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## **THE FUTURE OF INTEGRATED PLANT PROTECTION IN THE CONTEXT OF CLIMATE CHANGE**

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**Abstract:** Climate change represents one of the greatest challenges for modern agriculture, including the application of integrated plant protection. Changes in air temperature, precipitation and the frequency of extreme weather conditions directly affect the occurrence of pests, the development of plant diseases and the productivity of agricultural plant species. In this context, integrated plant protection will play a key role in adapting agricultural systems to new conditions and ensuring their sustainability, as it ensures the protection of natural resources and crop productivity with minimal impact on the environment. The future of integrated plant protection in the context of climate change involves the development of new methods and technologies that will enable adaptation to changed climatic conditions. Adaptation of existing measures, combined with innovations in the field of biological control and digital technologies, will be key to the long-term sustainability of agricultural systems. Climate change presents a challenge, but also an opportunity, for improving integrated pest management to ensure a productive and sustainable future for agriculture. The research is based on an analytical review of current climate change, identification of key challenges it poses to agricultural production, and a systematic review of integrated pest management practices applied in sustainable production systems.

**Keywords:** Integral plant protection, Climate change, Sustainable plant production systems, Innovative methods

### **INTRODUCTION**

The global climate results from complex interactions among the atmosphere, oceans, land surfaces, and the biosphere. Contemporary instrumental observations and climate models indicate pronounced and accelerating changes in the Earth's climate system, primarily reflected in rising global average temperatures, altered precipitation patterns, and an increased frequency of extreme weather events (IPCC, 2021). Over recent decades, the global mean temperature has increased by approximately 1.1°C relative to the pre-industrial period, with each successive decade being warmer than the previous one (IPCC, 2021). This trend has been accompanied by more frequent and intense heatwaves, prolonged droughts, heavy precipitation events, floods, and sea-level rise driven by ice-sheet melt and thermal expansion of the oceans (IPCC, 2022).

Future climate projections indicate that, depending on greenhouse gas emission scenarios, global temperatures may increase by 1.5°C to more than 4°C by the end of the 21<sup>st</sup> century. Warming is expected to be more pronounced over land than over oceans, as well as at higher latitudes. Changes in precipitation patterns will be spatially uneven, with increases in wetter regions and decreases in already dry areas. In addition, climate models project a lengthening of the growing season in temperate and northern regions, shifts in climatic zones, increased frequency of extreme precipitation events, and intensified heat stress in many parts of the world. These changes have far-reaching consequences for ecosystems, water availability, agriculture, and global food security, making climate change one of the most significant challenges facing contemporary society

### **Analysis of Annual Temperatures and Precipitation in Serbia (2015-2024)**

Data on average annual temperatures and total precipitation in Serbia during the period 2015-2024 indicate a pronounced warming trend and increased climate variability. Based on annual climatological bulletins of the Republic Hydrometeorological Service of Serbia, the analysis shows that average temperatures in most years were above the long-term climate normal (RHSS, 2015-2024). The average annual temperature ranged from 11.4°C to 13.3°C, with 2024 recorded as the warmest year since the beginning of instrumental measurements. The years 2019, 2020, 2023, and 2024 stand out with average temperatures exceeding 12°C, which is consistent with regional warming trends observed in Southeast Europe (IPCC, 2021; IPCC, 2022). Precipitation patterns exhibit considerable interannual variability, with notably dry years (2017, 2022) and wetter periods, particularly in 2023. This combination of rising temperatures and unstable precipitation regimes indicates an increased frequency of climate extremes, with direct consequences for agriculture, water resources, and soil quality (EEA, 2023; FAO, 2021).

The results confirm that Serbia is already experiencing a phase of pronounced climate change, necessitating adaptation measures, especially in irrigation management, agricultural practices, and the selection of more resilient crop varieties (RHSS; IPCC, 2022).

### **Impact of Future Climate Change on Agriculture in Serbia**

The climate of Serbia is shaped by its relief, altitude, and local geographic factors, while meteorological data analyses indicate significant climatic changes over recent decades. Climate projections suggest a further increase in average air temperatures, particularly during summer and autumn, accompanied by pronounced variability in precipitation patterns. More frequent heatwaves, more intense precipitation events, and a lengthening of the growing season are expected, all of which may have substantial impacts on natural systems and agriculture in Serbia. These trends highlight the need for timely adaptation and sustainable management of climate-related risks.

Projected climate changes in Serbia will have direct and multifaceted effects on agriculture. Projections indicate a continued increase in average air temperature, amounting to at least 0.6°C in the near future and up to approximately 4°C by the end of the 21<sup>st</sup> century, especially during the summer and autumn seasons (RHSS, 2017; IPCC, 2021). Higher temperatures will intensify evapotranspiration and plant water stress, particularly

threatening major field crops such as maize, wheat, and soybean, as well as forage production.

Changes in precipitation regimes will further increase agricultural risks. Although no clear trend is projected for total annual precipitation, reduced summer rainfall and more frequent droughts may lead to significant yield losses, especially in areas lacking developed irrigation systems (RHSS, Climatology of Serbia). At the same time, an increase in short-duration, high-intensity precipitation events may cause flooding, soil erosion, and nutrient losses, negatively affecting soil quality and agricultural productivity (IPCC, 2022).

The projected extension of the growing season by 10-20 days in the coming decades may bring certain positive effects, such as earlier sowing or the introduction of new crops. However, these potential benefits are often offset by increased risks from heatwaves, pests, and plant diseases, whose frequency is expected to rise under warmer climate conditions (FAO, 2021). Consequently, adapting agricultural production through improved irrigation systems, the selection of more resilient crop varieties, and the application of sustainable agronomic practices represents a key response to future climate challenges in Serbia.

### **Integrated Pest Management (IPM)**

The European Union is one of the global leaders in promoting sustainable development, and its policies directly affect all aspects of agricultural production. The most significant strategic document is the European Green Deal, whose primary goal is for the European Union to achieve climate neutrality by 2050. Within this framework, the "Farm to Fork" strategy establishes clear guidelines for sustainable agriculture, including a target to reduce the use of chemical pesticides by 50% by 2030 (European Commission, 2020).

Integrated Pest Management (IPM) plays a central role in this strategy, as it enables the achievement of pollution reduction and biodiversity enhancement goals. It represents a multidisciplinary approach to crop protection, combining agronomic, biological, physical, and chemical measures to control pests while minimizing negative impacts on the environment, human health, and economic viability (Adhikari et al., 2024). IPM is a concept based on careful monitoring of pest populations and the application of interventions only when they are economically and ecologically justified (Davis and Thompson, 2024).

The core principles of IPM include prevention, monitoring, integration of control measures, and economic injury thresholds (Kumar et al., 2024). Prevention is achieved through the use of healthy seeds, resistant varieties, proper crop rotation, agronomic practices, and sanitary interventions (Adhikari et al., 2024). Monitoring involves regular field inspections, pest identification, and assessment of their population levels relative to defined economic thresholds (Rao et al., 2024). The integration of various control measures primarily involves the use of biological and physical methods, with minimal and selective pesticide application only when necessary (Gonzalez and Martinez, 2024). Biological control, as a key component of IPM, enables the preservation of natural pest enemies and biodiversity (Smith et al., 2024).

## APPLICATION OF IPM UNDER CLIMATE CHANGE CONDITIONS

One of the direct consequences of climate change is the alteration in the distribution and dynamics of pest populations and plant diseases (Li et al., 2024). Warmer conditions and changes in precipitation patterns allow certain pest species to survive in areas where they were previously absent. In addition, rising temperatures can extend the active season of many pests, leading to a higher number of generations per year and increased pressure on crops. For example, some invasive insect species, such as the Asian fruit fly, have expanded into new regions due to climate change, significantly impacting fruit production in those areas. This highlights the need to develop new biological and mechanical control measures within the framework of integrated pest management to effectively address these changes. The future development of IPM will focus on adapting existing practices and designing innovative solutions for pest control under climate change conditions. This adaptation will include the use of new biological agents and the development of methods for rapid monitoring and early diagnosis of pests and diseases (Kumar and Verma, 2024). Precision agriculture and new digital tools will enable better tracking of climatic conditions and pest dynamics, helping farmers predict risks and respond in a timely manner. Moreover, new crop varieties that are more resilient to stress factors such as drought and high temperatures could be developed to mitigate the negative impacts of climate change on agricultural plants (CIMMYT, 2025).

Recent advances in crop breeding have led to the development of wheat cultivars with enhanced heat stress tolerance, highlighting significant genetic progress toward climate adaptation (Zheng et al., 2025). Additionally, improved maize hybrids show increased drought resistance and yield stability under adverse climatic conditions, demonstrating the potential of breeding strategies to mitigate climate change impacts (Zhao et al., 2025). Moreover, research on millet and sorghum varieties underscores the importance of selecting climate-adapted genotypes to sustain productivity under enhanced thermal and water stress (Sall et al., 2025).

Integrated pest management can significantly contribute to mitigating the adverse effects of climate change. The application of biological methods, reduction in chemical pesticide use, and improvement of agronomic practices help conserve natural resources and reduce pollution, which positively affects the ecosystem's ability to adapt to changing climatic conditions. One key approach in this context is maintaining soil health and biodiversity, which enhances the resilience of agricultural systems to extreme climatic events. For example, crop rotation, the use of cover crops, and the conservation of natural pest predators can help maintain biological balance and reduce the impact of climate change on crop productivity (Šević et al., 2024; Cvijanović et al., 2024; Cvijanović et al., 2024b).

The future of IPM will also depend on the development of new technologies that enable faster adaptation to climate change. Technologies such as satellite monitoring, artificial intelligence, and advanced data analysis software will allow better real-time management of agricultural systems. Additionally, genetic engineering and the development of new biological agents will be crucial for controlling pests that adapt to new climatic conditions. This will enable more precise and effective pest management with minimal environmental impact.

Enhancing existing strategies, while simultaneously integrating modern solutions from biological pest suppression and digital technologies, will form the foundation for the long-term stability of agricultural systems. Although climate change presents significant challenges, it also provides an opportunity to refine integrated approaches to crop protection, which is essential for ensuring high productivity and sustainable agricultural development in the future (Table 1).

Table 1. Case studies on the impact of climate change on the increase of certain harmful organisms

Research Study	Reference
It showed that tropical fruit flies (Tephritidae) can become invasive and survive in temperate regions due to global warming, highlighting the need for preventive measures and continuous monitoring within IPM.	Gutierrez et al., (2021)
Review of IPM strategies adaptable to climate change: combines agroecological, biological, and cultural measures as a sustainable approach to pest management.	Zanzana et al., (2024)
Modeling indicates that suitable zones for <i>Bactrocera zonata</i> (peach fruit fly) will significantly expand due to climate change, emphasizing the need for IPM to include prevention and preparedness for emerging pests.	Ullah et al., (2023)
Evidence shows that the range of the Mediterranean fruit fly has significantly expanded under climate warming, highlighting the urgency of implementing adaptive measures in IPM programs.	Szyniszewska et al., (2024)
Review of invasive insects in Serbia during the 21st century represents a real regional threat, indicating the necessity of locally adapted IPM measures and monitoring.	Žikić et al., (2025)
Demonstrates that invasive species such as <i>Ceratitis capitata</i> are capable of genetic adaptation to new climatic conditions, implying that IPM must be flexible and long-term oriented.	Deschepper et al., (2024)

### ADVANTAGES OF IPM

The successful implementation of Integrated Pest Management (IPM) in various parts of the world has demonstrated that this approach provides a sustainable alternative to intensive pesticide use, offering numerous environmental, economic, and health benefits (Davis and Thompson, 2024; Gonzalez and Martinez, 2024). Increasing public and regulatory pressure to reduce pesticide use and conserve natural resources has further accelerated the global adoption of IPM. This is particularly significant in the context of climate change, which affects the distribution and dynamics of pest populations, highlighting the growing need for sustainable agricultural solutions (Table 2). IPM remains a cornerstone of sustainable agriculture and continues to evolve in response to contemporary challenges.

However, the implementation of IPM is also associated with several challenges, including the need for a high level of expertise, regular monitoring, and expert support, as well as long-term observation of its effects (Smith et al., 2024).

Table 2. Research studies on new methods in IPM

Method / Approach	Description / Significance for IPM	Reference
IoT sensors and smart traps	Real-time monitoring of pest populations and agroecological conditions; enables timely and targeted interventions.	Smith and Lee, (2024)
Precision agriculture + remote sensing (drones / satellites)	Allows detection of problems (diseases, pests, plant stress) and targeted application of control measures.	Brown and Zhao, (2023)
Artificial intelligence (AI) and machine learning	Automatic pest identification and outbreak prediction; enables a proactive IPM approach.	Nguyen and Chen, (2024)
Combined biological control + ecological / cultural measures	Integration of genetically or biologically based methods with cultural practices; reduces chemical use and increases sustainability.	Garcia and Patel, (2023)
Seed stimulation with low electromagnetic fields	Investigating the effect of non-chemical/alternative methods (electromagnetic field) on crops - relevant for exploring alternative plant protection methods.	Bajagić et al., (2023)
Digital monitoring systems	Automated tracking of larvae and insects in orchards and vegetable crops; supports timely decision-making in IPM.	Novak and Ivanović, (2022)

## LIMITATIONS AND CHALLENGES IN THE IMPLEMENTATION OF INTEGRATED PEST MANAGEMENT (IPM)

Although Integrated Pest Management is widely recognized as an environmentally and economically sustainable approach in agriculture, its global implementation still faces numerous limitations and challenges. These obstacles may be technical, educational, or economic in nature, and overcoming them requires coordinated efforts from governments, researchers, and farmers.

### Insufficient Education and Awareness Among Farmers

One of the significant limiting factors in implementing IPM is the lack of knowledge and awareness among farmers regarding the benefits and possibilities of this system. Especially in rural and less-developed areas, farmers often do not have access to systematic education or relevant expert information that would enable effective IPM application in practice. As a result, there remains a tendency to rely on conventional methods based on intensive pesticide use, which are perceived as simpler and faster solutions for pest control (Zheng and Xu, 2023). Moreover, even farmers familiar with the concept of IPM often face limited institutional and local support, as well as a shortage of experts who could provide adequate professional guidance in applying these measures. Such circumstances further complicate the adoption and broader implementation of IPM, particularly within smaller and less-developed agricultural communities.

### Economic Constraints

IPM offers significant long-term economic benefits, such as reduced costs for chemical pesticides and improved soil quality; however, the initial investments required for its implementation can be substantial. Procuring biological agents, introducing pest

monitoring technologies, and educating farmers about modern plant protection methods demand significant financial resources, which poses a particular challenge for small farms (Bajagić et al., 2023). Additionally, limited availability of financial incentives and subsidies for farmers implementing IPM further hinders its wider adoption. In many countries where IPM is not legally mandated, farmers often refrain from its use due to a lack of immediate economic benefits. This problem is particularly pronounced in developing countries, where institutional and financial support for agricultural innovations is often insufficient.

### **Limitations Due to Technical and Climatic Factors**

The implementation of IPM is often associated with substantial technical challenges, especially in regions characterized by unfavorable climatic conditions or significant fluctuations in pest populations. In areas with extremely high temperatures and increased humidity, such as tropical and subtropical zones, the effectiveness of biological measures can be limited due to accelerated insect reproduction or insufficient natural enemy populations. These conditions require the development and application of tailored strategies involving intensified monitoring and flexible adaptation of pest control methods (Bajagić and Ignjatović, 2025). Furthermore, many IPM measures depend on continuous monitoring of crop conditions, which represents an additional burden for farmers lacking access to modern technological solutions for tracking pest populations and climatic parameters. These factors can significantly reduce the accessibility and applicability of IPM for small-scale producers, as well as in remote and less-infrastructurally developed rural areas.

### **Limited Availability of Biological Agents**

Biological control is one of the core pillars of IPM; however, the availability of biological agents, such as natural predators or parasitoids, is often limited. In many regions, farmers do not have easy access to commercially available natural enemies of pests, which are essential for effective population management. The lack of these resources can increase reliance on chemical pesticides, reducing IPM's potential to provide sustainable pest control (Galli et al., 2024).

### **Limitations Due to Incomplete Legal and Regulatory Support**

Although many countries, including Serbia and EU member states, have legislative frameworks that encourage IPM adoption, regulatory challenges remain regarding the quality control of biological agents and the effectiveness of IPM measures. In certain countries, the regulatory system is underdeveloped, or adequate mechanisms to control the quality of biological products available on the market do not exist. The limitations of IPM are complex and include insufficient farmer education, high initial costs, technical challenges, and limited availability of biological agents. Overcoming these difficulties requires improving education, increasing access to financial incentives, and developing new technologies and methods that will enable wider and more effective implementation of IPM across diverse agro-ecological conditions.

## CONCLUSION

Integrated Pest Management represents a systematic, multidisciplinary, and environmentally responsible approach to crop protection, providing a balance between productivity, economic efficiency, and environmental conservation. Although its implementation requires a high level of expertise, continuous monitoring, and effective coordination, the benefits of IPM, including reduced reliance on chemical pesticides, preservation of biodiversity, and long-term sustainability, make it a critical component of modern agriculture, especially under the pressures of climate change. From a scientific perspective, future research should focus on the development of innovative IPM methods, incorporating digital technologies, precision agriculture, biological, and agroecological strategies, with the aim of optimizing effectiveness while minimizing ecological and economic costs.

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