ABC, ESMC, and ESMME with four different concentration paths (Table 3). The results showed that when the annual average temperature is above 13°C, the growth rate of wheat yield begin to decrease. The average temperature in 2100 is as high as 19.93 °C under the ESMME, which is 4.73 °C higher than that in 2060, and the relative change rate is reduced by 286.74%, even lower than that in the base year 2016. In this scenario, high temperature seriously reduces the wheat yield. For Kazakhstan, wheat, as the main crop, determines the development of the country's agricultural industry, and also directly affects the national economy and foreign trade. Reducing emissions and controlling temperature rise is important for the future agricultural development, social and economic development of Kazakhstan.

From the perspective of geographical distribution, crop yields varies by different areas. In general, the wheat yield in the west is higher than that in the east. The relative change of wheat yield in the central and eastern areas increases slowly, while the wheat yield in the western areas increases the fastest under all scenarios. Wheat yield in Almaty, East Kazakhstan and Pavlodar in the eastern agricultural areas decreases significantly. Particularly under the RCP8.5 scenario, compared with the base year 2016, the relative change of wheat yield in Almaty, East Kazakhstan, and Pavlodar at the end of this century is −78.2%, −49.5%, and −45.1%, respectively. In the western agricultural area, wheat yield in Atyrau and West Kazakhstan increases significantly, reaching 50.8% and 47.1%, respectively. Overall, future climate change could improve wheat production in most parts of Kazakhstan, but it needs an appropriate emission scenario.

Maize: Maize grows only in five agricultural areas in Kazakhstan, which are Almaty, East Kazakhstan, Qyzylorda, South Kazakhstan, and Zhambyl. Maize yield in the base year 2016 accounted for only 3.67% of the total crop yield in Kazakhstan. Maize yield increases under four scenarios by 2060. However, the temperature adaptability of maize

is stronger than that of wheat because of its low sensitivity to temperature rise. In addition, the contribution rate of agricultural technology development to maize yield is higher than that to wheat yield (Fig. 9), thus the growth rate of maize is higher than that of wheat under the same scenario. The maize yield in the four scenarios increases to the same level by 2060, all of which exceeds 65%. And the yield growth rate of RCP8.5 is 6.37% lower than that of RCP4.5. The maize yield under three scenarios—RCP2.6, RCP4.5, and RCP6.0—increases by more than 100% in 2060 and even increases by 113.89% under RCP2.6, showing the largest improvement compared with the base year. In contrast, the highest yield is 21.69t/ha under the RCP2.6 scenario in 2100. The national maize yield increases by only 23.86% under the RCP8.5 scenario, and even shows a negative growth in Almaty, which decreases by 8.53% in 2100. The terrain, altitude, and climate factors were responsible for the decrease in maize yield.

Conclusions

This study found that it is feasible to conduct regional assessments of the implications of climate change for crop production. A quantitative method is proposed to estimate the sensitivity of relative crop yields to agro-technique development and temperature rise in Kazakhstan. Compared to other studies, this study is based on the historical crop data, and the results are more consistent with the reality of local agricultural development. In this study, wheat and maize were selected as the target crops. Based on the historical data from 1997 to 2016 provided by the Kazakhstan Statistics Agency, this paper selected four Concentration Paths of RCP2.6, RCP4.5, RCP6.0 and RCP8.0 to quantitatively estimate the relationship between crop yields and climate change. And this study also used ABC, ESMC, and ESMME models as comparisons to eliminate contingency. The conclusions are as follows:

Table 3 Relative change rate of wheat yield under different experiments in 2060 and 2100

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	abrupt4xCO ₂	esmRCP 8.5_ CanESM2	esmRCP 8.5_MIROC- ESM
Relative change in 2060	1.49255	1.53368	1.52751	1.43527	1.47083	1.52093	1.1205
Relative change in 2100	2.62845	2.61662	2.61676	1.32857	2.53899	1.02949	-2.09244
Relative change rate	76.10%	70.61%	71.31%	-7.43%	72.62%	-32.31%	-286.74%
Temperature change (From base year to 2100)	0.6	2.431	2.358	3.336	6.708	5.493	7.965
Temperature change (From 2060 to 2100)	1.602	0.459	0.234	2.643	0.013	3.808	4.734
The temperature in 2100(°C)	9.39	10.15	9.90	13.82	13.96	16.54	19.93

1. Under the scenarios of RCP2.6, RCP4.5 and RCP6.0, Kazakhstan's crop yields will be improved in 2060, and the development of agricultural technologies will further improve Kazakhstan's future crop productivity. However, the crop yield will increase at a relatively low rate under the scenario of RCP8.5 in 2060.
2. The relative wheat yields in East Kazakhstan, Almaty, Zhambyl, South Kazakhstan will increase greatly under the same emission standard. In particular, the relative wheat yield of the central and western areas will be significantly lower than that of the southern and eastern areas by 2100.
3. Maize is grown in the south-east of Kazakhstan, mainly in five agricultural areas: Almaty, East Kazakhstan, Qyzylorda, South Kazakhstan, and Zhambyl. The development of agricultural technology has a great impact on maize yield. Compared with wheat yield, maize yield can accept higher emission standards, so it has a great potential for increased yield in the future.
4. Overall, wheat yield will increase the most in the RCP4.5 scenario and maize yield will increase most in the RCP6.0 scenario.

This study will contribute to the future development of Agriculture in Kazakhstan. At the same time, the research on agricultural production potential provides powerful suggestions for the agricultural development of Kazakhstan and helps to move towards a more perfect and more suitable agricultural development path for Kazakhstan's national conditions. Although many studies have confirmed that climate change would have a significant impact on crop production in the future, the direction and extent of the impact on crop yield have not been clear at this stage due to the complex relationship between crop growth and environmental factors. The impact of climate change on crop productivity continues to be an important area of research. In further studies, other environmental factors, such as CO₂, precipitation, and crop adaptation should also be considered to ensure more accurate estimates of future crop yields.

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Declarations

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, author-ship, and publication of this article.

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