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Risks to the development of agriculture in Bulgaria in the context of climate change

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Abstract: This article outlines the potential risks to agricultural development in Bulgaria, within the context of climate change. Emphasis is placed on evaluating the impact of evolving climate patterns and water scarcity. Altered climatic conditions not only threaten agricultural productivity, but also contribute to reduced yields and economic instability for agricultural producers. Additionally, these changes pose a threat to the country's population, due to the increased likelihood of natural risks and disasters. There is a pronounced need for adaptive strategies that enable economic operators to effectively respond to current challenges, such as the increased use of drought-resistant crops, and the enhancement of sustainable soil management practices. Moreover, the article emphasises the importance of achieving critical sustainability in terms of resource access and knowledge for climate change adaptation in agriculture. Achieving such sustainability is vital for safeguarding food security and public health, given the indispensable role of agriculture in providing economic livelihoods to rural populations. The article also emphasises the need to enhance the accuracy and precision of forecasting the impact of climate change on agriculture, as well as the development of an indicator system and criteria for evaluating climate-smart agriculture.

Keywords: risks to agriculture; agricultural policy; climate change; climate-smart agriculture; food security

Рискове пред развитието на селското стопанство в България в контекста на климатичните промени

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Резюме: Настоящата статия представя потенциалните рискове за развитието на селското стопанство в България в контекста на климатичните промени. Поставен е акцент върху оценката на въздействието на променените климатични модели и недостига на вода. Променящите се климатични условия, освен че заплашват производителността в селското стопанство, се отразяват върху намаления добив и икономическа стабилност за селскостопанските производители. От друга страна, заплашват и като цяло населението на страната в резултат от възможностите за настъпване на природни рискове и бедствия. Потвърждава се необходимостта от използването на адаптивни стратегии, чрез които стопанските субекти да отговорят на съвременните предизвикателства, свързани с повишаването на използваните устойчиви на суша култури, както и свързани с възможностите за повишаване на устойчивото управление на почвата. Освен това, се потвърждава необходимостта от постигането на критична устойчивост относно достъпа до ресурси и знания за адаптация с промените, свързани с изменението на климата в областта на селското стопанство. Постигането на критична устойчивост е от съществено значение за осигуряването и гарантирането на продоволствената сигурност и общественото здраве, тъй като е безспорна съществената роля на селското стопанство за осигуряването на икономическия поминък на населението в селските райони. Представена е необходимостта от повишаване на точността и прецизността за прогнозиране на въздействието на изменението на климата върху селското стопанство, както и необходимостта от разработването на система от индикатори и критерии за оценка на климатично интелигентното земеделие.

Ключови думи: рискове за селското стопанство; селскостопанска политика; климатични промени; климатично интелигентно земеделие; продоволствена сигурност

INTRODUCTION

Climate change presents numerous challenges to agricultural systems, both within Bulgaria and internationally, particularly in vulnerable regions, where local livelihoods are heavily dependent on agricultural productivity. Additionally, Bulgaria ranks among the top ten countries, most impacted by climate change in 2022, as detailed in the latest edition of the Climate Risk Index (Adil et al., 2025). The observable climate phenomena are affected by climate change, given that the environment in which they occur has become warmer and wetter than previously, resulting in slight variations in mean values, leading to disproportionately large percentage changes in extreme conditions. Furthermore, there is a continuous increase in greenhouse gases and aerosols in the atmosphere, which significantly contribute to the escalation of global temperatures.

Individual climate change scenarios suggest that within a period of less than sixty years, the mild droughts presently observed are expected to intensify into severe drought conditions, particularly impacting the western and southeastern regions of the country, which are projected to be the most affected (Nikolova, 2023). The utilisation of evolving meteorological models as tools to generate precise weather forecasts, and reflect the increased frequency of extreme events, altered precipitation patterns, and rising temperatures - both globally and regionally - has the potential to enhance the prediction and assessment of the possible impacts of climate change on agricultural yields and food security. Effective research into the risks confronting agriculture amid climate change necessitates a mixed-methods approach, that integrates techniques for collecting both quantitative and qualitative data, thereby enabling a comprehensive analysis of the relevant variables. Consequently, the primary objectives of this study are to evaluate the socio-economic impacts of climate variability on agricultural practices, and to identify effective adaptation strategies that agrarian producers can employ to mitigate associated risks. Furthermore, this study aims to assess the efficacy of existing agrarian policies in addressing climate-related challenges, and to propose targeted mitigation measures.

The primary research challenge in this study pertains to examining the risks, associated with climate change, and their implications for agricultural development. The study aims to identify and elucidate the particular vulnerabilities confronting the farm sector. Considerable emphasis will be placed on the significance of adaptive strategies, that can mitigate the negative impacts of climate change on agriculture. In this context, the author's aims to synthesise and present the scholarly discourse concerning climate change and agriculture, whilst concurrently offering practical insights for stakeholders such as policymakers, farmers, and civil society organisations. To accomplish this, key areas for intervention are identified, and summaries are provided, to inform stakeholders on the progress toward sustainable, modern agricultural practices that can help safeguard food security.

MATERIALS AND METHODS

The consequences of climate change on agricultural development, particularly in vulnerable regions, underscore the necessity to present opportunities for addressing the complex risks confronting agriculture, within the context of climate change. These risks manifest through altered rainfall patterns, increased temperatures, and the proliferation of extreme weather events. The existence of a dialogue between environmental and social sciences regarding a comprehensive understanding and mitigation of the multifaceted challenges, posed by climate change to agriculture, necessitates an integrated approach. Such an approach should systematically evaluate risks to both natural systems and human populations, identify critical points, and highlight gaps in the development of adaptive strategies within the agricultural sector.

Numerous publications investigate the interrelationships among climate policy, agricultural innovation, and economic adaptability. They note that sustainable farming practices can enhance resilience (Ghafoor et al., 2024), while also emphasising the multifaceted impacts of climate change. This recognition necessitates the incorporation of socio-economic factors and community-level adaptations within research frameworks. By integrating traditional knowledge with modern agricultural techniques, it is possible to promote resilience and encourage the adoption of sustainable farming practices.

Research related to identifying risks to agricultural development within the context of climate change, involves a meticulous examination of existing comprehensive strategies, that consider not only climate forecasts, but also evaluate socio-ecological dynamics and economic processes, influencing the implementation of agricultural practices. It is essential to emphasise the importance of a holistic approach to understanding the risks, posed by climate change to agriculture, and to determine the necessity for integrated solutions. An exhaustive and detailed investigation into the dangers confronting agricultural development amid climate change reveals several interconnected themes, that highlight the complexity of this relationship. These themes include an assessment of the impact of extreme weather events, with researchers demonstrating how unpredictable rainfall patterns and rising temperatures directly threaten crop yields and livestock productivity. The conclusions derived from these studies can be summarised as follows: the sustainability of agriculture is significantly compromised by climate fluctuations. The second primary theme concerns the socio-economic dimensions of climate change on agriculture. Within this framework, research focuses on identifying vulnerable population groups, particularly in developing regions, that face heightened risks, which exacerbate pre-existing inequalities, mainly when agriculture constitutes the primary livelihood of these vulnerable groups. The role of innovative agricultural practices supporting the implementation of mitigation strategies is also delineated. The adoption of sustainable practices, such as agroecology and precision farming, is among the approaches through which some of the pressures exerted by climate change can be alleviated; however, challenges related to resistance stemming from resource insufficiency and knowledge gaps among agricultural producers remain significant.

It is unequivocal that there exists an intersection between climate threats, socio-economic impacts, and the development and implementation of adaptation strategies, that shape the future trajectory of agricultural development within the context of climate change. The presence of numerous challenges necessitates the adoption of integrated approaches, to address them effectively. Furthermore, it is essential to acknowledge that methodological approaches vary significantly when examining the critical intersection between agricultural development and climate change, as the risks confronting the agricultural sector are viewed from diverse perspectives. Quantitative studies primarily emphasise data-driven assessments, employing predictive models to forecast the impact of climate change on crop yields and agricultural practices. The effectiveness of such models in identifying risk-prone regions is undeniable, as this facilitates informed decision-making about targeted agricultural interventions. The application of qualitative methodologies is justified by the aim to comprehend the socio-economic dimensions of these risks. Case studies illustrating the vulnerability of small farmers to changing climatic conditions further underscore the need for integrated approaches that incorporate local knowledge, in addition to scientific data (Ardila et al., 2024). The integration of quantitative analysis with qualitative insights enhances the capacity to portray potential risks with a nuanced understanding, thereby capturing the complexity of farmers' actions and strategies for adapting to climate change. Relying solely on quantitative models is insufficient, as these methods cannot fully account for the socio-cultural factors, that affect agricultural sustainability. Consequently, the employment of diverse methodologies in combination is essential to accurately represent the current situation and delineate future challenges (Zeeshan, A. et al., 2019).

The existing methodological diversity in research concerning agricultural risks further underscores the necessity for a comprehensive approach to planning and implementing measures, aimed at addressing these risks within the context of climate change. Such an approach entails both analysing available empirical data and gathering information from agricultural producers to foster sectoral sustainability. The multifaceted challenges, confronting agriculture in the face of climate change, are corroborated by the various theoretical frameworks, predominantly employed across different studies. Analysing challenges from multiple perspectives is encapsulated in the concepts of vulnerability and resilience. For instance, studies grounded in the theory of socio-ecological systems recognise that agricultural practices are intricately embedded within broader ecological and social frameworks. Consequently, adaptation strategies must concurrently ensure environmental sustainability and socio-economic viability to effectively mitigate risks, associated with climate variability (Bayata and Mulatu, 2024) and (Antriyandarti et al., 2024).

When developing adaptive strategies for implementing successful agricultural policies in the context of climate change, various approaches can be employed, and a combination of different methods is appropriate for planning and implementing effective frameworks. Both the utilisation of statistical analyses and the inclusion of specific studies among stakeholders, enhance the reliability of conclusions and findings. This study is grounded in existing frameworks that illustrate the interrelationship between climate conditions and agricultural vulnerabilities, including research on socio-economic data related to rural development. Undoubtedly, understanding socio-economic development and analysing its interconnections with climate change are crucial for formulating effective adaptive strategies. On one hand, local knowledge must be incorporated when devising successful practices for coping with climate change; on the other hand, conducting comprehensive, in-depth analyses using diverse approaches and methodologies, provides a robust foundation for timely policy recommendations. These recommendations should aim to address the need for implementing sustainable agricultural practices within specific regions, thereby ensuring food security and enhancing the resilience and sustainability of agricultural communities in the face of climate change. Table 1 below presents various methodologies, employed in scientific research to assess agricultural risks in the context of climate change, along with brief descriptions of each methodology, and its principal advantages and disadvantages.

When employing a variety of risk assessment methodologies, it is essential to consult with agricultural producers, to gather their opinions and perceptions regarding the threats posed by climate change, as well as the necessary follow-up actions they should take. The extent to which technological advancements in agriculture can effectively mitigate the adverse effects of climate change remains an unresolved issue (Seyran et al., 2018; Iqbal et al., 2024). A significant challenge lies in the disparities in access to technology, which serve as prerequisites for further aggravating existing vulnerabilities. In this context,

Table 1. Various methodologies for evaluating agricultural risks associated with climate change

Methodology	Description	Advantages	Disadvantages
Empirical statistical modeling	It employs statistical methodologies to evaluate the responsiveness of agricultural systems to multiple facets of climate change, encompassing human adaptation.	Captures emerging climate risks; informs personalized sustainability strategies.	May necessitate extensive data collection; potential difficulties in modeling intricate interactions.
Vulnerability assessment based on indicators.	Constructs vulnerability indices by integrating relative scores allocated to identified risk variables, frequently employing methodologies such as the Analytic Hierarchy Process.	Based on sound mathematical reasoning; widely accepted among stakeholders.	The selection of the indicator and the associated weighting may be subjective; computational complexity could impede full implementation.
Simulation methodologies	Utilises crop growth simulators and climate change models to monitor crop responses to evolving climate, soil, and management factors.	Provides dependable scientific forecasts; facilitates scenario analysis.	May require substantial computational resources; the accuracy of the model is contingent upon the quality of the input data.
Crop simulation models (CSMs)	DSSAT (Decision Support System for Agrotechnology Transfer), APSIM (Agricultural Production Systems Simulator), EPIC (Environmental Policy Integrated Climate), InfoCrop, AquaCrop, SWAP, CERES, CropSyst and WOFOST (World Food Studies)	They offer a comprehensive, process-oriented understanding of the biophysical responses of crops to environmental changes. They facilitate the evaluation of specific management practices and hypothetical adaptation scenarios (such as altering sowing dates, selecting different varieties, implementing irrigation, and applying fertilization). These tools are extensively utilised, calibrated, and validated across numerous crops and regions worldwide.	The necessity of utilising multi-model ensembles Is underscored by their requirement for extensive and detailed input data, which is frequently unavailable, particularly in developing nations. Variability in model structure, parameterisation, and underlying assumptions contributes to uncertainty in forecasts, even when identical input data are employed. These models often simplify or omit critical factors such as pests, diseases, and weeds- elements also affected by climate- and which can substantially influence actual yields. The manner in which models incorporate the impacts of CO_2, extreme events, and farmers' adaptive behaviours may be limited or vary considerably across different models. Without careful application, and when accounting for other sources of variability beyond climate factors, there is a risk of overestimating the specific risks associated with climate change.

Source: Own interpretation, 2025.

it is of the utmost importance to integrate local knowledge with scientific research, when formulating strategies to enhance adaptive capacity. The confluence of traditional wisdom and modern scientific achievements should be duly considered, when developing a comprehensive approach to addressing agricultural risks within the framework of climate change.

RESULTS AND DISCUSSION

There is a strong interdependence between agriculture and climate change, underscoring the necessity of implementing decarbonization strategies to mitigate climate change and developing a climate-resilient strategy, to enhance agricultural adaptation. These measures are imperative for the sustainable development of agriculture. The subsequent figure illustrates the various processes underlying agricultural production, which in turn elucidates the challenges involved in assessing the sustainability of agriculture. There are general guidelines for cultivation and the corresponding operational stages for nearly all crops (e.g., sowing, irrigation, and harvesting). Variations are typically related to agronomic practices, types of machinery employed, levels of technology, and the quantities and types of materials utilised, which differ depending on the crop type, application practices, the country (including regional cultivation zones), and prevailing climatic conditions (Lampridi et al., 2019).

In light of the escalating interest in agricultural sustainability, numerous methodologies and tools have been developed that promote integrated and comprehensive approaches to assessment. Nevertheless, there is a currently lacks a consensus on standardising agricultural sustainability evaluation within a unified framework of sustainable development, as existing and newly introduced frameworks, predominantly offer tools tailored to specific cases. The emphasis remains on resource utilisation and its impact on the sustainability of agricultural practices. "Sustainable agriculture" should be understood as an activity, that meets certain conditions for an indefinite period of time (Sarov et al., 2023). When assessing sustainability, the primary focus is on three main pillars: economic, social, and environmental. There is also a proposal to include a fourth pillar of sustainability with a political and institutional dimension. In this context, it is acknowledged that institutional indicators of sustainability are linked to specific norms and institutional mechanisms. Indicators such as the farmer adaptability index, the number of visits and the distance to various administrative offices, and the regulation of property rights over fixed capital and land are utilised in the analysis of institutional sustainability (Sarov et al., 2023; Ivanov et al., 2012). The literature review indicates that a combination of methodologies exists, which complicates the clear differentiation between the processes, employed in studies concerning agricultural sustainability. The most frequently utilised methods include indicator-based tools, frameworks, and indices, followed by multi-criteria approaches such as stakeholder participation, which is vital in research related to agricultural sustainability. Figure 1 depicts the various processes encompassing inputs and outputs, associated with agri-

Fig. 1. Variables, involved in agricultural sustainability assessment

Source: Lampridi, M. G. et al., 2019.

cultural production. There are general guidelines for cultivation and activity stages applicable to nearly all crops, such as sowing, irrigation, and harvesting. Variations arise from existing agronomic practices, types of machinery employed, the current levels of technological advancement within a country and sector, as well as the quantities and types of materials used. These differences depend on the crop type, historically established cultivation practices, and are influenced by prevailing climatic conditions.

In this context, considering the identified risks to agriculture arising from climate change, the country should enhance its focus on developing and implementing smart agriculture, specifically climate-smart agriculture. The advancement of smart agriculture involves the application of technological innovations and intelligent farming techniques to foster sustainable agricultural production. This development is predicated on improving the precision of evaluating various factors, that influence efficiency and productivity in complex agricultural systems. It encompasses the development and deployment of intelligent agricultural systems that utilise advanced technologies, including large database analysis systems for environmental monitoring, wind pattern analysis, rainfall assessments, chemical composition, and soil pH measurements. Concurrently, climate-smart agriculture entails integrating decarbonization strategies and climate resilience measures simultaneously. Since its inception in 2010, the term "climate-smart agriculture" has been widely recognised as "a modern production approach to coordinate the promotion of food security, climate mitigation benefits, and the adaptation of agriculture to climate change in alignment with the Sustainable Development Goals" (Lou et al., 2024).

This definition implies that research related to the implementation of climate-smart agriculture, should focus on seeking opportunities to mitigate greenhouse gases in agriculture, increasing the carbon storage capacity of agroecosystems, assessing the impact of climate change on agricultural systems, and, last but not least, research aimed at exploring opportunities for adapting agrarian production to the challenges, posed by climate change. In fact, both Bulgaria and several other countries should accelerate the implementation of climate-smart agriculture, as the aim is, on the one hand, to mitigate the effects of climate change and, on the other, to ensure food security. The main challenges related to the development of climate-smart agriculture are related to:

- The need to standardise methodologies for monitoring and reporting carbon in agriculture;
- The need to determine the potential for reducing greenhouse gas emissions and carbon storage in agriculture remains;
- Improving the accuracy and precision of predicting the impact of climate change on agriculture;
- Developing a system of indicators and criteria for assessing climate-smart agriculture;
- Improving existing technologies and developing new technologies for coordinated increases in agricultural productivity, carbon sequestration, greenhouse gas emission reductions, and improved climate adaptation to climate-smart agriculture;
- High costs of implementing certain technologies in agriculture;
- The creation of a globally fair, inclusive, and coordinated policy mechanism to promote agriculture that is consistent with climate change trends, the global carbon emissions market in agriculture, and food security, as food security is the main guarantee for human survival.

Climate change threatens food production capacity, but at the same time, the world's population is growing, which is the reason why food security should also be considered as a fundamental principle of climate-smart agriculture. Both climate-smart agriculture (CSA) and carbon farming are considered as key methodologies in efforts to mitigate climate change, while maintaining the sustainability of agriculture. The goal of these strategies is to minimise greenhouse gas emissions, while improving soil vitality and ensuring food availability. Carbon farming can increase organic carbon in the soil through various measures, such as the use of cover crops and crop rotations, which can reduce carbon emissions by up to 60% in some areas. Additionally, carbon farming contributes to enhancing biodiversity, a critical factor in maintaining ecosystem sustainability. On the other hand, climate-smart agriculture involves the use of climate-resilient crop varieties and precision farming methods, which are crucial for maintaining productivity in changing climatic conditions (Bayata and Mulatu, 2024).

It is precisely climate change that advocates for the introduction of "new agricultural crops", which are associated, on the one hand, with scientific development and, on the other hand, with the imperative to meet the food requirements of a population threatened by climate change. Accordingly, organic crops may be considered an alternative to conventional production methods, and could occupy a significant role within the national economy; their potential as raw materials will be adapted to the needs and consumption patterns of both the processing industry and society (Petrov et al., 2025). In this context, it is crucial to establish a precise definition of adaptation readiness to complement adaptive capacity. When assessing adaptation readiness, it is essential to consider the presence and robustness of governance structures and ongoing political processes that influence the feasibility of implementing adaptation measures. Some scholars (Ford and King, 2015) identify six key factors in evaluating this readiness, as follows:

- Political leadership entails the existence of will and the provision of support for the planning and implementation of adaptation measures related to climate change.
- Institutional organisation pertains to creating opportunities to enhance the effectiveness of institutions responsible for implementing the process of planning and applying adaptation to climate change.
- Decision-making and stakeholder engagement encompass the organisation of the decision-making process, with the inclusion and active participation of key actors and all stakeholders, involved in climate change-related decision-making.
- Availability of and access to pertinent data and information are essential for making informed decisions regarding climate change adaptation.
- The adaptation financing process involves the pursuit and allocation of necessary funds to implement climate change adaptation activities within the region.
- Public support for climate change adaptation is manifested through the creation of conducive conditions to increase public understanding, and support for the necessary measures in combating climate change.

In fact, the proposed framework offers an opportunity to assess readiness for adaptation to climate change systematically. Its objectives include identifying and prioritising support needs, directing necessary resources to areas of impact, and serving as an indicator for monitoring the adaptation process. Undoubtedly, crucial for assessing risks to agricultural development amid climate change is the utilisation of indicator analysis to examine specific indicators, that elucidate observed trends in the impact of climate change on agriculture. Such analysis should be regarded as a structured technique, employing available historical data to reveal trends, identify significant upcoming changes in the studied area, and assist analysts in providing evidence-based forecasts with minimal cognitive bias. In the context of climate change, indicators may comprise the occurrence of specific events or actions that signify major changes within the study area, whether it is a territory, region, or country. Moreover, indicators can also consist of combinations of events, that elucidate the interrelationships between observed modifications in the natural environment, and may signal impending shocks or transformations. The application of indicator analysis in examining these indicators, enables the identification of agricultural trends and impacts resulting from climate change. Consequently, indicator analysis should be considered a structured analytical method, utilising historical data to identify trends and potential future changes, thereby supporting researchers in generating evidence-based forecasts. The selection of indicators may encompass individual events or actions within a single factor or a combination thereof, with primary emphasis on identifying those indicators that will signal imminent shocks and facilitate preventive measures (Mitov, 2024). In this regard, considerable attention should be directed toward developing indicators for monitoring and assessing regional development in rural areas across the country, aiming to represent the processes involved in rural regional development visually. To this end, a system of indicators may be proposed, which can be predefined to evaluate the policies enacted, thereby facilitating data collection concerning the state and progress of agriculture, actual costs incurred, and the outcomes of implementing relevant policies at the regional level. Some scientists, such as Petrov and Borisov (2025), propose categorising program indicators into four types: resource indicators, product indicators, result indicators, and impact indicators. It is therefore crucial to monitor the evolution of these factors over time, enabling timely analysis of emerging trends - an integral part of the indicator analysis process, which can foster opportunities for strategic planning and the deployment of preventive measures.

One possible approach to planning and executing preventive strategies, involves designing specific measures based on the identified vulnerabilities within the agricultural sector and anticipated impacts on the territory and its inhabitants. The following table illustrates the authors' interpretation of the interrelationship between climate change, economic, social, and political factors, as well as their respective impacts and effects on the country's socio-economic fabric.

Undoubtedly, climate change influences crop production through direct, indirect, and socio-economic effects, as illustrated in Figure 2. It is also evident that plant physiology is affected by climate variability. The increasingly frequent occurrence of extreme environmental conditions and the rising variability in climate observed, are consequently escalating the likelihood of multiple stress factors impacting plants in regions, heavily affected by climate change.

Table 2. Some key impacts of climate change on agriculture

Some key factors influencing agriculture	**Impact**	**Effect**
Extreme weather events such as frequent and intense heat waves, droughts, floods, storms, and forest fires.	The escalation of atmospheric CO_2 concentrations, the increase in temperatures, alterations in precipitation patterns, depletion of water resources, biotic stresses including weeds, diseases, and pests, as well as soil erosion, collectively pose significant environmental challenges.	Reduced crop productivity, increased soil erosion due to extreme rainfall, regional and seasonal variations in water availability impacting agricultural output, altered rainfall patterns, and a diminished capacity to provide essential ecosystem services.
Economic factors such as fluctuations in the prices of raw materials, fertilizers, and fuels; escalating competition; and access to financing influence the market dynamics.	Rising expenses for agricultural operations and restricted investment opportunities.	Decrease in income from agricultural production, reduced ability to adapt to changing conditions, and inability to restructure farms to respond to climate change.
Social factors Include an ageing population, migration, and inadequate infrastructure.	The deficiency of available labour, challenges in transmitting existing knowledge to small-scale producers, and inadequacies in infrastructure-including roads, irrigation systems, and storage facilities-impede agricultural activities.	Challenges in land cultivation, harvesting, and sustaining the competitiveness of agricultural producers due to escalating labour costs.
Political factors include unstable agricultural policies and a lack of support for farmers.	The frequent modifications in agricultural policies hinder long-term planning and investment endeavours. Additionally, inadequate financial and technical support from governmental bodies can result in losses and potential bankruptcies among farmers.	Regarding long-term planning and the implementation of investments pertaining to the impact of climate change on the advancement of agricultural producers.

Source: Own interpretation, 2025.

When evaluating the direct and indirect impacts of climate change on agricultural productivity, it is essential to review and enhance farmers' awareness of the effects of climate risks, as well as the potential for improving the effectiveness of existing adaptation measures. Agricultural producers should recognise that increasing air temperatures correlate with a heightened capacity of the atmosphere, to hold water vapour, which may lead to more intense rainfall events, even in regions experiencing decreased rainfall. These changes influence both crop production and the yield and quality of harvested crops. Furthermore, they impact soil degradation processes (Li and Fang, 2016), with adverse effects often being mutually exacerbated (Hlisnikovský et al., 2023). Overall, global warming and climate change exert both detrimental and beneficial effects on crops and human populations. Figure 3 illustrates the positive and negative im-

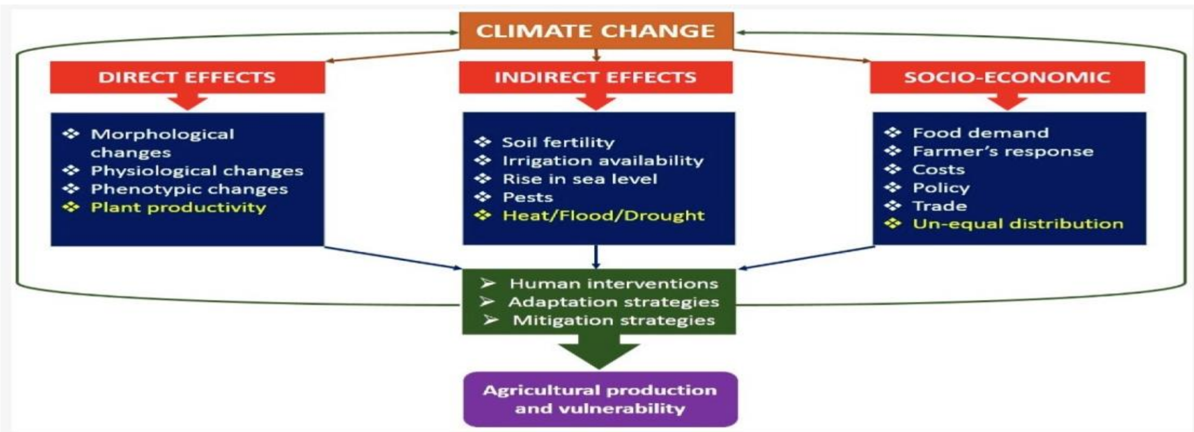

Fig. 2. The direct, indirect, and socioeconomic impacts of climate change on agricultural productivity
Source: Razzaq, A. et al., 2019.

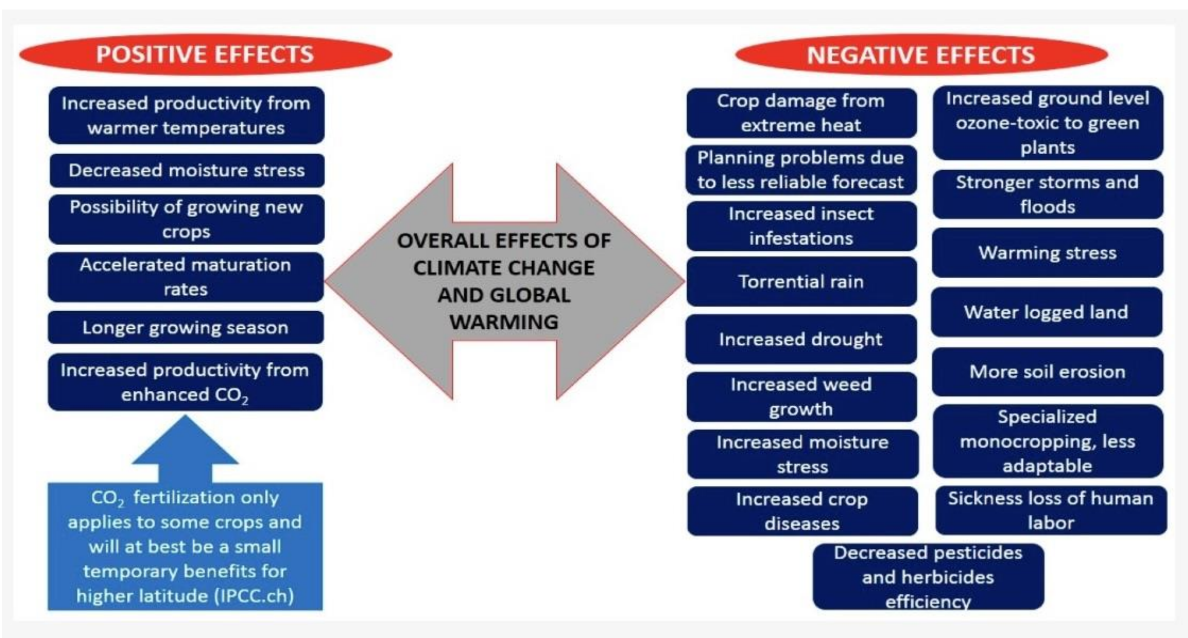

Fig. 3. Overall, the positive and negative impacts of climate change and global warming on crops and humans are evident
Source: Razzaq, A. et al., 2019.

pacts of climate change and global warming on agriculture and society.

The interconnection between the effects of climate change and the vulnerability of agriculture is indisputable. Therefore, research into climate risks and agricultural development is not only timely, but also imperative, emphasising the need for a coordinated response to address the multifaceted challenges, posed by climate change effectively. On a global scale, climate change can lead to conflicts, increased migration, and social instability, further exacerbating the impact on food security. In addition, climate change has significant implications for achieving sustainable development goals, including poverty reduction opportunities, policy planning to promote sustainable agriculture, and the fight against climate change. In this regard, achieving sustainable agriculture will contribute to food security and poverty reduction, however, the adverse effects of climate change on biodiversity and natural resources, must also be taken into account. Globally, the direct and indirect impacts of climate change on agriculture and food security can be illustrated by the following Figure 4.

On the one hand, by presenting the direct and indirect effects on a global scale, it is possible to further illustrate the problem of climate change, and the sustainability of agriculture in the development of local agricultural systems. The interaction between natural systems and human activities has become increasingly apparent in recent decades. On the other hand, the impact of climate change extends far beyond the boundaries of environmental science, affecting economic stability, food security, and human livelihoods on both a global and regional scale. Both the direct and indirect effects of climate change are crucial in shaping agricultural outcomes, with changes in temperature, precipitation patterns, and the frequency of extreme weather events being among the most significant factors, affecting crop yields and alterations in agricultural practices. Furthermore, a complex interplay exists between climate variables and socio-economic factors, further demonstrating that the sustainability of agriculture is substantially influenced by access to modern technologies, the development of market structures, and the implementation of institutional support for agricultural producers.

The challenges associated with biodiversity loss, are not solely an environmental concern. Instead, they, in conjunction with ecological damage caused by human activity, rank among the top five perceived threats to humanity in the latest global risks report. Furthermore, the depletion

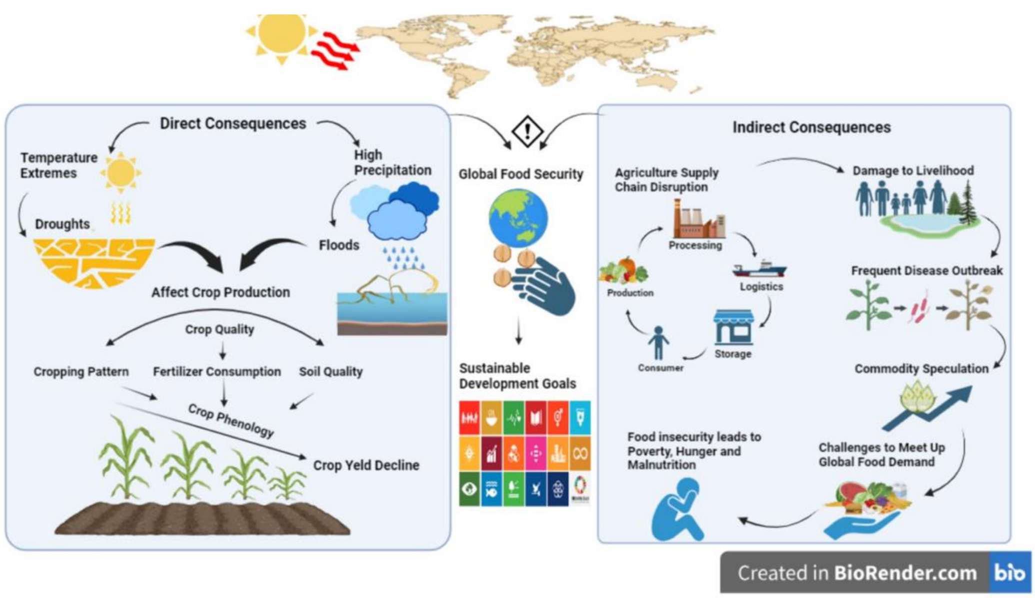

Fig. 4. Direct and indirect influences of climatic change on agriculture and food security
Source: Saleem, A. et al., 2024.

of biodiversity impacts food security, pollination, and agricultural systems, rendering them less productive and sustainable. It also influences efforts to reduce poverty across various regions worldwide. The potential reduction in the availability of traditional medicines and opportunities for drug development due to biodiversity loss, must not be overlooked. Climate change and ecosystem degradation do not impact all communities equally. Notably, climate change disproportionately affects impoverished and vulnerable populations, primarily attributable to their heavy reliance on nature and its resources for their livelihoods, subsistence, and health. The loss of biodiversity bears significant intergenerational implications, as failure to respect planetary boundaries may compromise the foundations upon which future generations will build. Establishing conditions conducive to the sustainable use of nature is crucial for both climate change adaptation and creating opportunities to mitigate biodiversity loss. Given that biodiversity loss and climate change are intricately linked through human economic activities that reinforce each other, it is imperative to implement measures, addressing both issues concurrently, where feasible. Sustainable management of ecosystems can contribute to climate adaptation, as healthy and diverse ecosystems enhance resilience to climate impacts. This is particularly pertinent, considering that species-rich ecosystems are often rich in carbon, with vegetation and soils playing vital roles in mitigating climate change through carbon sequestration. In addition, to terrestrial ecosystems, marine ecosystems also serve as significant carbon sinks. In this context, blue carbon ecosystems sequester and store more carbon per unit area than terrestrial forests, underscoring their increasing recognition in climate change mitigation efforts (Guyer, M. et al., 2022). The subsequent figure illustrates the impact of cli-

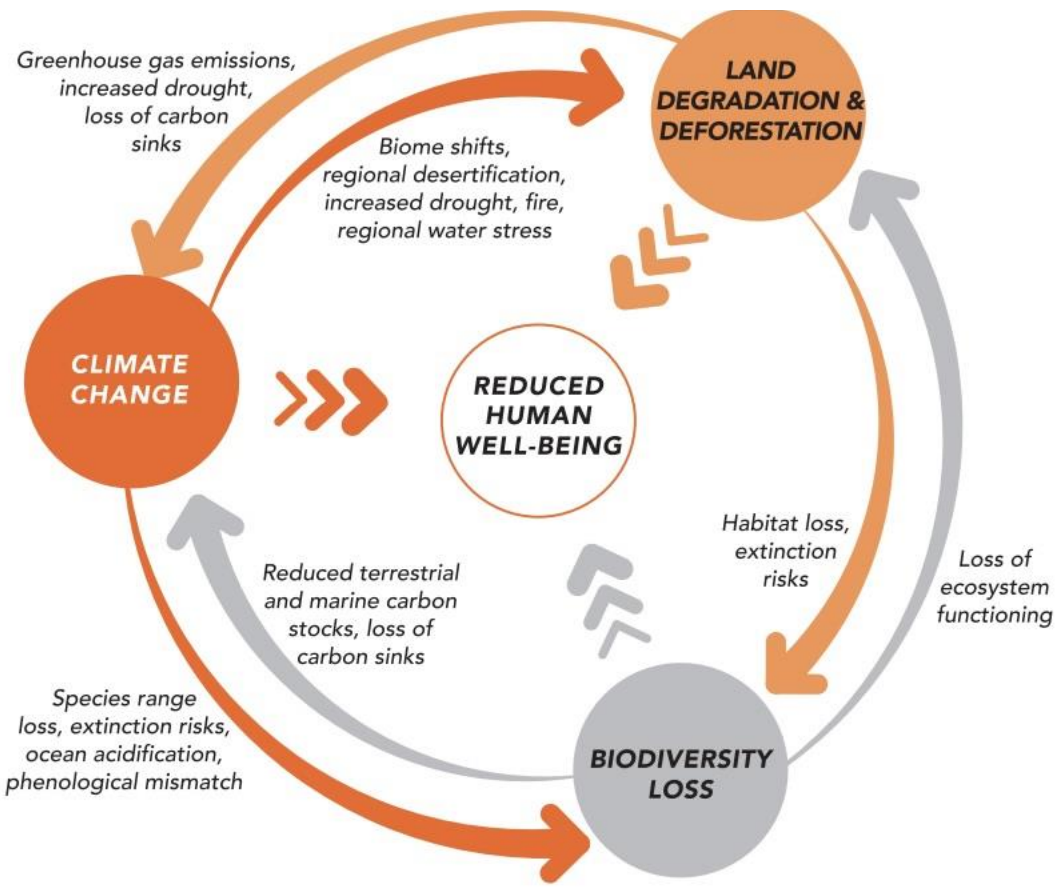

Fig. 5. Interactions between biodiversity, climate change and land use
Source: Steinemann, M., & Saalismaa, N., 2022.

mate change, biodiversity loss, and deforestation on the decline in human well-being.

The interrelationship between climate phenomena, policy planning, the adoption of measures, and the application of agricultural practices, is increasingly at the forefront of stakeholders' agendas due to the observable impacts of climate change. Globally, these effects are being monitored and researched owing to the reliance of a substantial portion of the world's population on agriculture for their livelihoods, economic stability, and sustenance. Climate change undoubtedly presents unprecedented challenges, including erratic weather patterns, prolonged droughts, and increasingly severe floods, which adversely affect the development of the agricultural sector.

Research into the various dimensions of risks threatening agricultural productivity and sustainability highlights the connection between elevated temperatures and fluctuations in crop yields, particularly for staple crops such as wheat and corn, which form the foundation of food security in numerous regions (Bayata and Mulatu, 2024). The profound consequences of alterations in rainfall patterns significantly influence water availability for irrigation, thereby exacerbating competition for this essential resource (Antriyandarti et al., 2024). There is an increasing recognition of the socio-economic dimensions, associated with agricultural risks stemming from climate change. This is particularly evident among farmers in developing nations, who are confronted, on one side, with economic vulnerability due to climate variability, and, on the other, with limited capacity to adapt owing to resource and knowledge deficiencies. Numerous studies have explored farmers' adaptation strategies, including the implementation of crop diversification and the adoption of climate-resilient varieties (Zeeshan et al., 2019). Despite the availability of promising approaches to address climate change, a substantial proportion of agricultural producers remain inadequately prepared to respond effectively to the swift changes, imposed by a changing climate (Seyran et al., 2018). A critical factor contributing to this gap is access to modern technologies and information, regarding shifting conditions in both geographical and socio-economic contexts, which complicates the agricultural response to climate change (Iqbal et al., 2024). The lack of information regarding key hazards further exacerbates existing disparities within and among communities across different regions (Adeyolanu et al., 2024). By reviewing scholarly research on agricultural challenges posed by climate change, a comprehensive understanding of the associated risks can be developed, aiding in the formulation of informed policy decisions, and the implementation of effective practices within the national agricultural sector.

Recent decades have seen a substantial increase in research aimed at identifying risks to agricultural development amidst climate change, reflecting observed climatic alterations. A primary challenge identified in the literature is climate variability itself, which contributes to unpredictable weather patterns, and elevates the risk of natural disasters, thereby causing significant losses in agriculture (Miteva, 2024). Conversely, several authors highlight economic factors such as market instability and reliance on foreign investment, which also influence agricultural development (Peneva and Marinova, 2024). Furthermore, attention is drawn to technological progress and innovation, highlighting the disparities in access to advanced technologies across regions, which exacerbate social inequalities within the sector (Stoyanova, 2023). Additionally, studies have examined risk factors specific to Bulgaria, particularly the influence of European Union policies and subsidies on sector development (Georgieva and Kirechev, 2022). These studies underscore the importance of developing adaptive strategies that mitigate the adverse effects of climate change, while promoting sustainable sector development. Investments in sustainable technologies such as drip irrigation and the adoption of good agronomic practices are highlighted as means to enhance productivity and reduce resource consumption (Kotseva-Tikova, 2022). An analysis of existing literature reveals a predominant focus on economic aspects, often at the expense of addressing the social and environmental impacts of agricultural policies (Georgieva, 2020). This underscores the necessity for an integrated approach in risk analysis and challenge identification, particularly concerning the establishment of conditions conducive to the long-term sustainability of agricultural development.

The direct correlation between rising temperatures and fluctuations in the yields of major crops is of paramount importance for ensuring food security. Conversely, alterations in rainfall patterns impact critical water resources necessary for irrigation and concurrently exacerbate competition and potential conflicts among stakeholders in agriculture.

A recurrent theme in the scholarly literature is the socio-economic vulnerability of farming communities, particularly in developing nations, where opportunities for adaptation are severely constrained by limited access to resources and information. Such communities face the imperative to adopt adaptive strategies, including crop diversification and the utilisation of climate-resilient varieties. Despite this, many farmers remain inadequately prepared to effectively address the rapid changes induced by climate impacts (Zeeshan et al., 2019). This vulnerability transcends immediate agricultural concerns, linking to broader issues of socio-economic stability and underscoring the risks faced by food production systems-risks, that threaten livelihoods and exacerbate existing inequalities within socially vulnerable communities.

An analysis of the existing research and literature underscores the necessity for integrated approaches that go beyond traditional disciplinary boundaries, combining scientific investigation of environmental issues with socio-economic analysis. The diversity of current methodologies demonstrates the need for a balanced approach, that incorporates empirical data alongside the lived experiences of stakeholders in agriculture, fostering sustainability and resilience. Climate change presents formidable challenges to agricultural development, demanding comprehensive, multidisciplinary research strategies that address both environmental and socio-economic factors. The development and deployment of adaptive strategy will not only enhance the sustainability of agricultural practices, but also ensure the socio-economic viability of farming communities as they confront the imminent climate crisis.

DISCUSSION

The intricate relationship between agriculture and climate change presents substantial risks, that could impede the development of agricultural sectors, particularly in vulnerable regions. A significant proportion of smallholder farmers experience adverse effects resulting from climate variability. The significance of access to reliable climate information is vital for enhancing the adoption rate of adaptation strategies, further emphasising the importance of raising awareness within the agricultural sector to facilitate adaptation.

In this context, discussions concerning the risks to agricultural development amid climate change should be connected to the necessity of implementing the following actions:

- The need for tailored interventions that prioritise support for smallholder farmers in developing adaptive capacities.
- Increasing government initiatives to support resilience-building efforts, through the formulation of more effective frameworks, that emphasise the use of local knowledge and community participation.
- Creating conditions conducive to successful adaptation by establishing local networks and institutions, to disseminate essential agricultural knowledge related to climate change.
- Augmenting investment in education, resources, and infrastructure to enhance farmers' adaptive capacities, which will also contribute to improving food security and socio-economic stability in regions most vulnerable to climate change.
- Enhancing the involvement of local stakeholders in the development of effective climate adaptation strategies aligned with farmers' realities.

CONCLUSION

This study emphasises the fact, that climate change presents unprecedented challenges, including unstable weather patterns, prolonged droughts, and increasingly severe floods, which will progressively impact the development of the agricultural sector. Consequently, it is imperative to monitor the evolution of these factors over time, and to conduct timely analyses of observed trends to facilitate the planning and implementation of preventive measures. Undoubtedly, the findings of this study underscore the necessity of developing methodological tools, through the modeling of indicators for monitoring and evaluating regional development in rural areas within the country, particularly in the context of the impact of climate change on agricultural progress. This involves visualizing rural development processes by establishing a system of indicators, that provide preliminary data for assessing implemented policies in agriculture, and climate change mitigation within the country's regions. Furthermore, there is a need to gather data on the state and development of agriculture, the actual costs associated with combating climate change, and the outcomes of relevant policy implementation at the regional level, reflecting the measures undertaken in the agricultural sector in response to climate change.

The analysis and findings presented herein, underscore the complex interrelationship between agriculture and climate change. They highlight the primary challenges faced by agricultural producers, particularly smallholders, in adapting to evolving climatic conditions. Climate variability, including changing weather patterns and increasing occurrences of droughts and floods, has a direct impact on yields, with a noted decline in productivity attributable to climatic factors. Concerning climate-related risks to agricultural development, there exists an urgent need for intervention strategies, that incorporate both local and scientific knowledge to bolster resilience within farming communities, and elevate the strength of agriculture to climate change.

There is an imperative to enhance educational outreach and improve access to climate information for farmers, thereby creating opportunities for capacity building in adaptation. Furthermore, collaboration among government agencies and stakeholders involved in agriculture, requires strengthening to facilitate adequate adaptation measures and enhance food security. Future research might focus on exploring the synergistic effects of multiple climate adaptation strategies, including agroecological practices and technological innovations, to promote a comprehensive understanding and planning for effective responses to climate change.

Additionally, further research is warranted into the socio-economic factors influencing farmers' adaptive capacities, as well as the development of innovative financial models, aimed at ensuring the sustainability of agriculture amid climate risks. Additional studies could also focus on managing the climate adaptation process with the participation and cooperation of local communities to develop solutions tailored to specific challenges posed by climate change. As climate change continues to threaten agricultural productivity, ongoing research efforts will be crucial to ensure the sustainable development of agricultural practices, ultimately fostering opportunities and enhancing the resilience of food systems at both regional and global levels.

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