DOI: 10.22620/agrisci.2025.45.014

Assessment of agricultural vulnerability in the Sofia region, Bulgaria under climate change scenarios: a multi-model ensemble analysis based on the Coupled Model Intercomparison Project (CMIP6)

Caihua Yang[2] (ORCID NUMBER: 0009-0000-5565-2696),
Rositsa Beluhova-Uzunova[1]* (ORCID NUMBER: 0000-0002-8780-6722),
Dobri Dunchev[1] (ORCID NUMBER: 0000-0003-3422-2819),
Boryana Ivanova[1] (ORCID NUMBER: 0000-0003-3858-3996),
Yifeng Qin[2] (ORCID NUMBER: 0000-0002-3765-6818),
Shengquan Che[2] (ORCID NUMBER: 0000-0003-3210-0818)

[1] Agricultural University – Plovdiv, Bulgaria
[2] Shanghai Jiao Tong University, Shanghai, China
***Corresponding author: rbeluhovauzunova@gmail.com**

Abstract

Due to the intensification of global climate change, agricultural production faces significant challenges such as frequent extreme weather events, exacerbated water scarcity, and rising temperatures which pose significant threats to crop growth and food security. This study evaluates the vulnerability of agriculture in Bulgaria, mainly maize and wheat production in the capital city of Sofia, under climate change scenarios based on multi-model ensemble data from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). By analyzing the spatiotemporal trends of temperature and precipitation from 2025 to 2100, the study reveals that the Sofia region will experience a fluctuating upward trend in temperature and a fluctuating downward trend in precipitation. Precipitation is identified as the primary factor influencing grain yield, while the impact of temperature changes is relatively minor. The yields of maize and wheat are projected to decline across three future periods (2025–2050, 2050–2075, and 2075–2100), with the most rapid decline occurring between 2025 and 2050. The study proposes adaptive strategies such as strengthening water resource management and promoting climate-smart agriculture to enhance the resilience and sustainability of agricultural systems and ensure food security.

Keywords: climate change, agricultural vulnerability, CMIP6, precipitation variability, grain yield

INTRODUCTION

As global climate change intensifies, it significantly impacts agricultural food systems (Farooq et al., 2023). Climate change is a driver for biotic and abiotic stresses, negatively affecting crop growth and yields (Raza et al., 2019). Variations in rainfall, temperature, heatwaves, and atmospheric carbon dioxide and ozone levels influence global agricultural production (Bagale, 2021; Raza et al., 2019). Over the past decade, staple crops such as rice and maize have slowed growth, with wheat, in particular, showing limited increases (Neupane et al., 2022). Declining arable land, reduced irrigation water, and shifts in resource use toward biofuels further exacerbate these issues (Hawkesford et al., 2013). According to the high-emission scenario (SSP) projections of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), one-tenth of the current crop-growing regions will become unsuitable for cultivation (Change, 2007), which threatens food production as global demand rises (Noya et al., 2018; Islam & Karim, 2019; Farooq et al., 2023). Ensuring food demand amidst climate change has become a global concern (Godfray et al., 2010). Therefore, analyzing the impact of climate change on food production is highly significant for sustainable development.

Climate Prediction Models (CPMs) indicate that intensified droughts, water scarcity, and climate variability will increase agricultural water demand fivefold, constraining efficiency and food supply (Hussain, 2011; Naumann et al., 2018; Neupane et al., 2021). Drought and high temperatures are major stressors limiting cereal yields (Barnabás et al., 2008). High temperatures (>35°C) disrupt the core photosynthetic enzyme Rubisco, halt photosynthesis (Griffin et al., 2004), reduce starch synthesis, and shorten grain filling by 15%-25% (Neupane et al., 2022). Rising global temperatures will further suppress yields, especially in tropical and subtropical regions (Parmesan et al., 2022). Therefore, droughts will increasingly threaten regional and even global food security (Cook et al., 2014; Wang et al., 2018; Dai, 2011; Lesk et al., 2016). Droughts primarily influence the reproductive stage of plant growth, and studies outlined that the flowering process and inflorescence development of cereals are significantly impacted by water scarcity (Winkel et al., 1997). Additionally, numerous studies indicate that the frequency and intensity of future drought events are expected to increase (Sheffield et al., 2012; Lesk et al., 2016).

Many studies have explored the influence of climate change on crop production and agriculture. Baroowa & Nirmal (2014) observed that legume plants (*Vigna mungo* L.) experienced a 31% to 57% reduction in yield due to drought stress during the flowering stage and a 26% yield decrease during the reproductive stage. Rising carbon dioxide emissions and temperature shifts threaten food security worldwide (Behera et al., 2024). While numerous studies analyze climate change's impact on food production, they often neglect temporal insights into food production, making it difficult to predict future trends and to shape sustainable food development strategies.

Based on the literature review, the survey selects Sofia, the capital of Bulgaria, as a specific case study. The paper examines the future of corn and wheat production in Sofia, Bulgaria, during three critical periods – 2025-2050, 2050-2075, and 2075-2100 – by deeply integrating prediction data from the Sixth Coupled Model Intercomparison Project (CMIP6). It identifies key factors influencing grain yield, assesses future risks, and proposes strategic solutions through technological innovation and policy guidance to enhance food security.

MATERIALS AND METHODS

Overview of the Research Site

The data utilized in this study consist of meteorological data, CMIP6 global data, and Bulgarian grain data. The CMIP6 data were sourced from (https://aims2.llnl.gov/search). When selecting CMIP6 models, previous studies focused on three key criteria: accuracy, applicability, and data availability.

Sofia, located in the west of Bulgaria, serves as the capital and largest city of the country. Nestled at the foot of the Vitosha Mountains, it boasts a strategic geographical location, benefiting from the fresh air of the mountainous region while enjoying convenient access to various regions within the country. Sofia's climate is temperate continental, characterized by distinct seasons: cold and snowy winters, relatively warm and dry summers, and pleasant springs and autumns. In terms of natural conditions, the surrounding areas of Sofia are abundant in water resources and fertile soil, providing favorable conditions for agricultural production. Regarding the food situation, Bulgaria is an important agricultural country in Europe, with grain production occupying a significant position in its national economy. As part of the capital economic circle, the Sofia region enjoys stable grain supply and a diverse range of grain production, primarily including wheat and corn. However, it also faces challenges such as climate change and limited agricultural resources, necessitating continuous optimization of agricultural structures and improvement of agricultural production efficiency to ensure food security.

Data Source

The data utilized in this study consist of meteorological data, CMIP6 global data, and Bulgarian grain data. The CMIP6 data were sourced from (https://aims2.llnl.gov/search). When selecting CMIP6 models, previous studies focused on three key criteria: accuracy, applicability, and data availability for application in Bulgaria (Xu et al., 2024; Yang et al., 2024). Consequently, we selected 13 CMIP6 global models, with detailed information presented in Table 1.

Delta Downscaling Method

Due to the high spatial resolution of global climate models, downscaling is required before they can be used for regional climate predictions. Statistical downscaling primarily encompasses three methods: probabilistic bias correction, quantile mapping, and the Delta method. Compared to other statistical downscaling techniques, the Delta method demonstrates significant advantages in reducing systematic biases between global climate models and regional climates, while also preserving the fluctuation characteristics based on surface processes and circulation physics parameterizations in global models (Schmidli et al., 2006). Based on these advantages, this study adopts the Delta method for downscaling. The principle of this method is to correct the predictions of global models by analyzing the differences between the historical data of global models and observational data. The specific calculation process is detailed in Equations (1)-(4).

Table 1. Global model information sheet

Serial number	Model name	Organization	Spatial resolution
1	ACCESS-ESM1-5	CSIRO	1.875°×1.25°
2	BCC-CSM2-MR	Beijing Climate Center	1.120°×1.120°
3	CanESM5	the Canadian Centre for Climate Modelling and Analysis	2.810°×2.770°
4	CMCC-ESM2	CMCC	1.120°×1.120°
5	CNRM-CM6-1	CNRM	1.406°×1.389°
6	CNRM-ESM2-1	CNRM	1.406°×1.389°
7	INM-CM4-8	Russian Institute for Numerical Mathematics Climate Model	2.000°×1.500°
8	INM-CM5-0	Russian Institute for Numerical Mathematics Climate Model	2.000°×1.500°
9	IPSL-CM6A-LR	IPSL	2.5°×1.27°
10	MIROC6	MRI(Meteorological Research Institute)	1.400°×1.400°
11	MRI-ESM2-0	MRI	1.4°×1.4°
12	NorESM2-LM	NCC	
13	NorESM2-MM	NCC	

Source: Own survey

Climate :

$$delta_{ymoni\_tmax} = gcm_{ymoni\_tmax} - obs_{ymoni\_tmax} \quad (1)$$

$$gcm(downscaled)_{dailyi\_tmax} = gcm_{dailyi\_tmax} - delta_{ymoni\_tmax} \quad (2)$$

Precipitation :

$$delta_{ymoni\_p} = obs_{ymoni\_p} / gcm_{ymoni\_p} \quad (3)$$

$$gcm(downscaled)_{dailyi\_p} = gcm_{dailyi\_p} \times delta_{ymoni\_p}. \quad (4)$$

Where, gcm_{ymoni_tmax} denotes the long-term monthly average of daily maximum temperature from historical global model data. Parameter obs_{ymoni_tmax} denotes the long-term monthly average of daily maximum temperature from meteorological station observation data, and gcm_{dailyi_tmax} represent the daily maximum temperature from global model temperature prediction data. Parameter gcm_{ymoni_p} denotes the long-term monthly average of precipitation from historical global model data. Parameter obs_{ymoni_p}denotes the long-term monthly average of precipitation from meteorological station observation data, and gcm_{dailyi_p} represent the daily precipitation from downscaled global model data (Yang et al., 2024).

RESULTS AND DISCUSSION

Spatial Trends in Temperature and Precipitation

The gridded temperature and precipitation data obtained from the aforementioned models were averaged across multiple models, and the annual average temperature and precipitation distributions for the years 2025-2050, 2050-2075, and 2075-2100 were calculated separately under the SSP126, SSP245, and SSP585 scenarios. This analysis examined the spatial variations in temperature in Bulgaria over the short, medium, and long term.

Spatial Distribution Results of Temperature Predictions

The data shows that the temperature distribution in Bulgaria exhibits a "layered structure gradually increasing from the southwest outwards," with the highest temperatures in the southeastern region (Fig.1). By observing the changes in the spatial distribution of temperature across the three time periods, it can be found that the areas represented by red (indicating high temperatures) and blue (indicating low temperatures) will gradually decrease in the future. In contrast, the areas with intermediate colours will significantly increase. This change suggests that the extreme regions of high and low temperatures are decreasing, but the overall average temperature shows an upward trend. The variation may be closely related to the background of global warming and also reflects the regional characteristics of climate change in Bulgaria. Further analysis reveals that the trend of temperature increments gradually increasing from the periphery to the centre is also intensifying, implying that the warming speed in the central regions of Bulgaria may be faster than that in the surrounding areas. This phenomenon may be related to topography, land-use changes, and human activities. For example, urbanization and industrial activities may affect the central regions, leading to more significant local temperature increases. Additionally, as the southeastern region is the hottest, its warming trend may have more pronounced impacts on agricultural production and ecosystems, such as exacerbating water scarcity and increasing the frequency of extreme weather events.

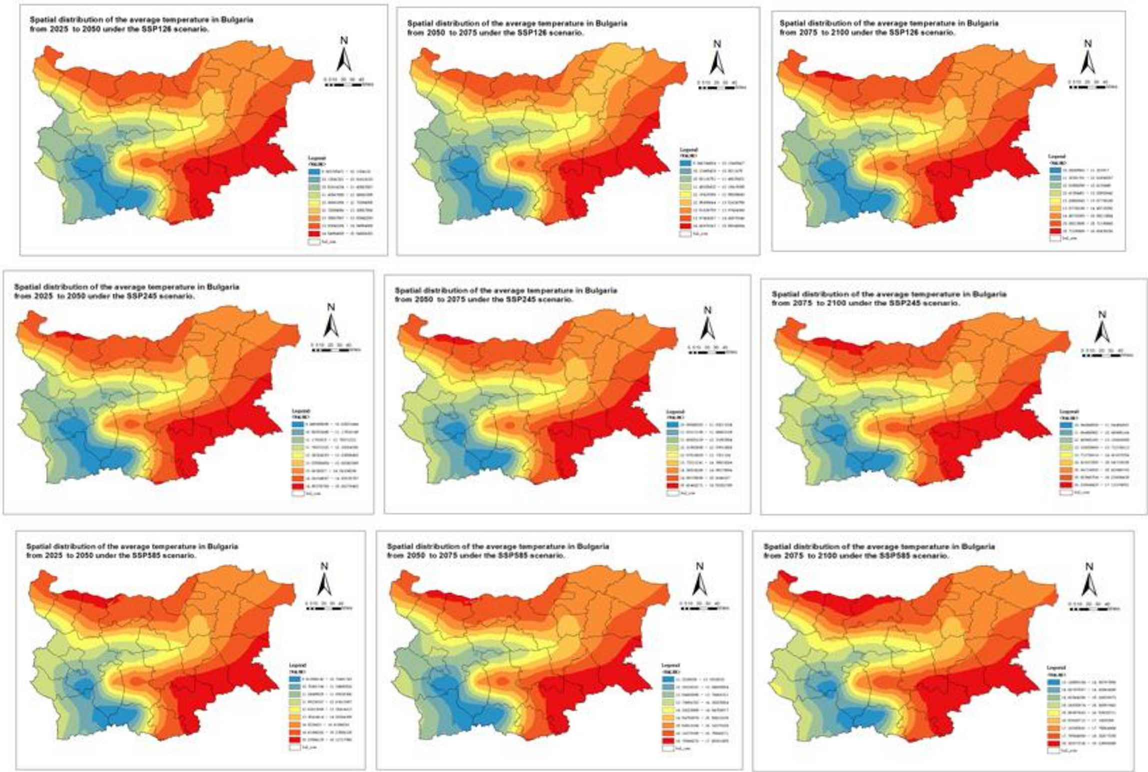


Figure 1. The spatial distribution of temperature in near, mid, and long-term phases under three scenarios

Source: Authors` calculations

Spatial distribution results of precipitation predictions

The results show that the spatial distribution of precipitation in Bulgaria gradually decreases from the southwest to the northeast (Fig. 2). This distribution characteristic is closely related to the topography and climate system interaction. The Mediterranean climate may influence the southwestern region, resulting in abundant precipitation, while the northeastern region is dominated by a continental climate, leading to relatively less precipitation. Over time, from the early to the later periods, precipitation changes show a gradual expansion of red areas (indicating increased rainfall) and a shrinking of blue areas (indicating decreased precipitation). This change indicates that, although the overall pattern of decreasing precipitation from southwest to northeast persists, the spatial distribution of precipitation is undergoing dynamic adjustments, with some regions experiencing an increasing trend in precipitation. These changes in precipitation may be linked to global climate change and the evolution of regional climate systems. For example, increased precipitation in the southwestern region may be related to the northward shift or the intensification of the Mediterranean climate belt. In contrast, the continental climate may further influence the trend of decreased precipitation in the northeastern region. Additionally, changes in precipitation can have far-reaching impacts on agricultural production, water resource management, and ecosystems. For instance, increased precipitation in the southwestern region may provide more water resources for agricultural production. However, it may also increase the risk of floods and waterlogging disasters, whereas decreased precipitation in the northeastern region may exacerbate water scarcity, affecting crop growth and ecological balance.

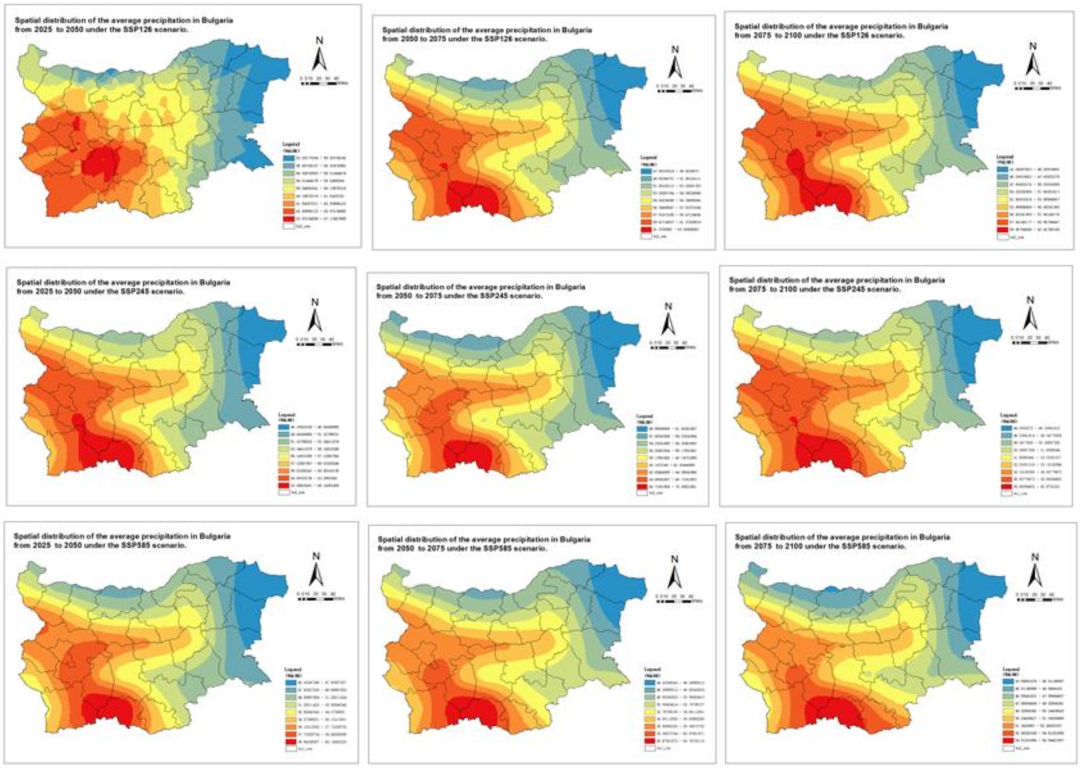


Figure 2. Spatial distribution of precipitation in near mid, and long-term phases under three scenarios
Source: Authors` calculations

In summary, Bulgaria's future temperature and precipitation distribution will be inversely correlated, with lower temperatures in regions with higher precipitation and higher temperatures in regions with lower precipitation. The southwestern region, influenced by the Mediterranean climate, experiences abundant precipitation and moderate temperatures. In contrast, the southeastern region, characterized by a continental climate, has high temperatures but low precipitation. Overall, temperatures show an upward trend, with faster warming in the central regions, possibly related to urbanization. The intensified warming in the southeast exacerbates water scarcity and extreme weather events. Increased precipitation in the southwest benefits agriculture but raises the risk of floods, while decreased precipitation in the northeast exacerbates water scarcity. Sofia, located in the western region with high temperatures and abundant rainfall, faces the dual challenges of intensified drought due to high temperatures and floods triggered by excessive rainfall.

Temporal trends of temperature and precipitation variability

The selected 13 models were downscaled under three scenarios: SSP126, SSP245, and SSP585, and a multi-model ensemble average was performed. This process aims to analyze the overall changes in temperature and precipitation in Sofia, Bulgaria, over a 75-year time span, which is divided into three periods: 2025-2050 (early period), 2050-2075 (mid-period), and 2075-2100 (long-term period).

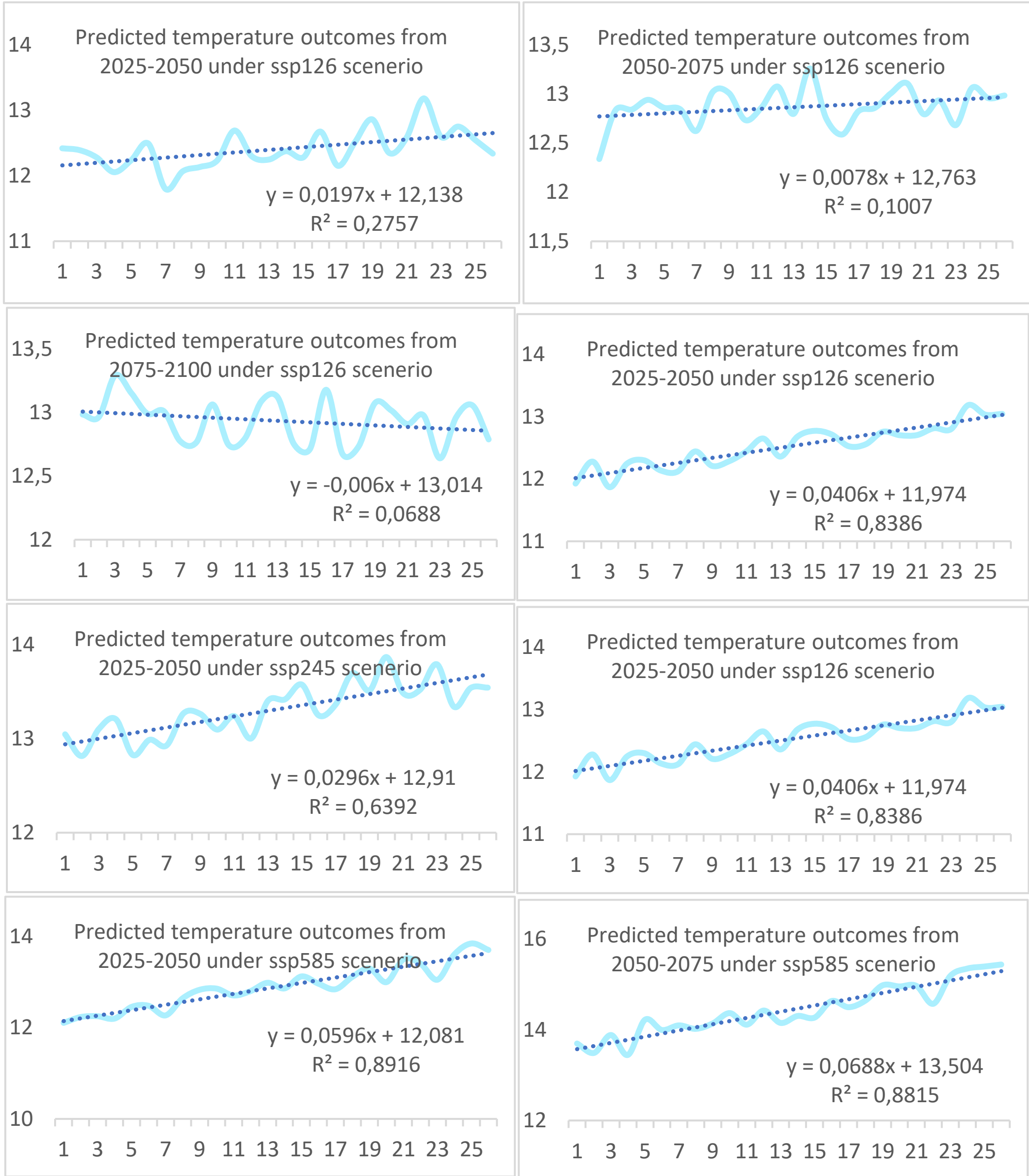
Temperature forecast results

Based on the analysis, it is projected that Sofia will experience a fluctuating upward trend in temperature between 2025 and 2100, with significant differences in the rate of temperature change at different stages (Fig. 3 and Table 2).

Table 2. Summary of temperature predictions

Period	Near term	Middle term	Long term
Range 0f annual temperature growth ratese	[0.0197,0.0596]	[0.0078,0.0688]	[-0.006,0.0763]
Average annual temperature growth rates	0.0399	0.0354	0.0299

Source: Own survey



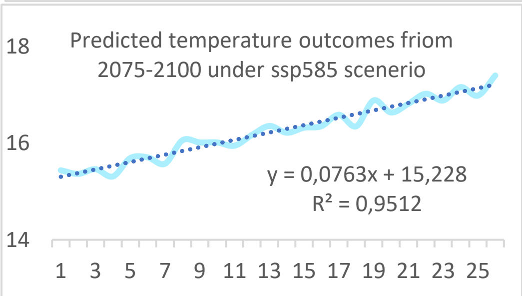


Figure 3. Temperature changes in Bulgaria from 2025 to 2100 under different scenarios
Source: Authors` calculations

Specifically, the temperature will rise most rapidly between 2025 and 2050, with an average acceleration rate of 0.0399, indicating significant impacts of climate change during this period. The trend may be related to the continuous increase in global greenhouse gas emissions and the rapid response of regional climate systems. In contrast, the temperature will rise slowly between 2075 and 2100, with an average acceleration rate of 0.0299. The result may be associated with implementing future climate policies, advancements in emission reduction technologies, and the self-regulatory capabilities of the climate system. During the early stage (2025-2050), the rate of temperature increase ranges from 0.0197 to 0.0596, showing relatively stable changes; during the mid-stage (2050-2075), the rate fluctuates between 0.0078 and 0.0688, with increasing volatility; and during the long-term stage (2075-2100), the rate varies from -0.006 to 0.0763, suggesting that temperature changes will become more severe and unpredictable. Such long-term temperature fluctuations may profoundly impact Sofia's ecosystems, agricultural production, and residents' lives, such as exacerbating extreme weather events, altering crop growth cycles, and increasing energy demand.

Precipitation forecast results

The results show that Sofia will experience a fluctuating downward trend in precipitation between 2025 and 2100, with significant differences in the rate of decline and volatility at different stages. (Fig. 4). Specifically, between 2025 and 2050, precipitation will decrease most rapidly and with the least fluctuation at an average rate of -0.1007.

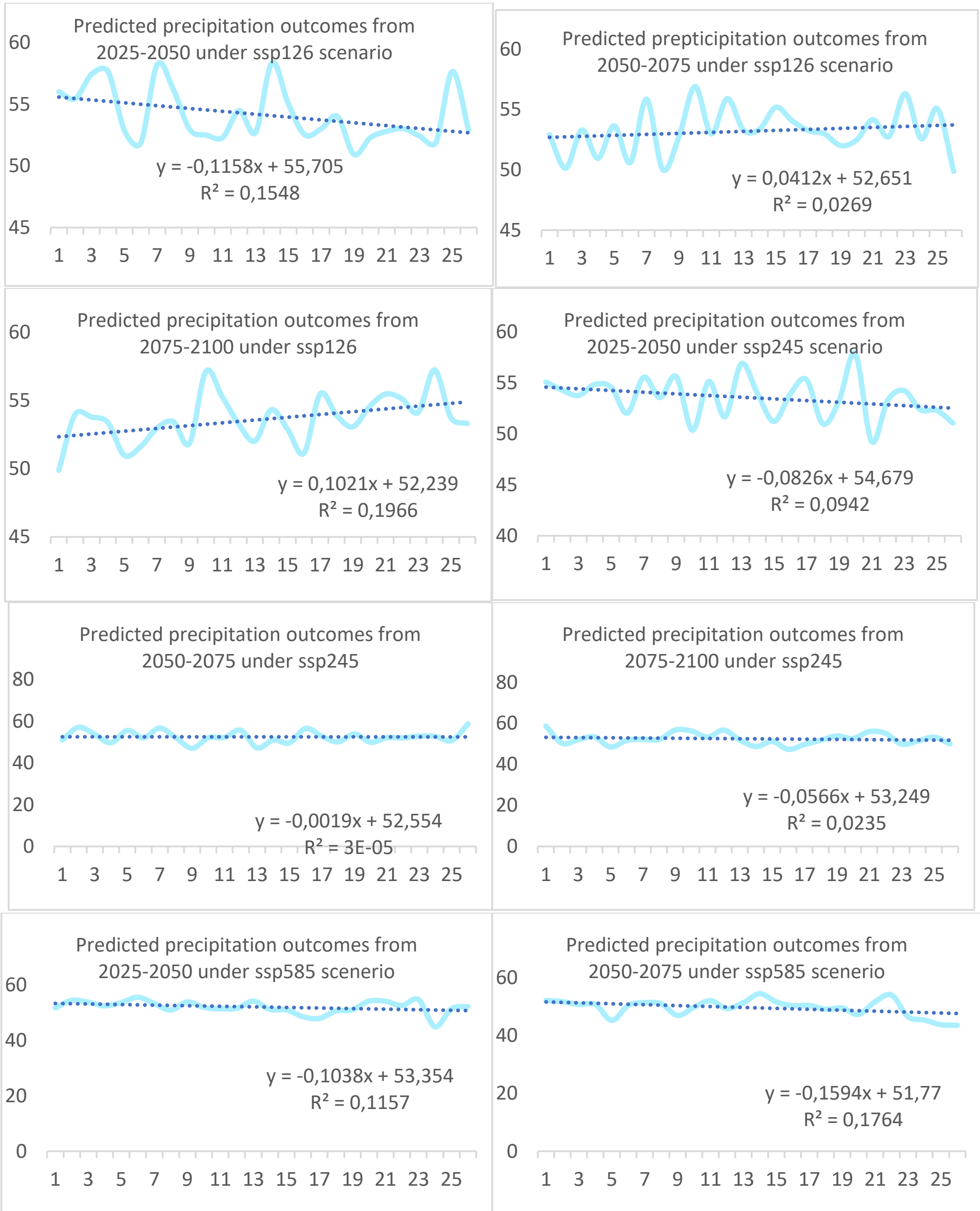
The trend indicates a relatively stable and significant decrease in precipitation during this period, which may be related to adjustments in regional climate patterns against the backdrop of global climate change. In contrast, between 2075 and 2100, precipitation will decrease at the slowest rate, with an average decline of -0.0047 but the largest fluctuation, ranging from -0.0596 to 0.1021. The result suggests that precipitation changes during this period will be more unpredictable, with potential localized increases in precipitation. During the mid-stage (2050-2075), the rate of precipitation change ranges from -0.1594 to 0.0412, indicating an increasing volatility in precipitation patterns. This downward trend in precipitation may profoundly impact agricultural development in Bulgaria by exacerbating water scarcity, affecting crop growth cycles, and increasing the unpredictability of agricultural production.

Based on the above analysis of temperature and precipitation, we have found that Sofia is projected to experience a fluctuating upward trend in temperature and a fluctuating downward trend in precipitation between 2025 and 2100 (Table 4). Temperature will rise most rapidly between 2025 and 2050, and slowest but with the greatest fluctuation between 2075 and 2100. Meanwhile, precipitation will decrease most rapidly and stably between 2025 and 2050, and slowest but with significant fluctuation between 2075 and 2100. These changes may exacerbate extreme weather events, water scarcity, and uncertainty in agricultural production, having far-reaching impacts on ecosystems and residents' lives. Therefore, enhanced adaptive measures are needed to address these challenges.

Table 4. Summary of precipitation predictions

Period	Near term	Middle term	Long term
Range 0f annual precipitation growth rates	[-0.1158,-0.0826]	[-0.1594,0.0412]	[-0.0596,0.1021]
Average annual precipitation growth rates	-0.1007	-0.04	-0.0047

Source: Authors` calculation



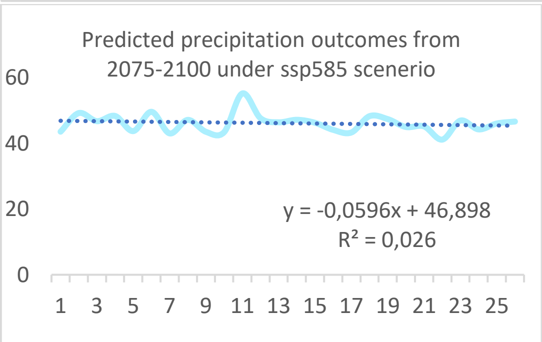


Figure 4. Precipitation changes in Bulgaria from 2025 to 2100 under different scenarios
Source: Authors` calculations

The relationship among temperature, precipitation, and grain yield in Sofia region

The polynomial regression is applied to model the relationship between precipitation and wheat and corn yields in Sofia from 1993 to 2021 (Fig. 5). The study reveals that wheat yields decrease when precipitation falls below or above 62.12 mm, and corn yields decrease when precipitation is below or above 61.53 mm. This finding indicates that precipitation significantly inhibits wheat and corn yields in Sofia, suggesting that excessively low and high precipitation levels adversely affect crop growth. This nonlinear relationship underscores the crucial role of precipitation in agricultural production and demonstrates that crop growth in Sofia is highly sensitive to changes in precipitation. When precipitation deviates from the optimal range, crop yields decline significantly.

The additional analysis, using polynomial regression to model the relationship between temperature and wheat and corn yields, reveals that the impact of temperature on these two-grain yields is relatively small. This result contrasts sharply with the impact of precipitation, indicating that temperature variations have a less significant effect on crop yields in the Sofia region than precipitation variations. This phenomenon may be related to the climatic characteristics of Sofia, where precipitation exhibits greater variability while temperature remains relatively stable, making precipitation the key determinant of agricultural production.

Overall, the yields of corn and wheat in Sofia are primarily influenced by precipitation, with temperature playing a relatively limited role. This finding holds significant implications for future agricultural production and climate adaptation strategies.

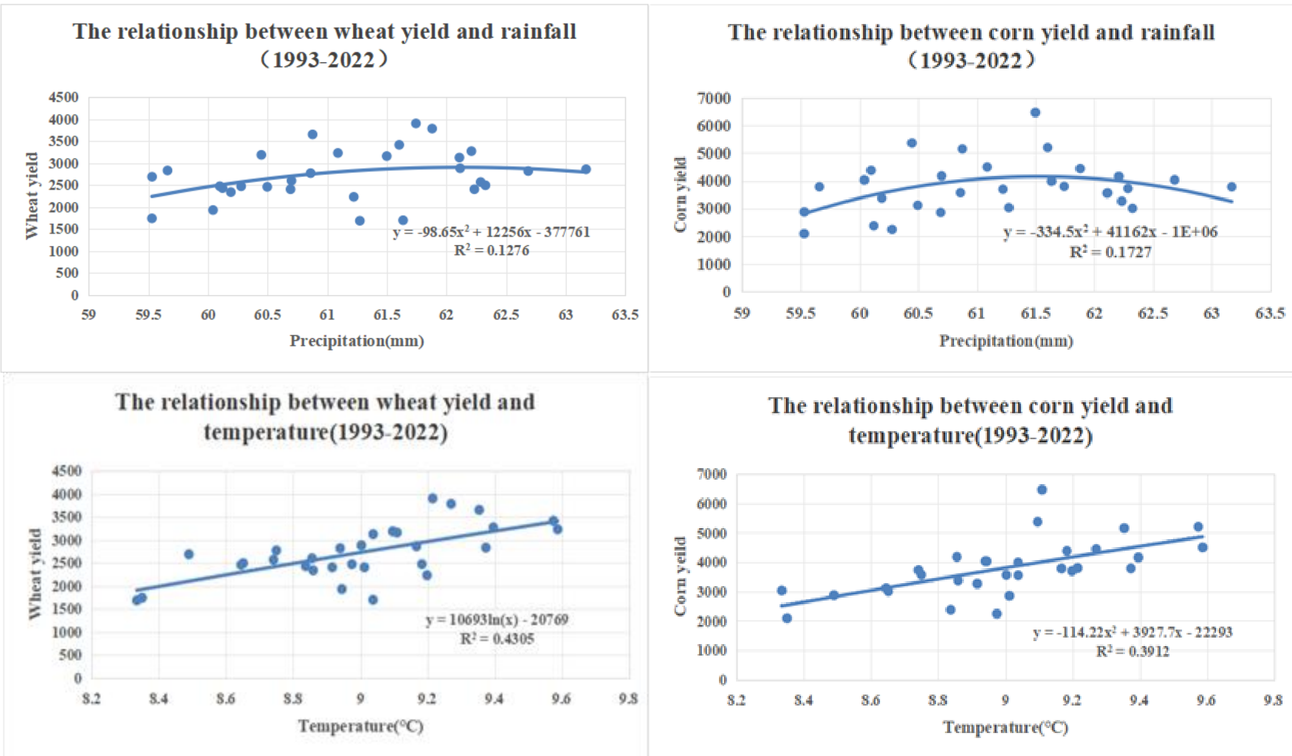


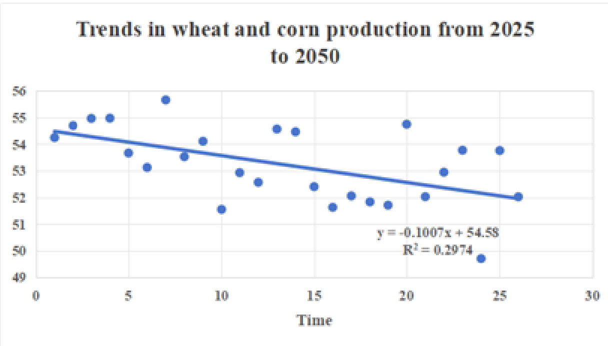
Figure 5. Relationship among temperature, precipitation, and grain yield
Source: Authors` Calculations

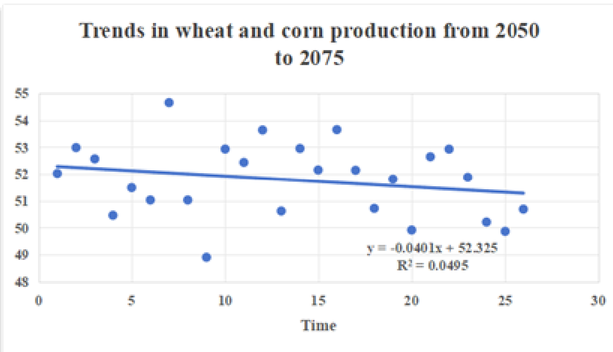
Firstly, when precipitation deviates from the optimal range, crop yields decline significantly, suggesting a need for greater focus on water resource management, such as optimizing irrigation techniques, developing drought-tolerant crop varieties, and enhancing precipitation prediction and regulation to address challenges posed by insufficient or excessive precipitation. Secondly, the minor impact of temperature on yields indicates that agricultural production should prioritize addressing precipitation variations rather than temperature variations in the Sofia region. Furthermore, this research provides important insights for policymakers. To ensure food security, governments and relevant departments need to increase investment in agricultural infrastructure, particularly in water resource management systems, and promote innovation and dissemination of agricultural technologies to enhance crop adaptability to precipitation changes. Meanwhile, farmers need to adjust planting strategies based on precipitation variations, such as selecting crop varieties more adapted to precipitation fluctuations or adjusting planting times to minimize the adverse effects of precipitation changes on yields.

In summary, the yields of corn and wheat in Sofia are primarily affected by precipitation, with temperature playing a relatively minor role. This finding emphasizes the central role of precipitation in agricultural production and provides important directions for future agricultural adaptation strategies and technological innovations.

Changes in corn and wheat yields in Sofia region from 2025 to 2100

Based on the simulated formulas and future temperature and precipitation predictions, an in-depth analysis of wheat and corn yields in Sofia for 2025-2050, 2050-2075, and 2075-2100 is conducted (Fig. 6). Since the average predicted precipitation for all future scenarios is below 60 mm (falling within the left half of the simulated quadratic curve), the changes in precipitation are used as the key indicator to measure changes in grain yields (averaged across the three scenarios).





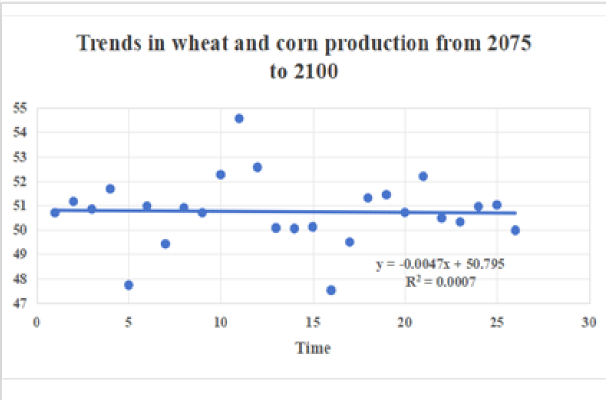


Figure 6. Trend in corn and wheat yields in Sofia from 2025 to 2100
Source: Authors` calculations

The research results indicate that during the periods of 2025-2050, 2050-2075, and 2075-2100, both maize and wheat yields show a declining trend, with the fastest decline occurring in 2025-2050 and the slowest in 2075-2100. Specifically, the most significant decline in corn and wheat yields is observed during the 2025-2050 period.

This phenomenon is primarily attributed to the combined pressures of decreasing precipitation and increasing temperature, leading to insufficient water supply during crop growth and affecting yields. The rapid decline during this period reflects the vulnerability of Sofia's agricultural system in the early stages of climate change. The results suggest that current agricultural technologies and adaptation measures have not effectively addressed extreme climatic conditions.

Entering the 2050-2075 period, the rate of yield decline slows down. This change may be related to gradual improvements in agricultural technologies and enhanced adaptation measures, such as introducing drought-tolerant crop varieties, optimized irrigation techniques, and strengthened water resource management. However, the continued decrease in precipitation still poses significant pressure on agricultural production, preventing a complete reversal of the yield decline trend.

By 2075-2100, the rate of yield decline further slows down. This stage of change may benefit from the accumulation of long-term adaptation strategies and continuous innovation in agricultural technologies, such as more efficient irrigation systems, the application of precision agriculture technologies, and the promotion of climate-smart agriculture. However, the persistent lack of precipitation remains the main factor constraining agricultural production, indicating that further policy support and technological innovation are needed to address future climate change challenges.

Overall, the declining trend in corn and wheat yields in the Sofia region is closely related to changes in precipitation. Although the rate of decline differs across periods, this trend highlights the profound impact of climate change on agricultural production. In order to overcome the emerging challenges, comprehensive measures need to be taken in technology, policy, and resource management in the future to enhance the resilience and sustainability of the agricultural system and ensure food security.

CONCLUSIONS

The study systematically analyses the future climate change trends in Bulgaria, focusing on the spatiotemporal distribution characteristics of temperature and precipitation based on thirteen models from CMIP6, with a detailed examination of the Sofia region from 2025 to 2100. A nonlinear fitting of the relationship between corn and wheat yields for 1993–2021 highlights precipitation as the key factor affecting agricultural production.

Based on the results, the following conclusions are drawn:

(1) Temperatures and precipitation in Bulgaria exhibit an inverse distribution pattern. Southwest has moderate temperatures and high precipitation, while the southeast region has higher temperatures but less precipitation. Sofia faces dual challenges of intensified drought due to higher temperatures and flooding caused by excessive rainfall;

(2) Sofia region temperature is projected to rise, with the fastest increase (2025–2050), with an average acceleration rate of 0.0399 and the slowest rise will be between 2075 and 2100, with an average acceleration rate of 0.0299 but the largest fluctuations, indicating more severe and unpredictable long-term temperature changes;

(3) Sofia region precipitation is expected to decline in a fluctuating manner from 2025 to 2100, most sharply from 2025 to 2050 (-0.1007), with increased fluctuations between

2075 and 2100, suggesting increased uncertainty in precipitation changes;

(4) Precipitation is the primary constraint on agricultural production in Sofia, while temperature changes have a relatively minor impact on grain yields;

(5) Wheat and corn yields in the Sofia region will decline most rapidly between 2025 and 2050. Precipitation levels below or above the optimal range significantly reduced yields;

(6) Strategies such as improved water resource management, climate-smart agriculture, optimised irrigation, and agriculture infrastructure investment are essential for agricultural resilience and sustainability.

ACKNOWLEDGEMENTS

This research was supported by Shanghai Municipality`s Action Plan for Science and Technology Innovation International Science and Technology Cooperation Project (Grand №22230750500) and the Guilin City Scientific Research and Technological Development Program Project (Grand №20230127-3).

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