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The Impact of Climate Change on Food Security: Evidence from Panel Data Analysis in Central Asia

Climate change leads to various impacts, including reduced production, lower crop yields, land degradation, soil erosion, and overall, food insecurity. It is projected that by 2080, between 5 million and 170 million people could encounter serious food shortages. Currently, approximately 5 million people are experiencing inadequate access to food in Central Asia. This study investigates the impact of climate change on food security in Central Asia by using panel data analysis for five Central Asian countries between 2000 and 2020. The findings indicate that weather shocks negatively affect food security dimensions. Based on the findings, the authors recommend improving education on adapting the agricultural sector to climate change, implementing technological improvements, and transitioning to sustainable agriculture.

Keywords: food security, vulnerability, climate change, temperature, precipitation, Central Asia

JEL classifications: Q15, Q18.

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Introduction

Climate change (CC) is no longer a theoretical or distant issue, as its widespread consequences are becoming increasingly clear around the world. Over the past century, the Earth's surface has experienced a temperature increase of 0.8 °C, with over 75% of this rise occurring in the past three decades (Hansen *et al.,* 2006). The resulting impacts include reduced agricultural productivity, declining crop yields, soil degradation, and erosion, all contributing to lower food security (FS). The concept of Vulnerability, Adaptation, and Resilience, outlined by the IPCC (2022), underscores that extreme weather events such as droughts, floods, and intense rainfall exacerbate the vulnerability of food systems, leading to food shortages, poverty, malnutrition, and volatile food prices. To mitigate these impacts, the food and agricultural sectors must adopt practices that build resilience and adapt to shifting climatic patterns. This includes the cultivation of climate-resilient crops, enhancement of soil health, efficient water management, and sustainable development strategies aimed at reducing susceptibility to climate stresses (IPCC, 2022).

The occurrence of extreme weather events, including high temperatures and severe droughts, poses an ongoing challenge to food security, threatening global nutrition and agricultural stability. Agriculture, inherently sensitive to climatic variability, faces increasing strain from changing precipitation patterns and higher temperatures, which in turn directly impact food availability and crop productivity (Godfray *et al.,* 2010). Experts have highlighted the harmful effects of CC on FS, predicting that by 2080, an estimated number ranging from 5 million to 170 million individuals worldwide could face intense food shortages (Schmidhuber and Tubiello, 2007). FS, particularly in its utilisation dimension, continues to be compromised by widespread malnutrition and micronutrient deficiencies. The Global Nutrition Report highlights that over 2 billion people suffer from at least one micronutrient deficiency, and 790 million people consume less than 2,100 calories per day. Moreover, 160 million children under the age of five are stunted, and 50 million are severely underweight. The degradation of a quarter of the Earth's land area, affecting 3.2 billion people, predominantly rural communities and smallholder farmers, exacerbates this global challenge (IFPRI, 2015). The research work presented here aims to draw attention to the localised implications of these global challenges, with Central Asia (CA) serving as a representative case study.

Currently, approximately five million individuals experience insufficient access to food sources who are residing in CA (Peyrouse, 2013). The region's agricultural sector faces significant threats from climate-induced challenges such as rising temperature, altered precipitation patterns, and fluctuations in river flows (Meyers *et al.,* 2012). Notably, the region's average surface air temperature has increased by 0.36 - 0.42°C for every ten years over the past 33 years (Hu *et al.,* 2014), while average precipitation has risen by 4.63mm per decade (Luo *et al.,* 2019). Heavy rainfall and storm-induced erosion further diminish the availability of arable land (Christmann *et al.,* 2009), while CC also impacts the prevalence and severity of pests and diseases, complicating agricultural management (Meyers *et al.,* 2012). Water scarcity is increasing, with competing demands from agriculture, industry, and domestic use adding to the strain (Hanjra and Qureshi, 2010). The increased frequency of extreme temperatures pushes crops closer to their thermal tolerance limits, undermining growth and yields (Lioubimtseva and Henebry, 2012). CA's heavy reliance on agriculture makes it particularly susceptible to CC's destabilising effects on food systems and regional economies.

While extensive research has been conducted globally on the influence of CC on the four pillars of FS – availability, access, utilisation, and stability – a significant gap persists in the literature focusing on CA. Most existing studies either address isolated aspects of FS or focus on regions such as Sub-Saharan Africa or South Asia, leaving the unique challenges of CA underexplored. The region's specific conditions, including acute water shortages, significant land degradation, and economic dependence on agriculture, necessitate a comprehensive and targeted analysis. Research is lacking on how CC – particularly temperature increases and precipitation variability – impacts all dimensions of FS in the region. This gap highlights the need for insights that can inform policy and foster strategies to bolster resilience and adapt to climate challenges.

This research aims to bridge this gap by assessing the multifaceted impacts of CC on FS in CA, with particular attention to temperature and precipitation changes. The study seeks to examine the implications for agricultural productivity, food access, and public health and to identify strategies that can enhance the resilience of food systems. Additionally, it aims to provide recommendations to secure food supply and improve the living standards of the region's population.

Literature Review

The issue of FS, encompassing whether there is enough food to feed the global population and the factors influencing this, has been the focal point of extensive research. Studies typically address key questions, such as: (i) Is global food production sufficient? (ii) Do people have adequate access and financial means to obtain food? (iii) Is food being utilised properly? (iv) Can sustainable food production be maintained in an environmentally friendly manner? The impact of CC has emerged as a critical element affecting these questions. A substantial body of research (El Bilali *et al.,* 2020; Kumar *et al.,* 2018; Muchuru and Nhamo, 2019) has underscored the significant consequences of CC on rural communities, where agriculture is pivotal.

The relationship between CC and FS has been studied at various levels – global, regional, national, and household (Maxwell, 1996; Pinstrup-Andersen, 2009). The findings, however, are inconsistent and often contingent on the analytical frameworks, methodologies, and data characteristics employed (Table 1).

Despite the breadth of existing studies, the findings on the impact of CC on FS are varied. While some research identifies significant negative consequences, others report minimal or context-specific effects. The debate continues, and further research is essential to reach a more comprehensive understanding.

The literature highlights that while many studies examine the influence of CC on specific dimensions of FS, integrated analyses encompassing all four pillars – availability, access, utilisation, and stability – are rare. Firdaus *et al.* (2019) highlight that while CC's impact on food availability has been well-documented, other dimensions such as access, utilisation, and stability are often overlooked. They advocate for future research to adopt a more holistic approach. In response to this gap, our research examines the comprehensive impact CC on all four pillars of FS in CA.

To illustrate the scope of existing research, we categorised studies into two main groups: (i) those that investigate the impact of CC on each dimension of FS separately, and (ii) those that address multiple or all dimensions simultaneously (Table 2). For example, many scholars have examined how climate change affects food availability (Abbas, 2022; Mekonnen *et al.,* 2021; Wu *et al.,* 2021; Fuller *et al.,* 2018; Zhao *et al.,* 2017). Similarly, the impact on food access has been reviewed by Asare-Nuamah (2021), Wang (2010), Alvi *et al.* (2021) and Wossen *et al.* (2019).

Climate Change and Food Availability

Research examining the link between CC and food availability indicates significant negative impacts. Zhao *et al.* (2017) demonstrated how global warming reduced the yields of staple crops such as maize, wheat, rice, and soybean.

Table 1: Reviewed studies on the FS - CC nexus at various levels.

FS Researchers Group			
Global level	**Regional level**	**National level**	**Household Level**
Zhao *et al.* (2017); Schmidhuber *et al.* (2007); Wheeler *et al.* (2013).	Singh *et al.* (2022); Mumuni *et al.* (2023); Lin *et al.* (2022); Fuller *et al.* (2018); Affoh *et al.* (2022); Alvi *et al.* (2021).	Mahapatra *et al.* (2021); Verschuur *et al.* (2021); Wu *et al.* (2021); Abbas (2022); Wang (2010); Wossen *et al.* (2019); Jibrillah et al (2018); Guo *et al.* (2023)	Mekonnen *et al.* (2021); Asare-Nuamah (2021).

Source: Own composition

Table 2: Categorisation of FS researchers.

<table>
<tr><th colspan="4">First Group</th></tr>
<tr><th>CC's Impact on Food Availability</th><th>CC's Impact on Food Access</th><th>CC's Impact on Food Utilisation</th><th>CC's Impact on Food Stability</th></tr>
<tr><td>Abbas (2022);
Mekonnen <i>et al.</i> (2021);
Wu <i>et al.</i> (2021).</td><td>Asare-Nuamah (2021);
Wang (2010);
lvi <i>et al.</i> (2021);
Wossen <i>et al.</i> (2019).</td><td>Dietz (2020);
Mahapatra <i>et al.</i> (2021).</td><td>Ribeiro <i>et al.</i> (2021);
Jibrillah <i>et al.</i> (2018).</td></tr>
<tr><th colspan="4">Second Group</th></tr>
<tr><th colspan="2">CC's Impact on Triple Pillars of FS</th><th colspan="2">CC's Impact on Quadruple Pillars of FS</th></tr>
<tr><td colspan="2">Mumuni <i>et al.</i> (2023);
Affoh <i>et al.</i> (2022).</td><td colspan="2">Singh <i>et al.</i>, (2022)</td></tr>
</table>

Source: Own composition

Fuller *et al.* (2018) found similar outcomes for banana yields in Central Africa, while Wu *et al.* (2021) showed that rising temperatures adversely affected maize production in China. In Pakistan Abbas (2022) highlighted that higher temperatures are expected to impede the long-term yields of major crops. Mekonnen *et al.* (2021) investigated Ethiopian household FS, noting that both rainfall and temperature significantly influenced crop productivity.

Climate Change and Food Access

CC also impacts food access. Alvi *et al.* (2021) employed an Integrated Assessment Model (IAM) to analyse FS in South Asia under climate scenarios, revealing rising food prices and diminished consumption. In Ghana, Asare-Nuamah (2021) noted that lower crop yields due to CC led to food insecurity as households struggled to afford sufficient food. Conversely, Wang (2010), using panel data from 1985 to 2007, found no significant impact of CC on food prices in China, demonstrating the variability in findings.

Climate Change and Food Utilisation

Dietz (2020) underscored the need for collaborative action to address the link between CC and nutritional outcomes. Mahapatra *et al.* (2021) found that in India, increased agricultural vulnerability due to CC correlated with poor nutrition among children, with significant percentages suffering from anaemia and malnutrition. Guo *et al.* (2023) used a copula approach to analyse food consumption in Nepal, demonstrating that even slight increases in climate risk reduced both calorie intake and dietary diversity.

Climate Change and Food Stability

Food stability is influenced by the other three pillars – availability, access, and utilisation (Stephens *et al.,* 2018). Ribeiro *et al.* (2021) developed a food stability model using expert insights and emphasised sustainable food production as a priority, especially with a growing population. In Nigeria, Jibrillah *et al.* (2018) reported that increasing temperatures and reduced rainfall over a decade led to significant vegetation loss, adversely impacting food stability and economic resilience.

Despite the extensive body of research, few studies comprehensively address all four dimensions of FS in a regional context. Manikas *et al.* (2023) noted that out of 78 publications in their systematic review, only three covered all four dimensions, none of which assessed the impact of climate indicators. Additionally, regional studies focusing on CA are scarce, with most research concentrating on areas like Sub-Saharan Africa or South Asia. Singh *et al.* (2022) conducted one such regional study for the South Asian AOR, but its scope and methods differ from our research.

This study aims to fill this gap by analysing how CC impacts the four pillars of FS in CA using regional panel data. The research will address the following questions:

- What climatic factors most significantly affect food production in CA, and how do temperature changes influence cropland areas and the food production indices?
- How do temperature changes in CA impact the stability of the food system, including the per capita food supply and average dietary energy requirement?
- Which climate variables contribute to the prevalence of anaemia among women of reproductive age due to temperature changes?
- What strategies can be developed to mitigate CC's negative effects on agriculture and public health in CA?

Theoretical/Conceptual Framework

Understanding the impact of CC on FS requires a comprehensive theoretical foundation that integrates both food security frameworks and vulnerability theory. This research draws upon two primary theoretical perspectives: (i) the FAO food security framework, which defines FS through its four key dimensions (availability, access, utilisation, and stability), and (ii) the IPCC vulnerability framework, which conceptualises vulnerability as the exposure, sensitivity, and adaptive capacity of a system to external stressors, such as CC as illustrated in Figure 1.

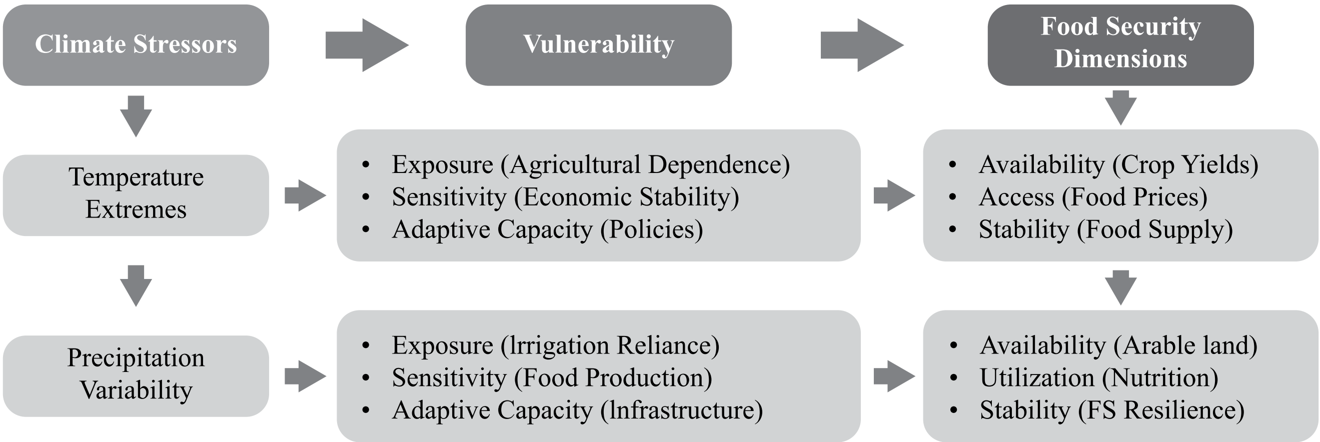

Figure 1: Conceptual Framework of the study.

Source: Authors' illustration

To make these frameworks more concrete, as well as to link them more directly to our empirical analysis, we identify some of the major theoretical components associated with key indicators of food security. For instance, food availability is associated with agricultural productivity, such as cereal yields, while food access is proxied by GDP per capita and undernourishment prevalence. While explaining in detail how vulnerability theory informs our understanding of how climate shocks exacerbate food insecurity through disruptions in the FS dimensions, we intend to provide an explanation of how each component of the vulnerability theory, namely exposure, sensitivity, and adaptive capacity, interacts with the dimensions of food security. Vulnerability theory helps explain how climate shocks aggravate food insecurity by the effect it produces on exposure, sensitivity, and adaptive capacity.

Extreme weather, such as floods and droughts, disrupts the production of agricultural produce, as a consequence reducing FS and availability. The sensitivity of the agriculture industry to climate-related factors means decreased crop yields and increased food prices due to rise in temperature and erratic rainfall, while lower access to food, and lower nutritional values impinge upon food utilisation to cause malnourishment. Adaptive capacity reflects how well a region can respond to these different challenges. Whereas solid infrastructure and economic stability in some countries can enable adaptation to the risks associated with climate change, in countries where poverty and weak governance prevail, the opposite occurs, exacerbating food insecurity across all its dimensions. Integrating these elements into the FAO food security framework helps in capturing how climate variability accentuates food insecurity by disrupting all four dimensions of food systems: availability, access, utilisation, and stability in CA. The integrated approach, therefore, permits an in-depth analysis of the socioeconomic and environmental drivers of food security in the region.

Materials and Methods

Data collection and variables

This study utilised a panel data analysis to assess the effects of CC on FS. The dataset spans 21 years (2000-2020) and includes countries within CA to capture temporal and regional variations in the data.

This study used four explanatory and three control variables: extreme hot temperature, extreme cold temperature, low rainfall, heavy rainfall, human development index, net migration, and political stability and absence of violence or terrorism. The indicators of FS used as dependent variables are GDP per capita (PPP), food production index, cereal yield, arable land, prevalence of undernourishment, per capita food supply variability, percent of arable land equipped for irrigation, average dietary energy supply adequacy, average dietary energy requirement, prevalence of anaemia among women of reproductive age and percentage of children under 5 stunted (see Table 3).

Table 3: Description of variables used.

	Variables	Unit	Symbol	Sources
Dependent	**Availability** Cereal yield	kg per hectare	Availability1	FAOSTAT
	Food production index (2014-2016=100)	index	Availability2	World Bank
	Arable land	%	Availability3	FAOSTAT
	Access Gross domestic product per capita, PPP	constant 2017 international $	Access1	FAOSTAT
	Prevalence of undernourishment (3-year average)	%	Access2	FAOSTAT
	Stability Percent of arable land equipped for irrigation (3-year average)	%	Stability1	FAOSTAT
	Value of food imports in total merchandise exports (3-year average)	%	Stability2	FAOSTAT
	Per capita food supply variability	kcal/cap/day	Stability3	FAOSTAT
	Utilisation Average dietary energy supply adequacy (3-year average)	%	Utilisation1	FAOSTAT
	Average dietary energy requirement	kcal/cap/day	Utilisation2	FAOSTAT
	Percentage of children under 5 years of age who are stunted (modelled estimates)	%	Utilisation3	FAOSTAT
	Prevalence of anaemia among women of reproductive age	15-49 years	Utilisation4	FAOSTAT
Independent	Annual minimum temperature	ºC	minT	WBCCKP
	Annual maximum temperature	ºC	maxT	WBCCKP
	Low rainfall	number of days	lowRainfall	NASA
	Heavy rainfall	number of days	heavyRainfall	NASA
Control	Human development index	index	HDI	WB
	Net migration	number of people	NM	WB
	Political stability and absence of violence/ terrorism	index	PS	WB

Source: Own composition

Data analysis

The fixed-effects regression model was used to analyse panel data and examine the impact of CC on FS indicators. This model is preferred over the random-effects model due to the presence of country-specific unobserved heterogeneity, which could otherwise bias the results. To formally justify the use of the fixed-effects model, we conducted a Hausman test, which compares the efficiency and consistency of fixed-effects and random-effects estimates. The results indicate that the fixed-effects model is more appropriate. The fixed-effects model was built following the methods of Otrachshenko *et al.* (2018) and Sun and Zhang (2021):

$$\begin{aligned} FS_{it} &= \beta_0 + \beta_1 minT_{it} + \beta_2 maxT_{it} + \\ &+ \beta_3 lowRainfall_{it} + \beta_4 heavyRainfall_{it} + \\ &+ \beta_5 HDI_{it} + \beta_6 NM_{it} + \beta_7 PS_{it} + \\ &+ \gamma_i + \mu_t + e_{it} \end{aligned} \tag{1}$$

where *i* and *t* indicate CA countries and time periods, accordingly. FS_{it} represents food security and its four dimensions: availability, access, stability, and utilisation. $MinT_{it}$ and $maxT_{it}$ are the group of temperature in country *i* during year *t*. $LowRainfall_{it}$ and $heavyRainfall_{it}$ are indicators of precipitation group in country *i* during year *t*, HDI - human development index, NM - net migration, PS - political stability and absence of violence or terrorism, country-specific fixed effects is γ_i, time-specific fixed effects is μ_t, and e_{it} is the random error term.

The temperature data used in this study was sourced from the Climate Change Knowledge Portal of the World Bank (CRU dataset), specifically focusing on temperature shocks and annual average minimum and maximum temperatures. Among these variables, the annual average mean temperature was excluded from the analysis, and the minimum and maximum temperature extremes were emphasised for their relevance in understanding climate dynamics. Temperature shocks are important as they directly influence agricultural productivity, crop yields, and the overall climate resilience of the region.

Precipitation data was collected on a daily basis from the POWER Project website, which is supported by NASA. The precipitation data was categorised into three bins based on the amount of rainfall: low rainfall (0-10 mm), normal rainfall (10-20 mm), and heavy rainfall (above 20 mm). Following the approach in Otrachshenko *et al.* (2017), the analysis specifically examines the impacts of low and heavy rainfall on FS, excluding the normal rainfall category as an intermediary state. This approach focuses on how extreme precipitation patterns (either too little or too much) affect food availability, access, utilisation, and stability, critical pillars in assessing FS.

This study covers multiple regions across CA, providing a comprehensive understanding of the region's diverse climatic conditions. The dataset includes:

- Kazakhstan: Temperature and precipitation data were collected from fourteen regions (oblasts), capturing regional variations across the country's vast expanse.
- Kyrgyzstan: Seven regions of Kyrgyzstan contribute detailed meteorological data to the study.
- Tajikistan: Four key regions in Tajikistan are part of the dataset, further enriching the geographic spread of the data.
- Turkmenistan: Data from five regions of Turkmenistan is included, contributing to the overall climatic analysis.
- Uzbekistan: Thirteen regions of Uzbekistan are involved, offering valuable insights into the climatic patterns in this key CA country.

This extensive geographical coverage ensures that the study incorporates a wide variety of climatic conditions, making the analysis of temperature and precipitation patterns across CA highly nuanced and robust.

The research methodology employs a comprehensive analytical model designed to evaluate the impacts of extreme temperature and precipitation shocks on FS across different regions of CA. This model uses extensive temperature and precipitation data collected from various regions to assess how fluctuations in these climatic variables affect the four pillars of FS.

The inclusion of regions with diverse climatic patterns enhances the reliability of the study's outcomes, ensuring that the findings are reflective of the broader climatic dynamics in CA. The focus on extreme temperature shocks and heavy or low precipitation ensures that the study captures the most disruptive climate events that are likely to exacerbate vulnerabilities in food systems.

By leveraging a rigorous model design and incorporating a wide geographical spread, this methodology enhances the robustness of the study's conclusions, offering a detailed exploration of how CC impacts FS in the region.

Results

The regression analysis, employing a fixed-effects model, reveals mostly a significant negative correlation between weather shocks and food security. By considering unobserved heterogeneity across countries, we enhance the reliability of our findings. The fixed effects help control for time-invariant factors that could otherwise confound the relationship between climate variables and FS, providing more reliable estimates of the impact of the temperature and rainfall on the various dimensions of FS. In CA, where climatic conditions have a major impact on the prosperity of the agricultural sector, even a slight change in temperature can have a significant impact on FS.

Surprisingly, the food production index can increase by a remarkable 15.76% with an annual minimum temperature increase of just one degree (see Table 4). This suggests that the colder months in the region are beneficial for crops. However, the situation is not as simple as it seems. The dynamics of the drought and the reduction in arable land highlight the vulnerability of the system. The drought reduces the area of arable land, which in turn limits the resources available for agriculture. The region loses 0.098% of its arable land for every additional day of drought. A decrease in temperature leads to an expansion of arable land equipped with irrigation systems. For every 1°C increase in annual minimum temperature in CA, the percentage of arable land equipped for irrigation increases by 0.139%. Conversely, for every 1°C increase in annual maximum temperature, the percentage of arable land equipped for irrigation decreases by 0.134%. This land is an essential resource to ensure the sustainability of the food system.

One of the most striking findings is that a 1°C increase in annual maximum temperature reduces per capita food supply variability by 22.060 kcal per person per day. Rising temperatures can disrupt the stability of the food system by increasing the energy required from food. A 1°C rise in annual maximum temperature reduces the average dietary energy requirement by 19.66 kcal per person per day. Temperature fluctuations are also linked to health problems. An increase of 1 degree C in annual maximum temperature leads to a 3.07 percent increase in the prevalence of anaemia among women of reproductive age. This illustrates the complex relationship between climate and health, and it is important to note that climate is not just weather, but a critical factor that affects quality of life.

The situation becomes more complex when global variables such as the Human Development Index are examined. While a prominent level of human development may appear to have a negative impact on crop yields, it promotes increased food production and improved quality of life. Political stability also plays a crucial role. A strong and stable government promotes agricultural development, whereas an unstable government may create significant social and economic problems.

CA, with its unique historical and geographical characteristics, serves as an important case study for analysing the relationship between climate factors and FS. The regression results reveal a complex mosaic in which CC, such as temperature increases or decreases and droughts, plays a key role in changing FS outcomes. This highlights the need for an integrated approach combining economic, social, and political measures to strengthen the region's food system. Using these analytical data and conclusions, it is possible to develop effective strategies and solutions aimed at ensuring the stability and well-being of everyone living in CA.

Table 4: Fixed effects analysis results.

Climate Variable	FS Dimension	Coefficient	P-value
minT	Availability2	15.766*	0.092
	Stability1	0.139**	0.049
	Utilisation4	-3.268**	0.038
maxT	Stability3	-22.060*	0.060
	Utilisation2	-19.663*	0.055
HDI	Availability1	-852.711**	0.032
NM	Availability1	0.008*	0.051
	Utilisation2	0.001***	0.006
PS	Availability2	19.651***	0.000
	Access2	-4.432***	0.007
	Stability2	0.120***	0.003
	Utilisation1	9.354***	0.000
	Utilisation2	5.523***	0.000
	Utilisation3	-3.736**	0.011

Note: *, **, *** means significant at 0.1, 0.05, 0.01 levels, respectively; *minT* – Annual minimum temperature, *maxT* – Annual maximum temperature, *lowRainfall* – Low rainfall, *heavyRainfall* – Heavy rainfall, *HDI* – Human Development Index, *NM* – Net migration, *PS* – Political stability and absence of violence/terrorism.
Source: Own calculations

Discussion

In our research, CC has had both negative and positive impacts on FS. According to our fixed-effects analysis, weather shocks mainly affected food availability, food stability, and food utilisation. These findings highlight the vulnerability of agricultural systems in CA to CC, with potential implications for crop yields and overall FS. Extreme temperatures and unstable rainfall patterns can disrupt agricultural production, lead to land degradation and malnutrition, and cause fluctuations in food availability, stability, and utilisation.

The result highlights both the positive and negative impacts of CC on food availability. Specifically, the fixed-effects analysis reveals that annual temperatures have a positive correlation with food production in CA. This contrasts with the broader global trend, where studies like Zhao *et al.* (2017) and Fuller *et al.* (2018) demonstrate the adverse effects of CC on key staple crops such as maize, wheat, rice, soybean, and banana. National-level studies, including Wu *et al.* (2021) and Abbas (2022) also underscore the vulnerability of local agricultural production to changing weather patterns. These differences between our findings and the findings of other studies can be explained by regional agro-climatic characteristics in CA. For instance, unlike tropical and temperate regions, CA's agricultural systems are highly constrained by cold temperatures, especially in early spring and late autumn. Moreover, a rise in minimum temperatures reduces frost frequency, extends the growing season, and improves conditions for winter crops such as wheat and barley. Further, the results of the research are consistent with the findings of Mekonnen *et al.* (2021), our analysis indicates that precipitation, especially excessive rainfall, negatively impacts food availability, leading to a reduction in arable land in the region. Extreme weather events such as floods and droughts further compound this vulnerability, undermining crop yields and overall agricultural productivity.

The impact of CC on food access in CA appears to be less pronounced according to our analysis. Panel data analysis suggests no significant effect of climate shocks on food access, which aligns with Wang (2010) study, which found that weather shocks had minimal influence on consumer prices. Despite this, our findings also confirm that CC negatively affects agricultural output, as noted by Asare-Nuamah (2021), leading to food insecurity for many households. In particular, those with limited resources struggle to afford sufficient food, thereby exacerbating food insecurity. Climate-induced disruptions in food production can limit the availability of affordable food, forcing households to rely on adaptive strategies that may not fully mitigate the adverse effects of these climatic shifts.

Food utilisation, particularly nutritional intake, is significantly impacted by CC. Our analysis shows that extreme temperatures have a harmful effect on dietary intake, with particular implications for productive-age women. This is consistent with research by Dietz (2020), who highlighted a strong link between CC and FS in CA. For instance, a 1°C increase in annual maximum temperature leads to a 3.07 percent increase in the prevalence of anaemia among women of reproductive age. This relationship suggests multiple pathways through which CC exacerbates malnutrition and micronutrient deficiencies. Firstly, temperature-induced crop yields decline and dietary changes, where rising temperatures reduce yields of iron-rich staple crops, such as wheat, maize, and legumes. Moreover, as Schmidhuber and Tubiello (2007) emphasize that heat stress reduces the nutritional quality of crops, leading to lower iron concentrations in staple foods. Secondly, micronutrient deficiencies increase incidences of food-borne and vector-borne diseases. As Dietz (2020) indicates, heat stress increases bacterial contamination of food, leading to gastrointestinal infections that impair iron absorption.

These changes in climate patterns disrupt food consumption patterns and nutritional outcomes, underscoring the need for policies aimed at improving the nutritional status of vulnerable populations. This finding further underscores the complexity of CC's impact on FS, which extends beyond mere availability to the very quality of the food consumed.

Our findings also align with studies such as those by Stephens *et al.* (2018) and Jibrillah *et al.* (2018), emphasising the role of CC in destabilising food supply systems in CA. The stability of FS is deeply interconnected with food availability, access, and utilization. Our analysis shows that a 1°C increase in annual maximum temperature decreases the percentage of irrigated arable land by 0.134%, indicating a negative impact of heat stress on water resource management. These phenomena can be explained by increased evapotranspiration and the necessity for water. This means that higher temperatures accelerate evapotranspiration, reducing surface water availability for irrigation. This effect is particularly severe in CA, where 80% of irrigated agriculture depends on river-fed irrigation, which is highly sensitive to climate fluctuations (Christmann *et al.,* 2009). Moreover, rising temperatures affect glacier retreats in the Tien Shan and Pamir mountains, which serve as water sources for irrigation systems in Kazakhstan, Kyrgyzstan, and Uzbekistan. Luo *et al.* (2019) emphasised that reduced glacial input has already contributed to declining water availability in major rivers like Amu Darya and Syr Darya.

These reductions in food availability and the ability to utilise water resources for agriculture contribute to diminished food stability, which in turn affects the resilience of households to food insecurity. Furthermore, as pointed out by Sirba and Chimdessa (2021) and Jibrillah *et al.* (2018), factors such as high temperatures and low precipitation have severely impacted food stability, particularly in regions with limited adaptive capacity. The reduction in crop yields, cereal production, and livestock output, exacerbated by changing weather patterns, threatens not only nutrition but also household income, further straining FS in the region.

Policy recommendations

Modern agriculture in CA countries faces complex challenges, including climate variability, resource constraints, and institutional limitations. Adapting to these challenges requires a strategic approach that balances technological innovation, policy support, and capacity building while considering CA's economic and governance realities.

Optimising irrigation systems is one of the key priorities, given CA's heavy reliance on glacier-fed seasonal water sources. However, widespread adoption of modern irrigation is often hindered by limited financial resources, outdated infrastructure, and governance inefficiencies. To address this, CA countries should establish regional cooperation on transboundary water management to improve water allocation efficiency. Moreover, Public-private partnerships can be set up to attract foreign investment in drip and precision irrigation.

Beyond these technological solutions, a more comprehensive strategic approach is needed to make the transition to sustainable agriculture. Priority should be given to environmentally friendly practices such as multi-layer farming, water-saving technologies, and the use of sustainable crop varieties. Such practices will not only reduce pressure on ecosystems. They will also improve soil quality, making crops more resilient to climate change.

Education has a key role to play in the adaptation of the agricultural sector to the new realities. An integral part of sustainable development is the expansion of training programmes for farmers and agricultural professionals, with a focus on adaptation to CC and the introduction of new agricultural technologies.

A crucial role is also played by research funding. The necessary tools to adapt to changing conditions can be provided by supporting basic and applied research to develop innovative technologies and hybrid plant varieties. However, sustainable development is not possible without the creation of the conditions for political and economic stability. This will provide a sound basis for the agricultural sector to invest, innovate, and develop over the long term.

Finally, a key role in maintaining public health and agricultural sustainability will be played by specific public health programmes to prevent the spread of climate-related diseases. To conclude, modern agriculture faces many challenges in Central Asia, but there are also many solutions that can help it develop sustainably. Through a comprehensive approach that includes innovating, educating, and supporting, agriculture can thrive in an era of climate change.

Conclusions

Climate change presents a significant challenge to agriculture and food security in Central Asia, due to its semi-arid continental climate, reliance on irrigation, and unique economic structures. This study examined how temperature extremes and precipitation changes impact the four pillars of FS, offering key insights into climate-related risks and adaptation needs.

The findings show that temperature extremes have mixed effects on food production. Rising minimum temperatures improve yields by reducing cold stress and extending growing seasons, while higher maximum temperatures reduce arable land due to water shortages and soil degradation. Precipitation variability poses a major risk to food stability, as both low and excessive rainfall disrupt crops and strain water resources.

While these results provide valuable insights for CA, they cannot be applied universally. The region's climate and agricultural systems differ from those in tropical or coastal areas, but the findings may still be relevant to other semi-arid, water-scarce regions such as Mongolia, Western China, and parts of the Middle East.

However, some limitations must be acknowledged. This research relies on country-level data for CA, which may hide subnational differences in food security. For instance, rural and urban areas or irrigated and non-irrigated regions within a single country may experience climate impacts differently, but these variations are not fully captured. Additionally, while the fixed-effects model controls for country-specific differences, it does not explicitly account for short-term shocks, such as economic crises, pandemics, or sudden policy changes, that may have temporarily influenced FS trends.

Beyond environmental, socio-economic, and political factors, other important determinants such as technological advancements, cultural influences, and biological factors were not included in this study but should be explored in future research. Another challenge was the availability of accurate, complete, and up-to-date data for certain countries and variables. Data limitations can affect the robustness of findings, highlighting the need for more comprehensive and reliable datasets. Addressing these data gaps in future studies will further enhance the understanding of climate and food security dynamics in CA.

These findings highlight the need for targeted adaptation strategies, including improving irrigation efficiency, diversifying crops, and strengthening policies to reduce climate risks. Future research should explore local variations, long-term adaptation efforts, and cross-regional comparisons to support more effective climate resilience planning.

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