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Impact of climate change on food security in the Central Asian countries

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Abstract The current and potential impacts of global warming have generated widespread concerns about food security among all sectors of society. Central Asian countries located deep in the interior of Asia with fragile ecological environments and lower agricultural technology are particularly more prone to severe threats from climate change. Based on panel data acquired in five Central Asian countries from 1990 to 2019, a C-D-C model was developed to study how climate change affects food security in the region and to predict future trends. The study found that the level of food security has generally increased for these five Central Asian countries over the past 30 years, with Kazakhstan and Tajikistan having the highest and lowest food security levels, respectively. The average annual temperature and precipitation exhibit an inverted U-shaped relationship with the region's food security, with the most positive effect on the food security of Kazakhstan. Extremely high and low temperatures have significantly affected food security in the studied region, with Turkmenistan experiencing the most significant negative impacts. The number of frost days had no significant effect on food security. An analysis of future climate showed that the temperature and precipitation in Central Asia will continue to increase from 2030 to 2090, which will negatively impact the food security of these countries. It is recommended that the Central Asian countries enhance their understanding of climate risks, strengthen scientific climate research, and develop multiple adaptation strategies in advance. Simultaneously, they are encouraged to consolidate international cooperation, reducing greenhouse gas emissions effectively and maintaining the ability to ensure food security.

Keywords Global warming, Extreme climate, Food security, Future forecasts, Five Central Asian countries

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1. Introduction

Food security is the foundation of economic development and social stability (Ye and Tuo, 2015; Wang and Qian, 2019). The four main aspects of food security include the food's supply, access, utilization, and stability (Li and Kang, 2016; Han et al., 2019; Chou et al., 2022). Today, the world is facing a severe problem related to food shortage. The ongoing Russia-Ukraine conflict has further exacerbated the global food crisis. About 400,000 people affected by the Russia-Ukraine conflict were facing food shortages as of February 2022, and about 1.1 million people need food and livelihood assistance (Zhong et al., 2022). According to the report from "The State of World Food Security and Nutrition in 2021" (http://www.fao.org/3/cb4474en/cb4474en), it is estimated that by 2030, about 660 million people in the world may still face food shortages, and the size of the human population lacking adequate food and nutrition security will

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also increase rapidly.

Food security is closely affected by climate change and especially by the frequent occurrence of extreme weather events such as heat waves, droughts, declining soil fertility, pest infections, plant disease, and land degradation (Dong et al., 2014; Grace et al., 2019; Liu et al., 2020; Holtermann, 2020; Kusainova et al., 2020; Rehman et al., 2021). These factors are increasingly affecting the food production, quality, prices, and supply chains (Zhang et al., 2017; Fan et al., 2019; Brizmohun, 2019; Ouyang et al., 2020; Pang et al., 2020; Xu et al., 2020; Chen et al., 2021; Javadi et al., 2023; Mirzabaev et al., 2023; Li et al., 2023).

However, the specific impacts of climate change on food crop production are complex and variable. For example, studies have found that climate warming enhances corn and soybeans' drought tolerance but decreases productivity (Yu et al., 2021). Other studies have found that although increased precipitation is not conducive to increased rice and wheat yields in India, but the increasing temperatures have positively impacted all food crops (Mishra, 2020). Some studies have also suggested that the food supply of North and East African countries is negatively affected by climate change (Fusco, 2022). A study by a Finnish research institution shows that about 30% of global food will enter a zero-yield state by the end of the 21st century if greenhouse gas emissions are not controlled (Zhang, 2021).

The Central Asian countries are situated remotely within the Eurasian continent (Figure 1) and have delicate ecological environments. Current uncertainties in the overall security landscape, economic progress, and in the trade and investment realms, have exerted substantial downward pressure on the economy. This situation has given rise to escalating debt risks and notable livelihood issues within these Central Asian countries (Wang and Yang, 2021). Furthermore, the historical origins and climatic characteristics of these nations have contributed to an unsound economic structure. This is exemplified by insufficient agricultural investment and the utilization of outdated agrarian production techniques. These factors significantly impede the development of the complete food industry chain (Li, 2022). Over the past 20–30 years, the birth and natural growth rates of the population within the region have been high, resulting in rapid population expansion. With the exception of Kazakhstan, the remaining four countries confront the challenge of an imbalanced food supply and demand scenario (Sun and Zhang, 2021).

Presently, global warming is instigating profound transformations within the climate and environment of Central Asia. Over the last 50 years, temperatures within this region have undergone a substantial increase, surpassing the average global warming rate (He et al., 2021). Furthermore, the glaciers situated in this area have experienced degradation, leading to a decline in river runoff. As a result, the conditions of water resources continue to deteriorate (Ma et al., 2015; Chen et al., 2017; Yang et al., 2017).

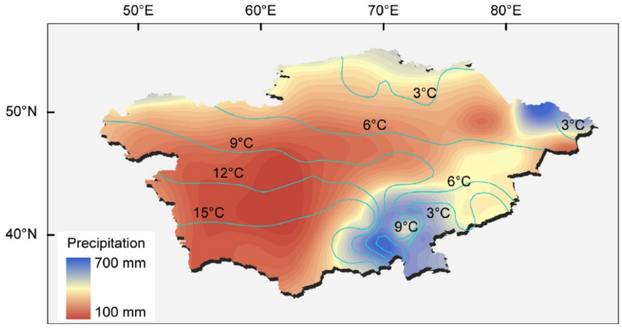

Figure 1 Average Temperature and Precipitation in Central Asia from 1990 to 2019.

What is the existing state of food security within the ecologically fragile territory of these five Central Asian countries? How are the impacts of climate change affecting food security, and what trajectory is food security likely to take in these nations in the future? The responses to these questions have the potential to offer valuable policy insights, aiding the Central Asian region in navigating the repercussions of climate change and ensuring food security. Moreover, these responses constitute a pivotal scientific foundation for prognosticating the security outlook of the entire Eurasian subcontinent.

In this study, we explore the impact mechanism and future climate change adaptation strategies on food security using the panel data of five Central Asian countries from 1990 to 2019. Compared to previous indicators for measuring food security, we have considered the level of food security from different aspects, such as food supply, access, utilization, and stability. In addition, we conducted a heterogeneity analysis among different national conditions of Central Asian countries to explore the impact of climate change and extreme weather on food security. Finally, based on the predicted results of climate change, we propose policy recommendations to ensure future food security in Central Asia.

2. Data and methods

2.1 Data sources

In this study, we utilized panel data acquired from Central Asian countries from 1990 to 2019 to verify the impact of climate change on food security. The data on average annual temperature and annual precipitation, extreme high and low temperatures, and frost days were obtained from the meteorological websites of these countries. Data on food security, agricultural technology investment, pesticide use, fertilizer application, and agricultural labor force were sourced from the official website database of the United Nations Food and Agriculture Organization. The data on the added value of the primary industry and foreign investment in the primary industry were obtained from the World Trade Organization database. Future climate prediction data sources included the United Nations Intergovernmental Panel on Climate Change (IPCC) database.

2.2 Variable description

A food security indicator system was created with four variables: food supply, food access, food stability, and food utilization. The secondary set of indicators includes 14 variables, and such as average dietary energy supply adequacy rate are considered tertiary indicators (Hu and Liu, 2013; Yao et al., 2015; Li and Kang, 2016; Gong and Wang, 2017) (Figure 2). Climate change is the core explanatory variable of this study1), with average annual temperature, average annual precipitation, extreme high temperature, extreme low temperature, and frost days selected as the key factors of climate change (Han et al., 2019; Zhao et al., 2021). In addition, this study introduced agricultural technology investment, pesticide use, fertilizer application, agricultural labor force, the added value of the primary industry, and foreign investment in the primary industry as control variables (Wang and Huang, 2018; Cui and Nie, 2019; Smith and Archer, 2020; Zhang and Yu, 2021). The measurement methods for all variables are shown in Table 1.

2.3 Model construction

Food security results from the interaction between socio-economic and natural factors (Li et al., 2021). Socio-economic factors include material inputs such as fertilizers, pesticides, technology, and labor, while the climate factors are most important among the natural factors. In the past, the traditional C-D production function model only considered a limited set of factors, leaving out climate elements. Researchers are now using an updated approach, as discussed in recent studies (Yang et al., 2020; Chou et al., 2022). They've expanded the C-D production function model to include climate factors, creating what's called the "economy climate" model, or the "C-D-C" model. This model allows us to better understand how climate factors influence food security (Han et al., 2019). The adopted model in this study also considers other variables like material factors. This approach paints a more complete picture of what affects food security. The model 1 calculations are laid out in eq. (1), where various factors are represented: food security(Y), climate factors (C), agricultural technology inputs (T), pesticide use (N), fertilizer applications (H), agricultural labor force(L), added value of the primary industry (G), and foreign investment in the primary industry (I).

$$Y = F(C, T, N, H, L, G, I). \tag{1}$$

Model 2 introduces the quadratic term of climate elements. The formula is shown in eq. (2), where $Y_{i,t}$ represents the food security index of the i country in the t year, $Q_{i,t}$, $J_{i,t}$, $K_{i,t}$, $O_{i,t}$, $S_{i,t}$ represents the annual average temperature, annual precipitation, extreme high temperature, extreme low temperature, and frost days of the i country in the t year, $\mu_{i,t}$ represents the error term, and $\varepsilon_{i,t}$ represents the random disturbance term:

$$\begin{aligned} Y_{i,t} = {} & \alpha_0 + \alpha_1 T_{i,t} + \alpha_2 N_{i,t} + \alpha_3 H_{i,t} + \alpha_4 L_{i,t} \\ & + \alpha_5 G_{i,t} + \alpha_6 I_{i,t} + \beta_1 Q_{i,t} + \beta_2 J_{i,t} + \lambda_1 K_{i,t} \\ & + \lambda_2 O_{i,t} + \lambda_3 S_{i,t} + \beta_3 \left(Q_{i,t}\right)^2 + \beta_4 \left(J_{i,t}\right)^2 \\ & + \lambda_4 \left(K_{i,t}\right)^2 + \lambda_5 \left(O_{i,t}\right)^2 + \lambda_6 \left(S_{i,t}\right)^2 + \mu_{i,t} + \varepsilon_{i,t}. \end{aligned} \tag{2}$$

To further consider the regional differences in the effects of climate change on food security, the present study established five regional dummy variables: Kazakhstan $D_1 = 1$, other countries $D_1 = 0$; Tajikistan $D_2 = 1$, other countries $D_2 = 0$; Turkmenistan $D_3 = 1$, other countries $D_3 = 0$; Uzbekistan $D_4 = 1$, other countries $D_4 = 0$; Kyrgyzstan $D_5 = 1$, other countries $D_5 = 0$.

$$\begin{aligned} Y_{i,t} = {} & \alpha_0 + \alpha_1 T_{i,t} + \alpha_2 N_{i,t} + \alpha_3 H_{i,t} + \alpha_4 L_{i,t} \\ & + \alpha_5 G_{i,t} + \alpha_6 I_{i,t} + \beta_1 Q_{i,t} + \beta_2 J_{i,t} + \lambda_1 K_{i,t} \\ & + \lambda_2 O_{i,t} + \lambda_3 S_{i,t} + \sum_{m=1}^{5} \rho_m D_m \times Q_{i,t} \\ & + \sum_{m=1}^{5} \varphi_m D_m \times J_{i,t} + \sum_{m=1}^{5} \chi_m D_m \times K_{i,t} \\ & + \sum_{m=1}^{5} \theta_m D_m \times O_{i,t} + \sum_{m=1}^{5} \pi_m D_m \times S_{i,t} + \mu_{i,t} + \varepsilon_{i,t}. \end{aligned} \tag{3}$$

3. Results

3.1 Trends in food security in the five Central Asian countries

Results indicate the five Central Asian countries' food security indices ranged between 0 and 1 during 1990~2019 (Figure 3 and Table 2), generally showing an increasing trend. Among them, Kazakhstan consistently had a relatively high and fluctuating food security index. Turkmenistan's index grew the fastest, surpassing Kazakhstan in 2016 to claim the top rank. Uzbekistan's index surpassed Kyrgyzstan's in 1995 and has since remained stable in third place. Kyrgyzstan ranked fourth in terms of food security, while Tajikistan consistently had the lowest food security index.

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1) In data processing, initially, the daily data from meteorological stations in major cities of the five Central Asian states (municipalities) were processed on monthly-basis to obtain monthly data, and then, annual data were calculated based on the monthly data.

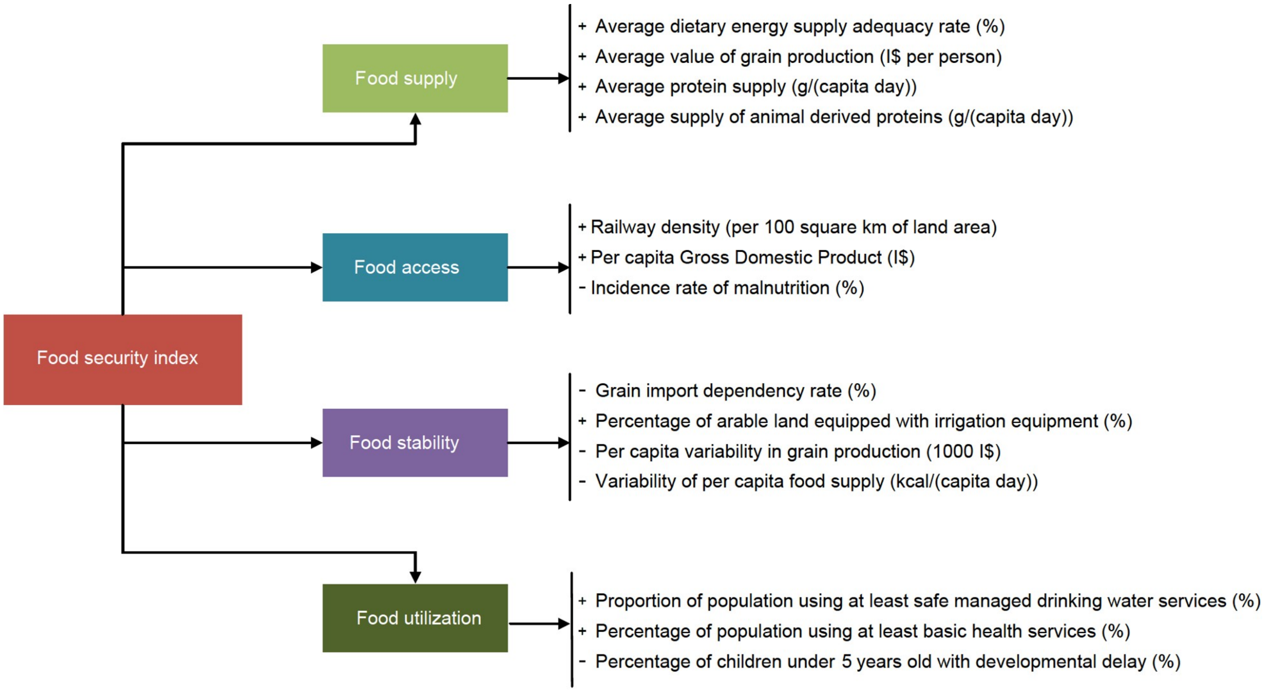

Figure 2 Food security indicator system. In indicator directionality, "+" indicates that the larger the indicator value, the higher the level of food security; "–" indicates that the larger the indicator value, the lower the level of food security.

Table 1 Variable description and statistical description[a)]

Variable name	Description	Min	Max	Mean
Food security	Food security index	0.03	1.00	0.46
Average annual temperature	Average annual temperature (°C)	0.72	1.24	1.04
Annual precipitation	Annual total precipitation (mm)	1.93	2.77	2.42
Extreme high temperature	The 90th percentile of daily maximum temperature (°C)	1.03	1.38	1.24
Extreme low temperature	10th percentile of daily minimum temperature (°C)	−1.14	1.05	0.53
Frost days	Days with daily minimum temperature ≤0°C (day)	1.49	2.25	2.00
Agricultural science and technology investment	Agricultural scientific research investment (10,000 $)	2.41	4.05	3.39
Pesticide usage	Total use of pesticides (t)	0.38	0.61	0.53
Fertilizer application amount	Total fertilizer usage (t)	3.30	4.22	3.72
Agricultural labor force	Agricultural practitioners (10,000 person)	1.73	5.25	3.39
Added value of primary industry	Added value of primary industry (10,000 $)	4.39	5.48	4.86
Foreign investment in primary industry	Foreign investment in primary industry (10,000 $)	1.52	4.84	3.68

a) All variable data are logarithmic.

The latter can be attributed to Kazakhstan's substantial investment in agricultural technology, a well-equipped agricultural labor force, abundant and consistently growing grain production, and lower food security pressure compared to the other Central Asian countries. These factors have positioned Kazakhstan as a major grain producer in the region and globally. Turkmenistan, a perpetually neutral nation, has maintained robust social and economic progress even amid complex international economic changes, thus ensuring stable conditions for food security. The country has consistently prioritized agricultural advancement, achieving increased grain production with a relatively small population, resulting in a high per capita grain yield. Furthermore, Turkmenistan's collaboration with China in modern agriculture, bolstered by the "Belt and Road" initiative, has progressively enhanced agricultural development in the country.

By analyzing secondary indicators of food security, we

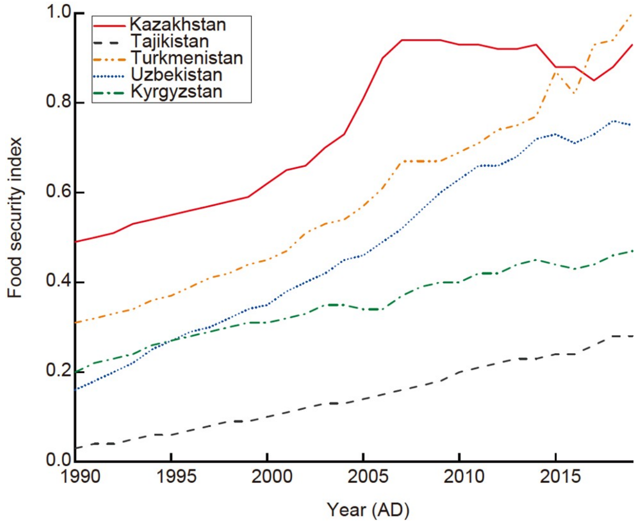

Figure 3 Trends of food security in Central Asian countries from 1990 to 2019.

Table 2 Food security index of the Central Asian countries at different time nodes[a)]

Countries	1990 AD	2000 AD	2010 AD	2019 AD
Kazakhstan	0.49	0.62	0.93	0.93
Tajikistan	0.03	0.10	0.20	0.28
Turkmenistan	0.31	0.45	0.69	1.00
Uzbekistan	0.16	0.35	0.63	0.75
Kyrgyzstan	0.20	0.31	0.40	0.47

a) The time nodes for the food security index of the five Central Asian countries are set at intervals of 10 years.

discerned trends in food supply, access, stability, and utilization across Central Asian countries from 1990 to 2019 (Figure 4). The data reveals that overall food supply has been increasing with Kazakhstan consistently leading and its index fluctuating between 0.6 and 1.0. Uzbekistan overtook Kyrgyzstan and Turkmenistan in 2009 and 2012 respectively, securing the second spot. Tajikistan maintains the lowest food supply level. Food access across Central Asian countries is generally improving, with Kyrgyzstan and Turkmenistan showing relatively high indices ranging from 0.5 to 0.75. Uzbekistan experienced the most significant increase, taking the lead in 2012, while Tajikistan consistently lags behind. Food stability demonstrates significant fluctuations among the four secondary indicators with Turkmenistan exhibiting the most stability, followed by Uzbekistan, Kyrgyzstan, and Tajikistan. Kazakhstan experiences the highest frequency of fluctuations. Overall, the food utilization index for Central Asian countries is ascending. Kazakhstan's index remains relatively high, fluctuating between 0.6 and 0.65. Turkmenistan and Uzbekistan, surpassing Kazakhstan in 2014, also maintain relatively high indices. Tajikistan sees a notable increase in food utilization, but still ranks lowest among the countries.

3.2 Climate change trends in the five Central Asian countries

Figure 5 illustrates changes in climate factors in Central Asian countries, including average annual temperature, annual precipitation, frost days, and extreme high and low temperatures. The average annual temperature displayed an upward trend, fluctuating between 9.5°C and 13°C. Notable peaks occurred in 1999 and 2004, with valleys in 1993, 1996, and 2014. Average annual precipitation exhibited instability, rising initially, then declining and stabilizing. A peak was observed in 1993, with low rates in 1995 and 2008. Frost days varied greatly annually, usually extending over 3 months. Exceptional periods were seen in 1992, 1994, and 2014, while 1999 and 2004 had shorter frost periods. Extreme high and low temperatures aligned with the average annual temperature pattern, remaining relatively stable. Extreme high temperatures ranged between 18°C and 20°C, while extreme low temperatures ranged between 3°C and 5°C.

3.3 Impact of average annual climate on food security

A regression analysis was conducted to assess the impact of the average annual climatic conditions on food security (Table 3). The average annual temperature and precipitation in Model 1 had a significant negative impact on food security. The coefficients of the model's first and second terms of the 2-year average temperature were positive (1.357) and negative (−0.475), respectively, indicating an inverted U-shaped nonlinear relationship between the next year's average temperature and food security. Based on the coefficients of the first and second terms of the model's 2-year precipitation alone, an inverted U-shaped nonlinear relationship was also observed between average annual precipitation and food security. This indicates that when the average annual temperature and precipitation are within a specific range, any increase in the average annual temperature and precipitation will be beneficial for ensuring food security. However, once the average annual temperature and precipitation exceed the threshold, subsequent increase in temperature and precipitation will lead to decreased levels of food security. Among the control variables, agricultural technology investment, agricultural labor force, and foreign investment in the primary industry have a significant positive impact on food security. Among them, agricultural technology investment had the greatest impact, while pesticide and fertilizer use had a negative impact on food security.

Further subdividing the studied area at the individual

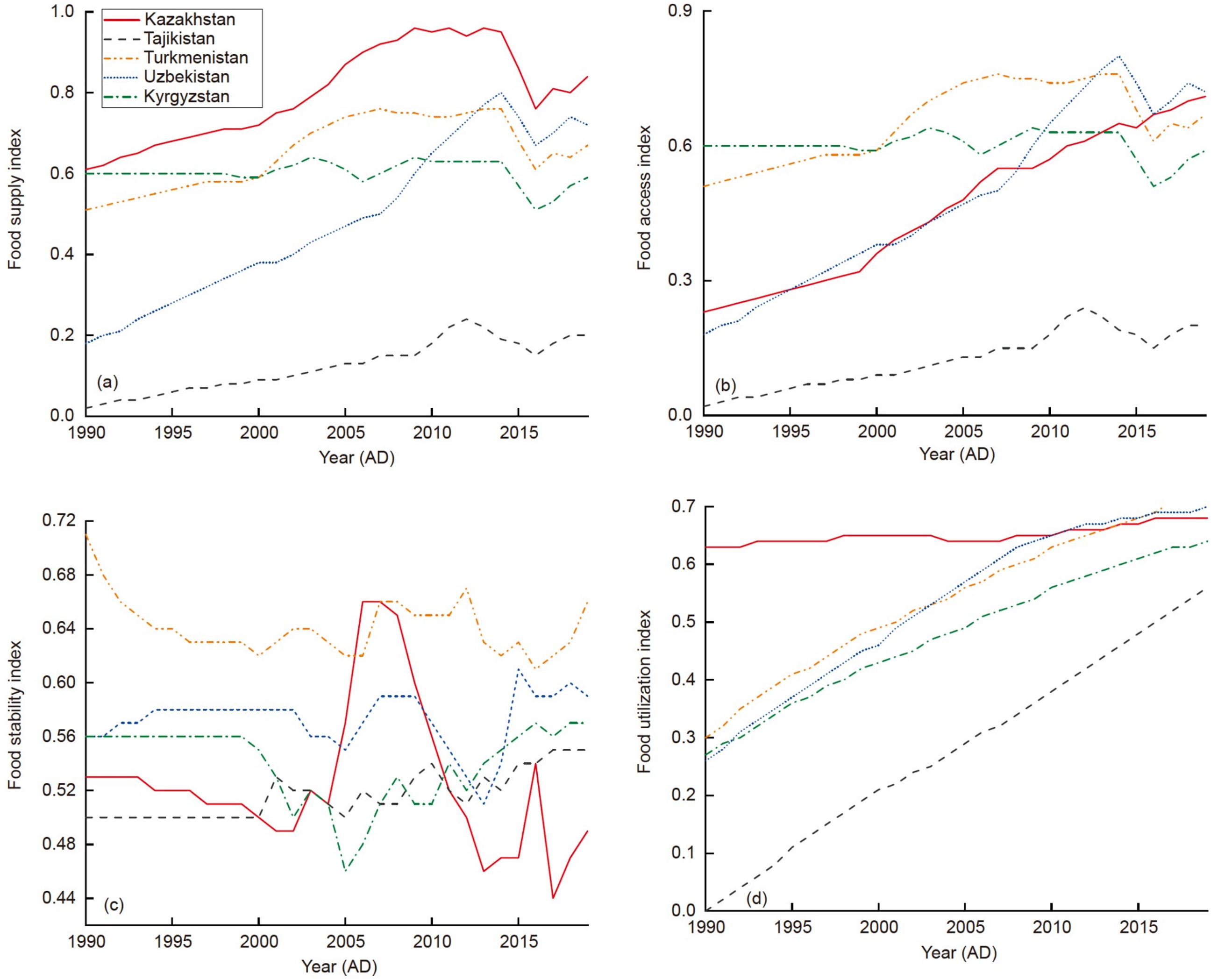

Figure 4 Change trend of secondary indicators of food security in the Central Asian countries from 1990 to 2019. (a) The changing trend of food supply in the five Central Asian countries from 1990 to 2019; (b) the changing trend of food access in the five Central Asian countries from 1990 to 2019; (c) the changing trend of food stability in the five Central Asian Countries from 1990 to 2019; (d) the changing trend of food utilization in the five Central Asian countries from 1990 to 2019.

country level, the impact coefficients of the annual average temperature on food security in Kazakhstan, Tajikistan, Turkmenistan, Uzbekistan, and Kyrgyzstan are 0.407, 0.184, 0.303, −0.284, and 0.167, respectively (Table 4). The impact coefficients of annual precipitation on food security in Kazakhstan, Tajikistan, Turkmenistan, and Uzbekistan are 0.151, 0.024, 0.006, 0.019, and 0.020 respectively (Table 4), indicating that the average annual climate has the strongest positive impact on Kazakhstan's food security.

3.4 Effects of extreme climate events on food security

Table 5 shows the regression results of the impact of extreme climate events on food security. Model 1 shows that extremely high and low temperatures had negative impacts on food security at a significance level of 5%, while the number of frost days had no significant impact on food security. In Model 2, only the primary and secondary terms of extreme low temperature had a significant impact on food security, and the coefficients were both negative, indicating that extremely low temperatures pose a significant threat to food security. In the control variables, agricultural technology investment, agricultural labor force, and foreign investment in the primary industry had significant positive impacts on food security, while the use of pesticides and fertilizers had negative impacts.

Extremely high temperatures had a significant negative impact on the food security of Kazakhstan and Turkmenistan, with Turkmenistan experiencing the greatest impact. Extremely low temperatures had negative impacts on the food security of Tajikistan, Turkmenistan, and Kyrgyzstan, with Turkmenistan experiencing the strongest negative impact. The impact of frost days on food security in the five Central Asian countries are insignificant (Table 6).

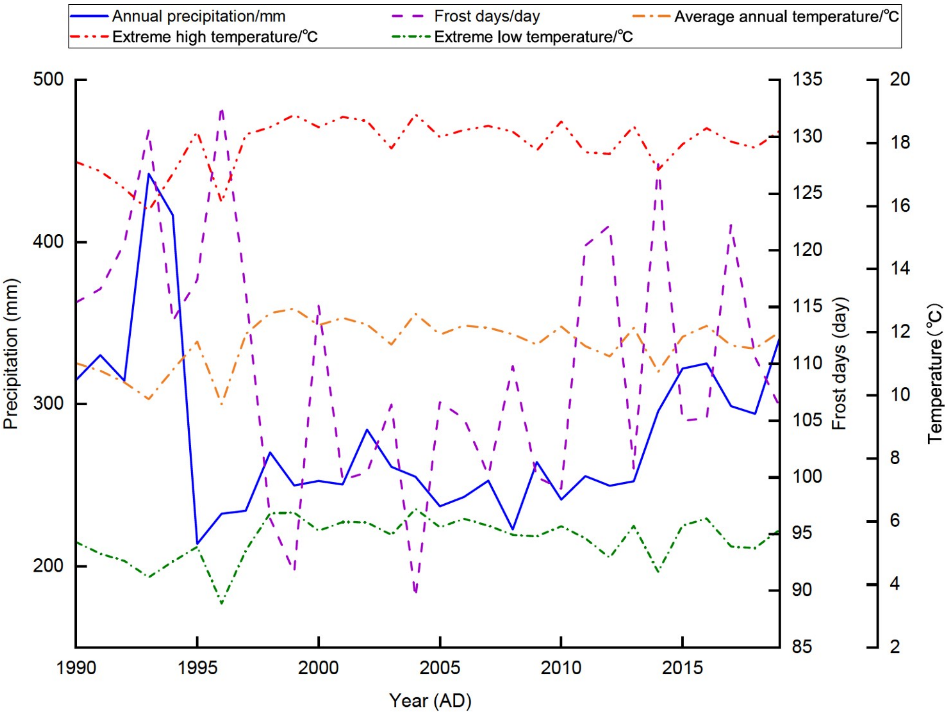

Figure 5 Climate change trends in the Central Asian countries from 1990 to 2019.

Table 3 Average annual climate impact on food security$^{a)}$

Variable name	Model 1		Model 2	
	Coefficient	Robust standard error	Coefficient	Robust standard error
Average annual temperature	−0.394***	0.039	1.357**	0.683
Annual precipitation	−0.038*	0.023	0.202	1.563
Secondary term of annual average temperature			−0.475*	0.334
Secondary term of annual precipitation			−0.047	0.321
Agricultural science and technology investment	1.262***	0.463	1.331***	0.513
Pesticide usage	−6.068*	0.463	−6.557*	3.685
Fertilizer usage	−0.274***	0.094	−0.262**	0.103
Agricultural labor force	0.075**	0.033	0.072**	0.029
Added value of primary industry	0.040	0.117	0.022	0.128
Foreign investment in primary industry	0.038*	0.022	0.035*	0.021
Constant term	0.416	0.271	0.648	2.381
R^2	0.880		0.881	

a) *, **, *** are significant at 10%, 5% and 1% confidence levels respectively.

3.5 Prediction of the contribution rate of future climate change to food security

Based on the above results, we further explored the development trends of food security under different future climate change scenarios. The Sixth Assessment Report (AR6) of the IPCC provides the prediction results of future surface temperature and precipitation changes in all regions of the world (IPCC WGI Interactive Atlas) based on the simulations from the 6th Coupled Mode Comparison Plan (CMIP6). These include five scenarios of shared socio-economic paths: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. We extracted the climate prediction results for these countries under the two climate scenarios of SSP1-2.6 and SSP5-8.5. The second-best scenario, SSP1-2.6, refers to a scenario where the reduction of global carbon dioxide emissions

Table 4 The results of regional differences in the impact of annual average climate on food security[a)]

Variable name	Coefficient	*Z*-statistic	Variable name	Coefficient	*Z*-statistic
Average annual temperature	−0.195*** (0.062)	−3.150	Average annual temperature*D_3	0.303*** (0.073)	−4.150
Annual precipitation	−0.009 (0.007)	−1.330	Average annual temperature*D_4	−0.284 (0.031)	−8.920
Agricultural science and technology investment	1.138*** (0.362)	3.140	Average annual temperature*D_5	0.167*** (0.022)	−7.470
Pesticide usage	−4.848 (3.825)	−1.270	Annual precipitation*D_1	0.151*** (0.052)	−2.860
Fertilizer usage	−0.597*** (0.158)	−3.760	Annual precipitation*D_2	0.024*** (0.007)	−3.140
Agricultural labor force	0.090*** (0.032)	2.770	Annual precipitation*D_3	0.066 (0.036)	1.820
Added value of primary industry	0.106 (0.118)	0.900	Annual precipitation*D_4	0.019** (0.009)	−2.090
Foreign investment in primary industry	−0.040* (0.021)	−1.840	Annual precipitation*D_5	0.020*** (0.006)	−2.910
Average annual temperature*D_1	0.407** (0.193)	2.100	Constant term	0.506** (0.244)	2.070
Average annual temperature*D_2	0.184*** (0.021)	−8.400	R^2	0.882	

a) *, **, *** are significant at 10%, 5% and 1% confidence levels respectively, the brackets are robust standard errors.

Table 5 Impact of extreme climate events on food security[a)]

Variable name	Model 1		Model 2	
	Coefficient	Robust standard error	Coefficient	Robust standard error
Extreme high temperature	−0.471**	0.205	−0.029	0.995
Extreme low temperature	−0.029**	0.011	−0.092*	0.054
Frost days	−0.014	0.090	−0.819	0.710
Extreme high temperature quadratic term			0.095	0.448
Extreme low temperature secondary term			−0.086**	0.043
Number of frost days secondary term			0.217	0.185
Agricultural science and technology investment	1.254**	0.476	−6.245	3.890
Pesticide usage	−5.889*	3.503	−6.557*	3.685
Fertilizer usage	−0.291***	0.098	−0.275**	0.107
Agricultural labor force	0.071**	0.122	0.039	0.031
Added value of primary industry	0.035	0.117	0.022	0.102
Foreign investment in primary industry	0.040*	0.021	0.030	0.018
Constant term	0.589**	0.258	0.663	1.197
R^2	0.883		0.885	

a) *, **, *** are significant at 10%, 5% and 1% confidence levels respectively.

worldwide would meet strict standards, reaching zero net emissions globally after 2050. SSP5-8.5 represents the worst-case scenario, with global carbon dioxide emissions roughly doubling by the mid-21st century and global average temperatures rising by 4.4°C by 2100. The results show that the changes in average annual temperature and precipitation in Central Asia in the near future (2026–2035), medium term (2046–2055), and long term (2086–2095) will be on the rise

Table 6 Results of regional differences of impacts of extreme climate events on food security[a)]

Variable name	Coefficient	*Z*-statistic	Variable name	Coefficient	*Z*-statistic
Extreme high temperature	−0.780* (0.416)	−1.880	Extreme high temperature*D_5	0.400 (0.255)	1.570
Extreme low temperature	−0.066 (0.057)	−1.170	Extreme low temperature*D_1	−0.029 (0.049)	−0.600
Frost days	−0.409** (0.189)	−2.160	Extreme low temperature*D_2	−0.131* (0.079)	−1.660
Agricultural science and technology investment	1.240*** (0.371)	3.340	Extreme low temperature*D_3	−1.953*** (0.516)	−3.780
Pesticide usage	−5.829** (2.849)	−2.050	Extreme low temperature*D_4	0.277 (0.523)	0.530
Fertilizer usage	−0.334*** (0.124)	−2.690	Extreme low temperature*D_5	−0.044* (0.051)	−0.85
Agricultural labor force	0.069** (0.035)	1.980	Frost days*D_1	−0.012 (0.022)	−0.580
Added value of primary industry	0.098 (0.126)	0.780	Frost days*D_2	−0.144 (0.082)	−1.750
Foreign investment in primary industry	−0.034 (0.034)	−1.000	Frost days*D_3	0.068 (0.079)	0.850
Extreme high temperature*D_1	−0.258* (0.165)	−1.560	Frost days*D_4	0.066 (0.130)	0.510
Extreme high temperature*D_2	0.235 (0.164)	1.430	Frost days*D_5	−0.180 (0.132)	−1.360
Extreme high temperature*D_3	−1.651*** (0.473)	−3.490	Constant term	0.286*** (0.047)	6.070
Extreme high temperature*D_4	−0.163 (0.545)	−0.300	R^2	0.883	

a) *, **, *** are significant at 10%, 5% and 1% confidence levels respectively, the brackets are robust standard errors.

under both of these climate scenarios (Table 7). Under the SSP5-8.5 scenario, the future increase in both temperature and precipitation will occur more rapidly than in other scenarios. In the Central Asian countries, the temperature will increase by 6.1°C and precipitation will increase by 8.8% by 2090. The future climate change situation under the SSP1-2.6 scenario is predicted to be relatively mild, with temperatures rising by 1.7°C and precipitation increasing by 4.5% by 2090.

The contribution rate of future climate change to food security is shown in Table 8, where the climate variable coefficients refer directly to the results in Table 3. The variable representing the rate of climate change, 'b', is the rate of change in the average values of each variable from 2030 to 2090 relative to the average values from 1994 to 1996. The contribution rate 'c' of each climate variable to food security is the product of the climate variable coefficient '*a*' and the climate variable change rate '*b*'. Table 8 shows that climate change had a negative impact on food security in both scenarios. In the middle of this century, the contribution rate of future climate change to food security under the SSP5-8.5 scenario was −0.595. By 2090, the contribution rate was as high as −1.038, far higher than the contribution rates of −0.366 and −0.388 under the SSP1-2.6 scenario. It can be seen that higher greenhouse gas emissions will result in more severe impacts from future climate change on food security in Central Asia; over time, the negative impact is predicted to intensify.

4. Discussion

4.1 Adaptative actions for food security in the Central Asian countries under the background of climate change

The Central Asian countries have abundant land, solar, and thermal resources as well as a relatively large proportion of agricultural laborers in the labor market. However, this region still has problems related to insufficient water resources, a lack of production and processing technology, and a need for development funds (Deng et al., 2010; Yan and Wang, 2016; Shi, 2020). The changes to the average annual climate and the effects of extreme climate events have had a variety of regional impacts on all five Central Asian countries analyzed here (Tables 4 and 6). These countries should

Table 7 Future average surface temperature and precipitation changes in the Central Asian countries[a)]

Year	SSP5-8.5 scenarios		SSP1-2.6 scenarios	
	Temperature rise (°C)	Increased precipitation (%)	Temperature rise (°C)	Increased precipitation (%)
2030 year	1.4	2.2	1.2	3.1
2050 year	2.7	4	1.6	4.1
2090 year	6.1	8.8	1.7	4.5

a) Based on the average climate value in Central Asia from 1995 to 2014, the data is a 10-year average. For example, “2030 year” represents the average value from 2026 to 2035.

Table 8 Contribution rate of future climate change to food security

Climate scenarios	Year	Climatic variable	Climate variable coefficient *a*	Climate variable change rate *b*	Contribution rate $c=a\times b$
SSP5-8.5scenarios	2030 year	Temperature fluctuation	−0.394	0.093	−0.037
		Precipitation variation	−0.038	8.956	−0.340
		Climate change			−0.377
	2050 year	Temperature fluctuation	−0.394	0.251	−0.099
		Precipitation variation	−0.038	13.045	−0.496
		Climate change			−0.595
	2090 year	Temperature fluctuation	−0.394	0.587	−0.231
		Precipitation variation	−0.038	21.222	−0.806
		Climate change			−1.038
SSP1-2.6scenarios	2030 year	Temperature fluctuation	−0.394	0.112	−0.044
		Precipitation variation	−0.038	7.983	−0.303
		Climate change			−0.347
	2050 year	Temperature fluctuation	−0.394	0.121	−0.048
		Precipitation variation	−0.038	8.372	−0.318
		Climate change			−0.366
	2090 year	Temperature fluctuation	−0.394	0.177	−0.070
		Precipitation variation	−0.038	8.372	−0.318
		Climate change			−0.388

respond to climate change from different directions based on the characteristics of their local agricultural development and should work to ensure food security. Kazakhstan has the largest scale of agricultural planting among these five countries. Kazakhstan actively promotes intensive and large-scale agricultural planting by using its advantageous geographical conditions such as being located in a landscape with plains and a vast area of arable land. These conditions enhance its extensive grain-processing capacity and promote the grain industry’s development, which help mitigate the threat posed by climate change and promotes the vertical development of the grain-based industrial chain. However, the role of Kazakhstan as the leader in grain production among the five Central Asian countries should be fully leveraged in several ways. The country should expand agricultural cooperation, trade, and investment with neighboring countries, actively introduce advanced agricultural machinery, employ mechanized production technology, and import agricultural product processing equipment from abroad. These measures will help the country to improve the efficiency of grain production, allowing Kazakhstan to actively promote the healthy development of regional grain trade while meeting the needs for its own food supply. For Uzbekistan, Kyrgyzstan, and Turkmenistan, which can achieve basic food self-sufficiency while ensuring the stability of the original food production environment, a need exists to deeply tap into the potential of food production, strengthen refined cultivation of grain planting, and effectively improve the rate of arable land resource use. Moreover, sufficient financial support should be provided for grain production;

mechanisms for benefiting farmers should be improved such as providing training for agricultural workers and subsidies for increasing agricultural production and enhancing the ability of grain growers to resist risks and improve their enthusiasm for grain production. Tajikistan cannot achieve food self-sufficiency and will continue to mainly rely on food imports. This country needs to prioritize the development of its own food industry. In the process of grain production, comprehensive supporting technologies should be adopted to enhance the ability of Tajikistan to resist natural disasters, actively introduce advanced grain production technologies and drought-resistant crop varieties, enhance the adaptability of crops to respond to environmental changes and enhance the hematopoietic capacity of the country's grain supply. Furthermore, a multi-channel grain import trade system should be established to enhance the ability of the county to avoid grain import risks.

4.2 Development path of food security in the Central Asian countries from the perspective of the human land system

Essentially, food security research is an extension and deepening of human-land relationships. It is also an effective way to seek coordination between human development and available resources. In the context of climate change, promoting the coordinated development of the human land system is the fundamental way to ensure food security, which helps to improve the quality of scientific research related to food production in response to climate change and lays a solid foundation for solving the food security problems of the five Central Asian countries. During the period from 1990 to 2019, extreme climate events, represented by extreme high and low temperatures, resulted in changes in essential production factors such as temperature, water, and soil for food crops, severely disrupting the stability of agricultural production environments and threatening food security (Table 5). According to the estimated results of the IPCC AR6 Working Group I report on future global climate, climatic warming will have a more complex and profound impact on food security in the future. Therefore, these five countries should have a forward-looking and systematic understanding of the relationship between human and land development. They should consider the needs of agricultural irrigation, energy consumption, and economic development, clarify key regulatory indicators and their scope for food production, energy security, ecological security, and socio-economic development. In addition, these countries should combine sustainable development adaptation scenarios so as to propose sustainable development plans and regulatory strategies in line with food security goals. In the grain production process, plans have been laid to develop green and water-saving agriculture to weaken the negative impacts of human activities on the agricultural production environment (Huang and Wang, 2021). Based on adhering to the goal of providing sufficient grain arable land, a reasonable development of arable land is being carried out, unreasonable reclamation has been restricted, and agricultural planting structure and regional adjustment are being adapted to the context of climate change (Riccò et al., 2018). Moreover, technological means should be used to create a suitable production environment for food crops and reduce the impact of climate change on food production. These include the development and application of agricultural water-conserving technologies such as water-conserving irrigation, agricultural drought resistance, and engineered water conservation; this method has effectively alleviated seasonal and local droughts, especially in the arid areas of Central Asia, which has played a major role in improving grain output (Han et al., 2021). In addition, agricultural monitoring technology should be used to promptly adjust the layout and structure of agriculture and promote the orderly development of unused land in a way that can effectively reduce the negative impact of climate change on agricultural production (Ruan and Yu, 2019).

4.3 Cooperation mechanism for food security of the Central Asian countries under the Belt and Road Initiative

The five Central Asian countries are important constituent countries of "the Belt and Road" Initiative (BRI). In the context of global climate change, both the impact of climate change on food security and the low level of agricultural modernization in these five countries can actively rely on the development opportunity of the BRI to adapt and alleviate the pressures created by climate change (Zhou et al., 2022). By taking advantage of the BRI, these countries can take advantage of their advantageous natural resource endowments and actively introduce foreign capital, advanced technology, and other factors that are relatively scarce in the region. They can strengthen the food trade and establish a food cooperation mechanism with China. For example, these five countries have abundant land resources, with a per capita arable land area of about six times that of China. The area of uncultivated agricultural land is relatively large in this region. Introducing advanced Chinese agricultural enterprises can not only allow the region to use advanced management concepts to promote the upgrading of the food industry chain but can also create employment opportunities and increase the income of practitioners in the agricultural industry (Huang and Wei, 2022). Relying on the Shanghai Cooperation Organization Agricultural Base, the BR High-end Forum for International Cooperation in Precision Agriculture, and the BR Forum for International Cooperation and Development in Agricultural Modernization, these five Central Asian countries can promote the communication of grain production technology among countries along the BR by new grain breeding through sharing agricultural research achievements and technological exchanges, mechanized agricultural tools' sharing, and cooperation in agricultural technology and industrial development (Gu and Li, 2022). In addition, through the BR trade, these five countries should actively participate in multilateral trade rules and consultation mechanisms to promote the efficient allocation of resources in their food industry chain and develop a deep level of integration in the market (Yu et al., 2021).

5. Conclusion and outlook

Based on data spanning from 1990 to 2019, a significant impact of climate change on food security within the five Central Asian countries over the past three decades has been identified. The analysis revealed a distinctive inverted U-shaped relationship between the average annual temperature, precipitation, and the levels of food security across these nations. Both extremely high and low temperatures exhibit a substantial adverse effect on the food security status of these Central Asian countries. Projections derived from a predictive model indicate an anticipated rise in temperature and precipitation across Central Asia from 2030 to 2090, which is poised to sustainably undermine the food security landscape of these nations. In response to these findings, the countries under study must bolster their comprehension of climate-related risks. It is imperative for them to fortify their commitment to scientific and comprehensive research concerning the intricate interplay between climate change and agricultural domains. In tandem, the formulation of multifaceted adaptation strategies becomes a pressing necessity. Additionally, the five nations must intensify international collaborations, embracing equitable and just climate action. Adequate resources ought to be allocated to facilitate technology transfer, endorse political resolve, and foster partnerships. These measures are essential to bolster the efficacy of climate adaptation, curtail greenhouse gas emissions, and enhance the resilience required for ensuring food security.

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