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The impact of climate change on maize production: Empirical findings and implications for sustainable agricultural development

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Continuous warming climate conditions have triggered numerous extreme weather events, exerting an unprecedented impact on agricultural and food production. Based on the panel data of 3,050 small farmers engaged in maize planting from 2009 to 2018 and collected by the National Rural Fixed Observation Point in China, this study uses the Transcendental Logarithmic Production Function model to estimate the impact of temperature, precipitation, and sunshine hours on maize output. Further, considering climate condition heterogeneity, this study analyzes the development potential of five major maize production areas in China. Results show that temperature and precipitation have a positive impact on maize output and that insufficient sunshine hour is an obstacle to the growth of maize output. Five major maize production areas are affected by climate condition differently, entailing the need for tailored response measures. Additionally, land, labor, and material capital input are key factors affecting maize output. Based on conclusion, we put forward the following suggestions to promote sustainable agricultural production, including strengthening the prediction of temperature, precipitation, and sunshine hours in major maize production areas, optimizing the agricultural production layout and the planting structure based on local endowment, enhancing farmers' adaptive behavior training toward climate change, developing irrigation and water conservation projects.

KEYWORDS

climate change, maize output, major production area, transcendental logarithmic production function, coping measures

1 Introduction

The global temperature has been rising in recent decades and climate warming has been accelerating. Continuously warming climate conditions have also triggered more extreme weather events that affect agricultural production, which is highly sensitive to natural resources (Crost et al., 2018). Research suggests that climate change is placing great pressure on agricultural production (Wilson et al., 2022). Under the stress of climate change, food production has been facing prominent negative shocks (e.g., the increase in disaster areas and food production reductions), which may lead to hunger and malnutrition. Thus, these issues have been catapulted into the forefront of international discussions across numerous countries. Indeed, researchers propose that various countries urgently need to look for effective strategies to address the adverse effects of climate change, such as promoting the training for farmers on climate change adaptation behaviors (Moore and Lobell, 2014), enhancing the irrigation facilities (Aragón et al., 2021), and further developing a "climate-smart food system" (Wheeler and von Braun, 2013).

China is one of the countries most affected by climate disasters. Meteorological changes and extreme weather adversely affect China's agricultural production and have a negative impact on agricultural total factor productivity and input utilization rate. Global warming has also caused huge economic losses to the country's grain output (Chen et al., 2016). Furthermore, China is one of the most populous countries in the world. According to the data of National Bureau of Statistics of China, in 2020, the national population reached 1.41 billion, accounting for about 18% of the world's total population. Feeding more than one billion people entails many problems, and solving these problems is important for both the national economy and people's livelihoods. Accordingly, the impact of climate change on the food supply in China cannot be ignored. Furthermore, climate change's influence on agricultural output leads to changes in market prices, which impacts the livelihood of agricultural producers and causes social problems. From this perspective, assessing the impact of climate change on agricultural production is of great significance for studying the relationships among climate change, agricultural product supply, market prices, and other economic issues, as well as for effectively formulating policies to tackle climate change (Aragón et al., 2021; Filho et al., 2022; Oyinlola et al., 2022; Wheeler and von Braun, 2013).

Recent research on the effects of climate change on food production mainly focus on natural and economic aspects. Regarding the research on natural aspects, they mainly focus on how to build crop models for the dynamic simulation of crop growth and on the impact of climate change on crop growth (Hasegawa et al., 2022; Hawkins et al., 2013; Tonnang et al., 2022; Wang et al., 2022). Nonetheless, these studies require many hypothetical parameters to be set, which may lead to uncertain evidence (Carr et al., 2022). This may be the limitation of research in this field. Regarding the research focusing on economic aspects, for example, Lin et al. (2011) used household data and a nonlinear production function model to calculate the output elasticity of changes in temperature, precipitation, and average sunshine hours for three major food crops. In the United States of America, Coffel et al. (2022) calculated the output elasticity of changes in temperature, precipitation, and sunshine for maize and soybean crops. In China, Song et al. (2022) calculated the economic impact of climate change on maize yields based on the Ricardian model. Despite these studies providing valuable insights, they didn't reach a consistent conclusion owing to differences in data sets and methods. Other researchers show that farmers can adjust their behavior to adapt to climate change by collecting relevant information on the topic (Tazeze et al., 2012). Based on these remarks, some scholars discuss the influencing factors and effectiveness of farmers' measures to deal with climate change from the perspective of farmers' subjective initiatives (Huang et al., 2015; Rijal et al., 2022; Shariatzadeh and Bijani, 2022; Zobeidi et al., 2022).

These research highlights the significance of current studies, mainly focusing on maize. According to the data of National Bureau of Statistics of China, maize is the largest grain crop regarding sowing area and output in China. Maize is also an important feed and industrial raw material (Shukla and Cheryan, 2001; Klopfenstein et al., 2013). With the rapid development of China's economy, the dietary structure of national residents has changed and the demand for meat has increased rapidly, stimulating the development of animal husbandry and the "rigid" growth trend of feed grain demand (Shimokawa, 2015; Fukase and Martin, 2016). Accordingly, it is of great practical significance to provide data for stakeholders that enables them to effectively ensure maize output, reasonably plan maize production areas according to local conditions, and optimize the allocation of agricultural resources.

The above research has mainly given us the conclusion about climate change's influence on the agricultural output from the regional level. However, few relevant studies have explored the impact of climate change on China's maize output using a national scale panel data comprising data at the micro level (e.g., farmer household level). Compared with previous studies that assess the impact of climate change based on a regional level, it is more meaningful to study the impact of climate change from the farmers' perspective. Farmers are the main body most directly affected by climate change, especially for developing countries like China, where small farmers are the main body. Whether farmers can respond to climate change in a timely and effective manner is crucial. Therefore, exploring the impact of climate change on maize output at the farmer household level can more accurately project the actual impact of climate change on agricultural output in developing countries. This paper uses a nationally representative farmer household-level panel data and

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employs the fixed-effect model to control for time-invariant factors, such as the management ability of agricultural producers, the quality of household contracted farmland and other factors to more accurately identify the impact of climate change on maize output.

Accordingly, using data including 3,050 small farmers engaged in planting maize for 10 consecutive years from National Rural Fixed Observation Point of China, and based on the macro-overview of China's maize production and climate change, this study first tests the impact of temperature, precipitation, and sunshine hours on farmers' maize production at the national level. Then, the heterogeneous characteristics of the climate conditions of the five major maize production areas in China are considered, and the methods to stimulate the future development potential of maize in each production area are employed. Finally, relevant countermeasures and suggestions are presented.

2 Maize output change and climate change in China

2.1 Output change in the five major maize production areas in China

Maize has a variety of uses in the grain, economics, forage, fruit, and energy fields. It is a grain crop with the longest industrial chain in China and holds a great strategic significance for the country. From 2009 to 2018, maize output increasing from 163.97 to 257.17 million tons (growth rate: 56.84%) in the country (Supplementary Table A1). Maize is playing an increasingly prominent role in the national agricultural production.

Furthermore, this grain crop is widely planted across 31 provinces (autonomous regions and municipalities) of China. In fact, by combining *The Atlas of Growth Periods of Major Crops in China* with the available data, the country can be divided into the northern spring sowing maize area (hitherto Production area 1), HuangHuai Plain spring and summer sowing maize area (hitherto Production area 2), southwest hilly maize area (hitherto Production area 3), southern hilly maize area (hitherto Production area 4), and northwest inland maize area (hitherto Production area 5).

Supplementary Table A1 shows that Production area 1 is the largest maize production area in China, accounting for nearly 50% of the country's total maize output. From 2009 to 2018, its maize output shows an increase from 67.17 to 119.64 million tons (growth rate: 78.12%). Production area 2 is the second-largest maize production area, accounting for approximately 30% of the country's total maize output. From 2009 to 2018, its maize output shows an increase from 58.53 to 80.19 million tons (growth rate: 37.01%). In the other production areas, the total maize output accounted for approximately 20% of the total output during this same period, as well as show an increase from 38.26 to 57.36 million tons (growth rate: 49.89%). Overall, China's maize shows a steady output increase over the analyzed period, with slight fluctuations across the years.

2.2 Climate change in the five major maize production areas in China

Generally, human activity relies on the natural environment, and agriculture is one such activity that is highly sensitive to climate change. Therefore, the impact of climate change on maize output cannot be ignored. Temperature, precipitation, and sunshine are basic elements of the climate, as well as key factors affecting maize output. The abnormal temperature and water imbalance due to abnormal climate conditions have different effects on maize growth. With the available data, Supplementary Tables A2–A4 show the changes in temperature, precipitation, and sunshine hours in the five major maize production areas of China.

Supplementary Table A2 shows that from 2009 to 2018, the monthly average temperature is the highest in Production area 4 (16.88°C) and the lowest in Production area 1 (7.81°C). Further, Production areas 3, 2, and 5 show an monthly average temperature of 16.15°C, 12.95°C, and 9.95°C, respectively. Supplementary Table A3 shows that from 2009 to 2018, the monthly average precipitation is the highest in Production area 4 (98.92 mm) and the lowest in Production area 5 (29.33 mm). Further, Production areas 3, 1, and 2 show a monthly average precipitation of 86.37, 51.36, and 49.27 mm, respectively. Supplementary Table A4 shows that from 2009 to 2018, the monthly average sunshine hour is the highest in Production area 5 (206.59 h) and the lowest in Production area 3 (125.62 h). Further, Production areas 1, 2, and 4 show monthly average sunshine hours of 195.62 h, 188.58 h, and 135.07 h, respectively.

In summary, Production area 1 has longer sunshine hours, average precipitation levels, and the lowest temperature over the analyzed period. Production area 2 has average temperature, sunshine hours, and less precipitation. The temperature and precipitation conditions in Production area 3 are high, but sunshine hours are the lowest. Production area 4 has the highest temperature and precipitation conditions, but sunshine hours are shorter. Finally, Production area 5 has the longest sunshine hours, cooler temperatures, and less precipitation.

3 Model settings and data source

3.1 Model setting

Theoretically, input factors are key elements affecting maize output, and they include land input, labor input, and material inputs (e.g., seeds, fertilizers, pesticides, agricultural film, agricultural machinery, and irrigation). Land is the material basis for maize growth, and in theory, the sown area has an important positive impact on maize output. Labor is also an important factor affecting maize output. In this study, the number of working days is used as an indicator of labor input in maize output. Materials are the main input factors for maize output, and upon considering that the quantity of different types of materials is not comparable, we used total costs to reflect material input in maize output.

Based on previous research (Jones and Thornton, 2003; Lobell and Asner, 2003; Lin et al., 2011), crop growth is affected not only by the input of production factors but also by climate change. Hence, maize growth results from the joint action of sunshine hours, temperature, precipitation, and other factors. Although these factors are not directly invested in maize production, they affect the efficiency of the production factors.

In addition, researchers have shown that there may be a quadratic relationship between climate factors and grain crop output (Kabubo-Mariara and Karanja, 2007; Schlenker and Roberts, 2009; Adhikari et al., 2015). A Cobb-Douglas production function calculates the relationship between production output and inputs (factors), which is used to predict technological change (Zellner et al., 1966). Compared to C-D production function, Translog production function may be more general and flexible, which has been widely applied to the area of agricultural production accounting. Compared to the fixed elasticity of various input factors and output in C-D production function, Translog production function can relax this hypothesis, thereby more accurately estimating the impact of climate change on agricultural output.

In this paper, controlling for the fixed effects of farmer household and year, two-way fixed-effects model is used to evaluate the impact of temperature, precipitation, and sunshine hour variation on maize output. Farmer household fixed effect denotes the farmer household-level time-invariant unobservable factors which may be related to maize output, such as farmer's labor capacity and cropland quality; Year fixed effect denotes the time-variant factors, including the other climate and social factors. In summary, we constructed a transcendental logarithmic production function of variable elasticity that is easy to estimate and highly inclusive, as shown in Eq. 1:

$$\begin{aligned} LnY &= \alpha_0 + \alpha_1 LnS + \alpha_2 LnL + \alpha_3 LnK + \frac{\alpha_4}{2}(LnS)^2 + \frac{\alpha_5}{2}(LnL)^2 \\ &+ \frac{\alpha_6}{2}(LnK)^2 + \alpha_7 LnS \times LnL + \alpha_8 LnS \times LnK + \alpha_9 LnL \times LnK \\ &+ \alpha_{10} LnTe + \alpha_{11} LnRa + \alpha_{12} LnSu + \frac{\alpha_{13}}{2}(LnTe)^2 + \frac{\alpha_{14}}{2}(LnRa)^2 \\ &+ \frac{\alpha_{15}}{2}(LnSu)^2 + \alpha_{16} T + \mu \end{aligned} \tag{1}$$

where Y is a farmer's total maize output; S is the farmer's sown area of maize; L is the number of working days for maize production; K is the material cost for maize production; Te is the temperature condition (°C); Ra is the precipitation condition (mm); Su is the number of sunshine hours; and T is the time trend variable. We selected a two-way fixed-effects panel data model for the analysis.

Notably, following previous literature (Rurinda et al., 2015; Ureta et al., 2020; Wu et al., 2021), there are multiple reasons to use maize output rather than maize productivity as dependent variable. First, China's small farmer households are still the main body of cropping maize, and their production decisions are mainly based on maize planting area and output (Huang and Ding, 2016). Thus, using maize output is more in line with Chinese farmers' production condition. Second, in Translog production function, maize planting area has been absorbed as land input factors, which also helps to better estimate maize output.

Since this study focuses on the contribution of different factors to maize output changes, we also calculate the contribution of factor changes to maize output changes by obtaining the output elasticity of factors (i.e., the ratio of output increases when factor input increases by 1%, while other conditions remain constant).

3.2 Data sources

For the empirical analysis, we use farmer household-level data from the National Rural Fixed Observation Point. The National Rural Fixed Observation Point are a micro-level panel data set based on farmer households. The survey began in 1986 and now covers 31 provinces (autonomous regions and municipalities), 368 counties, 375 sample villages, 23,000 account-keeping agricultural (pastoral) households, and more than 1,600 new agricultural management subjects. The survey covers all aspects of farmers' production, operation, consumption, and investment. Especially in grain production, detailed and reliable survey records are available for the output, sown area, and expenditure of related inputs of each crop. We selected farmers who had been producing maize for 10 consecutive years (from 2009 to 2018) as the sample for the empirical analysis, totalizing 3,050 households. The climate data sources are the monthly data of the China National Meteorological Observatory from 2009 to 2018, which is provided by the China Meteorological Science Data Sharing Network. According to the coordinates of the county center point and the meteorological observation point, based on the principle of the shortest spatial distance, the connection between the farmer household data set and the meteorological data set is realized. It should be stated that we use maize growing season data (The growing season of Production area 1 is from May to October; the growing season of Production area 2 is from June to October; the growing season of Production area 3 is from March to September; the growing season of Production area 4 is from March to August; the growing season of Production area 5 is from April to September).

The main variables and their meanings are shown in Supplementary Table A5. Farmers' average total maize output is 4,587 kg. Regarding inputs, farmers' average sown area of maize is 8.24 mu, labor input is 59.92 days, and material input is 2,251.71 yuan. Regarding climate, during growing season the monthly average temperature in the area where the sample farmers are located is 20.65°C, the monthly average precipitation is 97.15 mm, and the monthly average sunshine hours are 188.14 h.

4 Results

4.1 Analysis of estimated results

4.1.1 Estimation results of the model of influencing factors of maize output

For estimations using the 10-year farmer household panel data set, we use a two-way fixed-effect model regression method. Missing variables and time changes are controlled as much as possible (through individual fixed-effects and time fixed-effects, respectively) to identify the impact of climate change more accurately on maize output. Supplementary Table A6 presents the results of the influencing factor model for maize output. The adjusted R^2 of the entire model is 0.8962, indicating that the independent variables explain 89.62% of the dependent variables. In addition, we also conducted an over identification test and rejected the assumption of using the random-effect model.

Furthermore, as shown in Supplementary Table A7, the mean values of output elasticity of land, labor, and material input (main input factors) are 0.6740, 0.0531, and 0.2470, respectively. That is, for every 1% increase in land, labor, and material input, maize output increases by 0.67%, 0.05%, and 0.25%, respectively. Overall, land inputs (sown area) remain the most important factors affecting maize output, followed by material and labor inputs. With the continuous development of society and the economy, the problems of non-agricultural land competition, non-grain use of farmland, and land abandonment have become increasingly prominent. Further, industrial and domestic pollution have led to a decline in the quality of arable land and to a small number of farmlands with high and stable outputs. Therefore, great importance should be attached to stabilizing grain cultivation areas. Simultaneously, under the influence of economic laws, the opportunity cost of labor for agricultural production continues to increase, and more farmers choose to work to increase their income. On the one hand, this leads to reduced labor input; on the other, this leads to a more aged and feminized labor force (Palacios-López and López, 2015; Liu et al., 2019; Rigg et al., 2020), which in turn reduces the quality of labor input and is not conducive to maize output improvements. In addition, researchers have thoroughly demonstrated the important role of agricultural capital investment in promoting agricultural technological progress, meaning that an increase in physical capital plays an important role in promoting agricultural output (Binswanger and Rosenzweig, 1986; Smith, 2004; Syed and Miyazako, 2013).

Regarding climate factors, temperature, precipitation, and sunshine hours have significant effects on maize output, meaning that climate change will increase maize output fluctuation. The output elasticities of temperature, precipitation, and sunshine hours are 0.3940, 0.0153, and −0.0515, respectively (Supplementary Table A7). As maize is a temperature-loving crop, it is very sensitive to temperature fluctuations, with an increase in this variable being beneficial for maize output. Precipitation has a significant positive impact on maize output, indicating that an appropriate increase in precipitation levels can also increase maize output. From the model results, the output elasticity of sunshine hours is negative, meaning that there is insufficient lighting to some extent.

4.1.2 Contribution of various factors to maize output growth

In this section, the output elasticity of each factor is multiplied by the change rate of the factor within the sample year, and then divided by the change rate of maize output within the sample year. This serves to express the contribution of factors to maize output. The results are presented in Supplementary Table A7.

Supplementary Table A7 shows the contribution of input and climate factors to maize output. Regarding input factors, the contribution rates of material, land, and labor input to maize output are 53.71%, 46.33%, and −3.47%, respectively. These results further illustrate the roles of land and material input in maize output, which is in line with previous literature (Sheng et al., 2019; Qiu et al., 2021). Regarding climate factors, the contribution rates of temperature, precipitation, and sunshine hours to maize output are 2.20%, 0.58%, and −0.51%, respectively, indicating that these variables have limited contributions to maize output. This may be because of the high concentration of production in the analyzed areas. Specifically, Production areas 1 and 2 account for nearly 80% of the country's total maize output, and both are less affected by climate change. Therefore, it is necessary to further subdivide and understand the impact of climate change in each area to propose more effective measures to deal with climate change and ensure the supply of maize in China.

4.2 Heterogeneity test

Since China has a vast territory, different production areas have different natural conditions and socioeconomic characteristics. In the process of maize production, farmers are affected not only by their own characteristics (individual effects) but also by their living environment, that is, environmental background effects. Accordingly, this section further divides the sample into the five production areas, repeats the analyses, and focuses on the impact of climate factors on maize output. This serves to determine the characteristics of the impact of climate change on maize output in different production areas, grasp the future trend of maize production layout, and put forward targeted policy recommendations for stakeholders to reference. Supplementary Table A8 presents the model estimation results by area. The calculations for output elasticity of the climate factors in each area and their contribution rate to maize output growth (Supplementary Table A9) are based on the results described in Supplementary Table A8.

In Production area 1, the impact of climate factors on maize output is small, with temperature having a negative effect on the output elasticity and contribution to maize output. This is mainly because although Production area 1 has climate conditions that are very suitable for maize growth and unique climate resources, low temperatures and chilling damage are among the main agro-meteorological disasters affecting this area. Hence, temperature fluctuation is an important factor for changes in maize output. In most regions of Production area 1, the temperature in spring is relatively low, and there is the problematic phenomenon of "cold springs." Insufficient accumulated temperature leads to slow maize growth, indicating another important explanation for the negative output elasticity and contribution rate of temperature in this production area.

In Production area 2, output elasticities for precipitation and sunshine hours are negative, while the contributions to maize output for temperature and precipitation are positive. Production area 2 has a warm and semi-humid climate with abundant rainfall, providing sufficient conditions for crop irrigation. Accordingly, maize planting methods are more diverse in this area, and intercropping and multiple cropping can coexist. However, in two cycles of multiple cropping, the utilization of solar thermal resources was low, only early maturing maize varieties can be planted, resulting in a low maize output (Wang et al., 2020; Zhai et al., 2017; Zhai et al., 2021). In addition, owing to the high temperature and humidity in summer, Production area 2 is prone to diseases and insect disasters, which adversely affect its maize output.

In Production area 3, output elasticities for temperature and precipitation are positive, and the contributions to maize output for sunshine hours are negative. The topography of Production area 3 is relatively complex when considering its natural landscape. Specifically, mountains, hills, and plateaus account for more than 90% of the total land area. Accordingly, regional differences in ecological conditions are very large and production conditions are poor. Due to the high temperature and humidity in the growing season of maize in Production area 3, as well as the lack of sunshine in the area, the problems of pests and diseases tend to be more serious, and this situation is not conducive to maize output and crop quality. From this point of view, Production area 3 is not suitable for maize growth.

In Production area 4, output elasticities for temperature and precipitation are positive, and contributions to maize output for temperature is negative. Around 10°C is a suitable temperature for the growth and development of maize, but Production area 4 has a higher temperature and abundant rainfall, which are more suitable for rice cultivation. Accordingly, the climate conditions in autumn and winter in Production area 4 are more favorable for maize production.

In Production area 5, output elasticities for temperature, precipitation, and sunshine hours are positive, and contributions to maize output for sunshine hours is negative. Production area 5 is characterized by dryness, and precipitation depends mainly on the melting of snow or river irrigation systems in the region. This area also has the advantage of abundance in heat resources, having great potential for improving maize quality and increasing income. Still, it is necessary to ensure appropriate supply of irrigation water. Since the contribution of sunshine hours to maize output is negative in this area, attention should be paid to the selection of new maize varieties that are density-tolerant, high-output, drought-resistant, and suitable for machine harvesting.

5 Analysis of the changes in maize production in the five major production areas in China

This section analyses the climate conditions and maize production inputs and outputs characteristics in the five major production areas at the farmer household level from 2009 to 2018. It also investigates the future layouts of these five production areas and proposes targeted countermeasures and suggestions.

5.1 Changes in the input of production factors in the five production areas

Regarding land input changes, a horizontal comparison of production areas shows that the average maize sown area per household in Production area 1 (15.18 mu) is prominently higher than that in other areas, being 193.27%, 433.82.32%, 479.90%, and 295.38% higher than that in Production area 2, 3, 4, and 5, respectively. Then, a vertical comparison of production areas shows an overall upward trend from 2009 to 2018 for maize sown area per household. In Production areas 1, 2, 3, and 5, the average maize sown area per household in 2018 is 27.68%, 29.53%, 24.60%, and 25.71%, respectively, higher than that in 2009. The exception is Production area 4, as its average maize sown area per household diminished by 20.22% during this period.

Regarding labor force changes, a horizontal comparison of production areas shows that the average labor force input per household in Production area 1 is the highest, followed by Production areas 5, 2, 3, and 4. Vertical comparison of production areas shows an overall downward trend from 2009 to 2018 for average labor force input per household. In Production areas 1, 2, 3, and 4, the average labor force per household in 2018 is 29.09%, 25.79%, 6.10%, and 47.66%, respectively, lower than that in 2009. The exception is Production area 5, which shows an increase of 15.86% in the average labor force input per household during this period.

Regarding material input changes, a horizontal comparison of production areas shows that the average material costs of maize production per household in 2018 is the highest in Production area 1 (4,296.29 yuan), followed by Production areas 2 (1,359.00 yuan), 5 (1,237.92 yuan), 3 (577.79 yuan), and 4 (539.49 yuan). Vertical comparison of production areas shows an overall upward trend from 2009 to 2018 for average material cost of maize production per household, except for Production area 4 (the average material cost of maize production per household in 2018 is 0.03% lower than that in 2009). In Production areas 2, 3, 1, and 5, the average material cost of maize production per household in 2018 is 125.92%, 104.98%, 75.03%, and 64.61%, respectively, higher than that in 2009. Regarding the average cost per household, Production area 5 shows the smallest increase margin and Production area 1 shows the largest absolute value during this period.

5.2 Climate changes in the five production areas

Regarding temperature changes from 2009 to 2018, there is a rise in the monthly average temperature during the growing season in Production area 1 of 0.64°C (increase of 3.46%), and the temperature fluctuation is 0.23°C. For Production area 2, these values are 0.40°C (increase of 1.79%) and 0.34°C. In Production area 3, these values are 0.03°C (increase of 0.15%) and 0.25°C. In Production area 4, these values are 0.77°C (increase of 3.58%) and 0.50°C. In Production area 5, these values are 0.09°C (increase of 0.48%) and 0.28°C. In general, the temperature remained stable across areas with a relative upward trend, especially in Production areas 1 and 2, the two largest maize production areas in China. This temperature increase has advantages, such as the promotion of maize growth.

Regarding precipitation changes from 2009 to 2018, the monthly average precipitation during the growing season in Production area 1 increased by 20.90 mm (increase of 26.89%) with a standard deviation of 10.62 mm. For Production area 2, these values are −0.57 mm (decrease of 0.63%) and 11.90 mm. In Production area 3, these values are 34.90 mm (increase of 30.96%) and 14.31 mm. In Production area 4, these values are −13.18 mm (decrease of 9.82%) and 16.80 mm. In Production area 5, these values are 32.13 mm (increase of 91.62%) and 10.49 mm. In general, the precipitation in Production areas 1, 3, and 5 show an increase from 2009 to 2018, and this increase is significant in Production areas 3 and 5. Further, the increase in precipitation in Production area 3, which generally has sunny days, led to maize production damages. Therefore, measures need to be taken to deal with the difficulties related to pests and diseases caused by high precipitation. Nonetheless, in Production area 5, which generally has a relatively arid climate, the increase in precipitation is beneficial because it promotes the potential for greater local maize output. Meanwhile, the precipitation in Production areas 2 and 4 decreased slightly from 2009 to 2018, with more obvious fluctuations appearing in Production area 4.

Regarding sunshine hours changes from 2009 to 2018, the monthly average sunshine hours during the growing season in Production area 1 and 2, 7 years show numbers lower than those in 2009. In Production area 3, there is only 1 year with lower numbers. In Production area 4 and 5, there are 4 years with lower numbers. In general, sunshine hours in northern China are significantly higher than those in southern China during the period, and they are the highest in the northwest. Recently, due to human activity intensification, the decrease in sunshine hours has become more obvious. This emphasizes the need to develop reasonable planting structures that enable the full use of solar energy resources.

5.3 Maize output changes in the five production areas

Production factors and climate factors jointly affect maize output. A horizontal comparison of the production areas shows that climate factors in Production area 1 are suitable for maize crops, as well as that the land, labor, and material inputs are higher, leading to a high maize output. Specifically, in 2018, Production area 1 shows an average maize output per household of 9,610.43 kg, which is 237.59%, 739.14%, 1288.90%, and 384.15% higher than that of Production areas 2, 3, 4, and 5, respectively. This further verifies that production area 1 is the largest dominant production area. Production area 5 has the advantage of heat, and the increase in precipitation from 2009 to 2018 is conducive to solving the irrigation problems in the region; therefore, Production area 5 has great potential for maize output, albeit the small planting area per household is an obstacle.

A vertical comparison shows an upward trend for average maize output per household from 2009 to 2018. In Production areas 1, 2, 3, and 5, the average maize output per household in 2018 is 38.21%, 48.94%, 23.46%, and 61.76%, respectively, higher than that in 2009. The exception here is Production are 4, which shows a value in 2018 that is 32.74% lower than that in 2009. Based on the analyses in this section, it seems necessary to adjust the agricultural structure for maize production by local conditions. Further, for regions where the natural conditions are not suitable for maize cultivation, it is essential to emphasize their comparative advantages and improve agricultural production efficiency as much as possible.

6 Conclusion and countermeasures

Using micro-level household data of the National Rural Fixed Observation Point from 2009 to 2018, this study incorporates climate factors such as temperature, precipitation, and sunshine hours into the transcendental logarithmic production function and constructs a two-way fixed effect model. With the econometric model, then we empirically study the impact of climate change on maize output in China and the changes in farmers' maize production in different production areas. Furthermore, we analyse the developmental potential of each main maize production area in China. The main conclusion are as follows.

First, temperature, precipitation, and sunshine hours show significant effects on maize output. The output elasticity of temperature is 0.3940, that of precipitation is 0.0153, and that of sunshine hours is −0.0515. Maize is a crop that likes temperature and light and is most sensitive to temperature fluctuations. An appropriate increase in precipitation can also increase maize output, but there is the potential problem of insufficient sunshine hours that may also hinder output.

Second, temperature and precipitation generally positively contribute to maize output, and sunshine hours negatively contribute to maize output. The contribution rates of temperature, precipitation, and sunshine hours to maize output are 2.20%, 0.58%, and −0.51%.

Third, from a subregional perspective, different production areas are affected differently by the climate. Production area 1 has climate conditions that are very suitable for maize growth and is generally not greatly affected by climate, but attention should be paid to problems related to low temperature and chilling damage. The climate of Production area 2 is hot and humid in summer, easily leading to plant diseases, insect disasters, and adversely affecting maize output. The geomorphic environment of Production area 3 is complex, and in the growing season of maize, high temperatures are usually reported together with wet and rainy weather conditions, and these characteristics are not conducive to improvements in maize output and quality. The climate conditions of Production area 4 are suitable for rice production. Production area 5 is characterized by sufficient light for maize production, and it is also dry and has little precipitation; therefore, attention should be paid to ensuring the supply of irrigation water to maize crops.

Fourth, different production areas must take different measures to deal with climate change. Regarding temperature changes, the temperature conditions of the production areas are generally stable and show an upward trend from 2008 to 2019 in general. Regarding precipitation changes, the total precipitation in Production areas 1, 3, and 5 increased. Production area 3 experienced adverse impacts related to the increase, highlighting the necessity to strengthen pest control in the region. In Production area 5, nonetheless, higher precipitation can effectively alleviate the problem of droughts. Meanwhile, Production areas 2 and 4 show a decrease in precipitation levels over the studied period. Regarding sunshine hours changes, human activities have caused a reduction in sunshine hours, which are generally higher in the north than in the south; this emphasizes the need for the development of a reasonable planting structure and making full use of the available solar energy resources.

Fifth, land, labor, and material input remain key factors affecting maize output. Overall, the output elasticities of land, labor, and material input are 0.6740, 0.0531, and 0.2470, respectively. The opportunity cost of the labor force engaged in agricultural production is increasing, and material capital input has become an effective substitute for labor input. Different production areas have various divergent advantages, showcasing that the agricultural structure should be adjusted according to local conditions and agricultural production efficiency should be improved as much as possible.

Based on these conclusion, this study proposes relevant countermeasures and suggestions: In terms of the agricultural production layout, adjust the planting structure according to local endowments and match the local climate and economic condition during the process of crop selection. In terms of farmer's response to climate change, enhance technology training for farmers' adaptive behaviours toward climate change and minimize the damage to farmers from climate shocks. In terms of agricultural infrastructure constructure, develop farmland and water conservation projects and further strengthen irrigation facilities in areas with insufficient rainfall. In terms of sustainable agriculture development, prevent soil pollution and hardening from excessive application of pesticides and fertilizers and thereby ensure the planting area of maize and the cropland quality.

Data availability statement

The data is not publicly available and further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization, ZZ and MG; methodology, ZZ; software, JW; validation, JkL, ZZ, and JW; formal analysis, ZZ; resources, MG; data curation, JW and YJ; writing—original draft preparation, ZZ; writing—review and editing, JkL and WW; visualization, ZL and JL; supervision, MG; project administration, MG; funding acquisition, MG, ZZ, and JK. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.954940/full#supplementary-material

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