Article

Climate change impacts on pest and beneficial insects: Challenges and management strategies for adaptation

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Abstract
Among the serious current global challenges, climate change significantly impinges on different organisms, including arthropods. Rising temperature, changing precipitation pattern and increasing levels of greenhouse gases that result in the expansion of insects' geographical distribution, increased survival, and generation rates, while the synchrony between plants and pests is disturbed. These alters are also associated with increased risk of invasive agricultural pests, increased prevalence of diseases by vector insects, and reduced effectiveness of biological control by natural enemies. Moreover, climate change enhances the invasive species risk through habitat alteration and reduction of biodiversity. Thus, all these climatic variables bring different outbreaks of certain pest species that cause critical economic damages in agriculture, influencing the reduction of safe food production globally. Adaptation to climate change means adopting strategies related to innovation mainly focused on integrated management approaches and using new monitoring technologies and prediction tools. The review will cover the impact of climate change on insect population and methods of its mitigation, contributing to sustainable food security.

Keywords climate change; pest; pollinators; natural enemies; disease vectors.

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1 Introduction

There is strong evidence that most of the world will see climate change in the form of warming, sea-level rise, heavy rainfall, and associated flooding and heat-stress-related damage (Lawrence et al., 2020). Climate change is defined as long-term changes in weather patterns due to human and non-human activities and is considered one of the most significant challenges that severely impact the global economy (Chandio et al., 2020). Climate change is a global phenomenon that takes place across the world, impacting ecosystems and species survival. The effects that it has on the organisms of an ecosystem are direct and indirect. Increased temperature, concentration of greenhouse gases, and changes in precipitation are major elements of climate change, according to Sattar et al. (2021). Ambient temperature, altered by these elements, further causes alterations in rainfall. Changes in precipitation may, for many areas, especially those where agricultural production is already much reduced by dry seasons, be even more critical than the rise in temperatures (Rafiei et al., 2023). The last few years have shown that the atmospheric temperature is rising at an unprecedented rate. According to a report by the WMO, the world is currently about one degree warmer than before industrialization. As can be seen, the last three decades have become increasingly warmer. According to the global climate models, Earth is projected to undergo a significant increase in temperature of about 1.4 to 5.8 degrees Celsius over the next century (Field et al., 2014). Global warming is mainly caused by the increase of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), by human activities like the burning of fossil fuel and a change in land use (Zhang and Liu, 2012). These gases have been increased very highly during the period of industrialization, with carbon dioxide being the major one (Filonchyk et al., 2024). By the end of the century, atmospheric carbon dioxide concentration is expected to rise between 550 and 1000 ppm, causing a global average temperature increase of 1 to 3.7 degrees Celsius. High latitudes and tropical areas will experience severe warming; similarly, there will be significant warming in Arctic regions (Ciais et al., 2013).

Arthropods are sensitive bioindicators of environmental change; they strongly respond to changes in temperature and precipitation that alter abundance, distribution, and life cycles. Understanding how climate change impacts arthropods is crucial for biodiversity conservation and evaluating broader ecological implications. According to Wallen (2024), climate change has a deep disruption to insect pest ecology, completely altering the biological aspects and geographical distribution. This environmental transformation has precipitated a significant escalation in pest-related agricultural challenges, causing substantial economic losses and critically threatening global food security (Subedi et al., 2023).

Climate change is affecting insect pests, natural enemies, and pollinating species that are essential for agriculture. The ability of such pests to rapidly colonize and reproduce in simplified agricultural systems and landscapes could result in even more severe attacks on key staple crops throughout the world. Many pests are becoming more frequent and severe under conditions of rising temperature, and climate change-related declines in crop productivity and performance may worsen the situation. However, information on the linkage between warming and pest intensity is conflicting; some key agricultural pest species are increasing in severity whereas others are declining. Other factors appear to be modifying dynamics as well, such as alterations in precipitation, frequency of weather extremes, and increases in anthropogenic atmospheric CO_2. Such complex drivers of change demand that the fit-for-purpose response of climate-smart integrated management of pests and pollinators be promoted (Eigenbrode and Adhikari, 2023; John et al., 2024).

Rising temperatures and altered precipitation patterns have not only expanded pest population ranges and reproductive cycles but also necessitated increased pesticide interventions. Consequently, these environmental shifts generate multifaceted challenges, including enhanced agricultural vulnerability, elevated chemical residue levels in food commodities, and potential ecosystem biodiversity disruption. The intricate interplay between climate change and insect pest dynamics demands comprehensive, interdisciplinary research and innovative agricultural strategies to mitigate potential long-term ecological and economic consequences. Integrated pest management, climate-resilient crop technologies, and sustainable agricultural practices emerge as crucial approaches to address these complex, interconnected challenges in the contemporary agricultural landscape (Yadav et al., 2024; Ma et al., 2021).

2 Materials and Methods

In this study, more than 200 related articles published in the databases Google Scholar, Taylor & Francis, Springer, Elsevier, PubMed, and John Wiley & Sons were reviewed for their titles and abstracts. Among them, 60 articles were selected and examined in the study of Climate change impacts on pest and beneficial insects. In this study, phrases such as climate change and insects, global warming and pest spread, climate change and biodiversity, climate change and pollinator insects, climate change and beneficial insects, climate change and the spread of disease-carrying insects, and climate change adaptation strategies were used in the databases. Finally, by comparing and categorizing the articles, the information related to the impact of climate change on insects was reviewed and extracted.

3 Results

3.1 The impact of increasing temperature on biology, ecology and physiology of insect

Temperature is one of the main determining variables in an ecosystem, responsible for the distribution of living organisms. Due to the physiological limitations of different species, changes in temperature affect their pattern of abundance. Similarly, it affects growth rate (Parmesan and Yohe, 2003). Pest insects show different reactions to climate change. Various studies have determined that as temperature continues to rise, insects may emerge earlier and prolong their life cycles (Subedi et al., 2023).

Increased temperature facilitates the entry and establishment of unwanted organisms including arthropods, pathogens, and weeds. This is sufficient to create an uncommonly warm and unusual winter in temperate climates that will allow the emergence of establishment of invasive pest insects. On top of that, international trade and transportation of agricultural products in recent years, along with rising temperatures, have resulted in very congenial conditions for the migration, invasion, and establishment of pests around the world. Most published studies indicate that, in general, the risk of pest invasions in ecosystems affected by climate change increases (Gulino et al., 2023: Rafiei et al., 2023).

Temperature is the most important environmental factor affecting insect population fluctuations. Global warming causes the geographical range of pests to expand, increases winter survival rates, increases the number of generations, raises the risk of invasion by non-native species, and facilitates the transmission of plant diseases by insects. These changes also impact the interactions between pests and host plants, as well as natural enemies (Skendžić et al., 2021).

Climate change is altering the distribution and phenology of herbivorous insects and their natural enemies. Rising temperatures have the potential to speed up the development rate of herbivores more than their predators or parasitoids, causing a non-synchronous relationship between the herbivore and natural enemy populations. The result could be unrestrained herbivore populations with greater outbreaks that are difficult to deal with from an agricultural viewpoint (Costaz et al., 2023; Boullis et al., 2015). Global warming disrupt biological control of the cereal leaf beetle due to a phenological mismatch between its natural predator and prey, weakening biological control efforts (Evans et al., 2013). In addition, rising temperatures alter the frequency, severity, and size of insect pests, such as outbreaks of bark beetles. Recent warming, for instance, has sped up development while reducing winter mortality of the mountain pine beetle, which allowed population numbers to explode during drought (Lantschner and Corley, 2023; Robbins, 2022).

Global warming will cause insects to expand their range and survive winters better, making corn crops more susceptible to pests such as hornworms and cotton bollworms. Higher temperature can lead to accelerated development of multivoltine insects, such as aphids. Temperature is considered the most significant abiotic factor governing development in insects since they are poikilothermic organisms (Hullé et al., 2010; Subedi et al., 2023). Aphids respond to an increased temperature by accelerating development, increasing reproduction, improving winter survival, modifying life cycles, modifying timing of migration, or changing population dynamics. The small generation time, high reproduction rate, and the nature of telescopic development in aphids make them a good model in experiments related to insect responses in climate change conditions (Dampc et al., 2021). Aphid species, with small body size and a rapid life cycle, may undergo significant changes in their migration patterns driven by increasing temperatures, thus causing sudden fires and great losses in agriculture and forestry (Radwan et al., 2024). The Armyworms develop quickly when the temperatures are at average of 29°C and slower when temperatures are well below this temperature. A mean temperature above 10°C will be conducive for voracious feeding on plant leaves and stem by the armyworm. For insects, a rise of temperature by 2°C can result in one to five additional life cycles in a season. A rise in temperature surface may significantly influence the start and end of diapauses, and therefore voltinism will shift. Changes in diapause requirements due to climate change can affect some insect species if the probability of meeting the requirements is lower (Adunola et al., 2020). In studies on the influence of climate change on the population dynamics of *Helicoverpa armigera*, the cotton bollworm, research illustrates that increased temperature has brought a considerable change in population dynamics. It is noted in long-term studies that global warming advances the emergence of diapausing pupae and prolongs the active period for adults, improving larval recruitment in the first generation and leading to more pronounced damage against the early growth stages of wheat. The rise in temperature and crop growth rate is asynchronous, which could result in more serious crop yield losses in the future (Ouyang et al., 2016).

Higher temperatures accelerate the biological development of the vector-borne disease species like mosquitoes and ticks. For example, a warmer climate reduces the developmental cycle of mosquitoes, such as *Anopheles* spp. and *Aedes* spp., increasing reproduction rates and leading to more abundant vectors. This consequently enhances the transmission potential of diseases such as malaria, dengue fever, and chikungunya. Higher temperatures allow the vectors to expand their geographical area to those that have previously been unsuitable due to temperature reasons and reach higher altitudes and latitudes (Paz, 2024; Kumar et al., 2024).

Changes in climatic indices that may affect immune system and detoxifying enzymes will eventually lead to resistance against bio-agents and result in increasing damage (Skendžić et al., 2021; Rafiei et al., 2018). For instance, it is indicated by Mozdahi et al. (2022), that climatic changes, particularly temperature, have an impact on the activity and oviposition of the olive fruit fly. Climate change affects the enzyme activity of insects through complex mechanisms driven by temperature. With an increase in environmental temperature, insect enzymes undergo prominent metabolic changes, including increased reaction rates, improved catalytic efficiency, and adaptive alterations in proteins. These enzymatic responses involve multiple biochemical pathways, including metabolic, stress response, and detoxification enzymes (Francis et al., 2005; Krishnan et al., 2006; Chrzanowski et al., 2012; Rafiei et al., 2016). These physiological adaptations enable insects to maintain cellular functionality in an altered climate, which may also alter their geographical distribution, reproductive strategy, and ecological interactions. Important enzymatic alterations include an increase in antioxidant production, the speed of biochemical processing, and cellular protection mechanisms. While such adaptations do reveal impressive evolutionary plasticity, they also outline complex and perhaps not very foreseeable consequences of global climate change for insect physiology and ecosystem dynamics (Dampc et al., 2020; Chown and Terblanche, 2006).

3.2 The role of change in rainfall patterns on insect’s population

Since the mid-20th century, significant changes in weather events have been observed. Increased heavy rainfall in multiple regions and the occurrence of droughts in other areas are among these changes. In higher latitudes and the Pacific Ocean, the average annual rainfall has increased. In the land areas of the mid-latitudes and subtropics, the average precipitation has decreased, while in the humid regions of the mid-latitudes, there is a possibility of increased average precipitation. Frequent heavy rainfall has been observed in most mid-latitude and humid tropical regions (Field et al., 2014).

Changes in frequency, amount, and intensity of precipitation are good indicators of the shift in climate. In many instances, it has manifested as a decrease in frequency and an increase in intensity of precipitation. This pattern, involving scanty rainfall, has increased the frequency of both floods and droughts. Simultaneous precipitation directly influences the overwintering insects on soil. Basically, the flooding and long stagnation of water due to heavy rain affect insect survival and eventually alter their overwintering periods. Heavy rain and flooding can wash away eggs and larvae of insects. Heavy rains also wash away small insects such as aphids, mites, jassids, and whiteflies. (Shrestha, 2019; John et al., 2024).

Rainfall directly influences the insect's population by dislodging eggs and larvae from host plants, disrupting feeding and development, and increasing mortality rates, particularly in early larval stages. The nutritional quality of the host plants affects larval development time, fecundity, and adult longevity. Studies have shown that changes in rainfall under climate change may differentially affect insect herbivores and, as a result, disrupt trophic interactions, leading to the destabilization of ecosystems through altered dynamics of food webs and species interactions. *Plutella xylostella*, the diamondback moth, is an important pest of cruciferous crops worldwide and is capable of causing in excess of 90% crop losses during severe infestations. Survival, development, and reproduction of *P. xylostella* are affected by rainfall (Chen et al., 2019).

Rainfall changes will significantly affect the abundance and diversity of pest insects and natural enemies. In the event of severe drought, the ecosystem composition (environment and organisms) will change. Habitats will be reduced to smaller units due to drought, and their area will decrease. Such changes can have a significant impact on the species composition of an area. Considering climate change, the current extinction rate will be 100 to 1000 times higher than what has occurred previously, with nearly 45 to 275 species at risk of extinction daily (Subedi et al., 2023). Studies on leaf and root-feeding insect species show that with increased rainfall, the abundance of these pests increases. On the other hand, during drought, the sensitivity of host plants increases, while the activity and abundance of natural enemies often decrease, resulting in increased damage to agricultural products (War et al., 2016; Lahlali et al., 2024).

3.3 Increase in greenhouse gases

Climate change will be a factor affecting the insect pheromonal communication in an outstanding way, considering it as a basic mechanism for survival (Alarm pheromone), reproduction (Sex pheromone), and ecological interactions (Semiochemicals). Increased temperature, associated with increased levels of atmospheric CO_2 and O_3, can disturb the processes of production, release, and perception of pheromones in insects. Species dependent on long-range chemical signals are particularly vulnerable because such signals may deteriorate during dispersal due to oxidative stress caused by increased levels of ozone. The potentially compromised behaviors would involve mating, alarm signaling, and foraging, each with cascading consequences to population dynamics and ecosystems (Boullis et al., 2016). Increased CO_2 levels may interfere with neurological processing (the enzymatic activity of acetylcholinesterase) in insects such as aphids, thus decreasing their capability for alarm pheromone responses and weakening their defense mechanisms. These disruptions in behavior may weaken intra- and interspecific interactions crucial for maintaining ecological balance (Sun et al., 2010; Boullis, 2018; Roggatz et al., 2022).

Altered atmospheric composition directly impact the physiological and biochemical pathways of pheromone synthesis and response. Increasing CO_2 concentrations may also affect the production of insect pheromones. Changes in CO_2 concentrations affect plant biochemistry in a number of ways, including the formation of secondary metabolites. As some phytophagous insects utilize precursors from their host plant in the synthesis of their pheromone components, these insects have been speculated to be amongst the most sensitive to altered atmospheric CO_2 concentrations due to the cascade effects of CO_2 on plant chemistry (Bidart-Bouzat et al., 2008; Boullis et al., 2015). The sex pheromones in moths of the genus *Holomelina* spp. are synthesized using leucine as the precursor. While the mevalonate pathway is the major source of de novo pheromone production in bark beetles, some of the aggregation pheromone components are produced through hydroxylation of secondary metabolites received from the host trees (Boullis et al., 2016; Blomquist et al., 2010).

The increase in the concentrations of greenhouses gases, especially CO_2, significantly influences plant growth and, indirectly, interactions between herbivorous insects and their natural enemies. Elevated levels of CO_2 raise the rate of photosynthesis, ultimately increasing plant biomass and productivity. This increased plant growth has the potential to support larger population sizes of herbivorous insects that can develop faster, have higher reproduction rates, and overall larger populations. Thus, herbivorous pests can accordingly benefit more from nutritional improvement and food supply under these conditions (Boullis et al., 2015; Lindroth et al., 2010; Skendžić et al., 2021). This contribution might well lead to an imbalance in tritrophic interactions: while herbivores will have advantages from resource abundance, their enemies, predators, and parasitoids may not benefit from these advantages. Such disparity-the rapid population growth of herbivores being met with the sluggish response of their natural enemies-foments the weakened role of such biocontrol agents. Taken in tandem with rising temperatures, which also accelerates the development of herbivores but sometimes may hamper the efficacy of the natural enemies, it is only conducive to an outbreak (Chen et al., 2005; Walker and Jones 2001).

3.4 Strategies to mitigate the adverse effects of climate change

Climate change enormously influences biodiversity. As was mentioned, studies on the plant pest insects demonstrate clearly that this organism is highly adaptable towards changing and altering environmental circumstances and, therefore, can successfully outlive when living under quite adverse life conditions. Under such circumstances, insects rapidly colonize suitable habitats and new territories in agricultural ecosystems and are able to build up their abundance and geographical distribution. Such characteristics make them superior over other species and increasing economic damage of pests (Skendžić et al., 2021; Leddin, 2024).

The control of insect pest populations, in view of changing climate, requires modern methodologies of monitoring. The new approaches to monitoring involve methods using molecular techniques that provide an exact identification, such as DNA barcoding. Further, the application of Geographic Information Systems (GIS) enhances the understanding of the distribution pattern and dynamics of pests, which enables the formulation of management strategies responsive to changes in environmental conditions. Integration of new methods of monitoring pest facilitates early detection and assessment of population density for effective management at an economic level (Yadav et al., 2017; Deleon et al., 20017). The black soldier fly, can recycle organic waste into high-quality protein and organic fertilizer, thus playing a dual role in food security and soil health. Insect farming requires much lower inputs, such as land and water, compared to traditional livestock, making it an environmentally friendly alternative. Insect consumption could be vital for making food systems more sustainable and resilient with a minimum impact on the environment (Sokame et al., 2024).

Climate change increased the prevalence of pests, thus leading to higher consumption of pesticides. On the other hand, high humidity and temperature result in the degradation and breaking down of pesticides, whereas high temperatures cause their quick evaporation, resulting in less concentration of pesticides in the environment. Increased rainfalls involve the loss of pesticides and a loss in their effectiveness. Hence, with respect to climate change, the risk for pesticide residues in agricultural products is increased, putting consumers at risk. For all these risks, the introduction of new and biopesticides in integrated pest management can minimize all these hazardous impacts (Delcour et al., 2015; Rafiei and Bastan, 2022; Rafiei and Kioumarsi, 2024).

One of the important issues related to climate change is the threat to food security. The decline in the availability of food, especially protein, makes its appearance among individuals within society. The increase in insect population can serve as an opportunity towards adaptation to climate change. Insects will reduce the challenge of producing healthy food and animal feed consumption. Insects are also composed highly of protein, between 37-63%, and fat at 20-40%, are good sources of amino acids, fatty acids, minerals, and vitamins (Chai et al., 2019). Insect production, on the other hand, tends to have less impact on the ecosystem because of its limited environmental requirements, thus requiring less land and water and using less in the way of resources for its production. The end result of these factors, therefore, is a reduction in the emission of greenhouse gases and carbon dioxide (Dicke et al., 2018).

The contribution of livestock is a direct source of green house gases, accounting for about 9 percent of total carbon dioxide emissions (excluding respiration), 37 percent of methane, and 65 percent of nitrous oxide. The overall contribution of livestock to climate change is around 18 percent. Insects emit a negligible amount of GHGs. In one study, the cost-benefit analysis of five edible insects was made considering greenhouse gas production as an environmental cost and food production as a benefit. Rearing of four insect species namely, *Tenebrio molitor*, *Blaptica dubia*, *Acheta domesticus*, and *Locusta migratoria* produced lower amount of green house gases than pigs and ruminants per kg weight gain. Also, the ammonia level in insect farming is less than that in normal livestock. Low water requirement, ability to be cultivated in streams and capability of growing in warm climate will help assure their production in extreme climates (Oninex et al., 2010; Shi et al., 2022).

Methane, produced mainly by agricultural activities such as cattle raising and rice growing, is another potent greenhouse gas contributing heavily to climate change (Nunes, 2023). Insect farming, with its easy and low-cost rearing techniques, and the possibility of breeding on organic waste, could become an important means in combating food insecurity. Insect farming does not need direct contact with the ground and can take place in places already used earlier. Land use is, therefore, reduced and even contributes to the restoration of ecosystems if insects are considered as an alternative for conventional livestock. Besides being a food source, insects can also be applied as feed in animal production. Within livestock farming, the feed supply chain is one of the most important environmental chains. A reduction in the production of plants like soy and corn for feed contributes to better biodiversity and reduces desertification. Insect farming can help contribute to the sustainability of marine resources. Aquatic farmed insects have the potential to reduce overfishing by either fully or partially replacing fishmeal and fish oil in animal feed. Indeed, a large part of the aquaculture is presently carried out to provide feed and has an enormous environmental burden. Insect farming may thus help reduce directly or indirectly adverse effects (Morazzo et al., 2021; Huis and Oonincx, 2017).

Mitigation and adaptation are two strategies to lessen the effects of climate change. By restricting human activities and greenhouse gas emissions, mitigation works to reduce long-term global warming. Reforestation increases carbon sink capacity (Mavhura et al., 2017).

Carbon sequestration in agricultural lands reduces the concentration of greenhouse gases by improving crop residue management, conserving tillage methods, establishing vegetation cover, reducing tillage operations, using marginal lands for forest development, and reducing crop rotation (Morgan et al., 2010).

Climate change largely affects biodiversity. From the study of plant pest insects, it shows that organisms highly capable of adapting to the change in environmental conditions, hence the ability to survive under unfavorable conditions. Under such circumstances, insects rapidly colonize suitable habitats and new territories in agricultural ecosystems and are able to build up their abundance and geographical distribution. Such characteristics make them superior over other species. Studies have shown that one of the ways to mitigate the effects of climate change is nature-based agriculture. Nature-based agriculture aims at the protection of food security, biodiversity, and the environment. Its types include ecological, organic, and biodynamic agriculture. The production of food without harming resources is the aim, hence contributing to sustainable agriculture. Nature-based agriculture has the potential to reduce greenhouse gas emissions, improve soil health, and absorb carbon dioxide through practices such as organic fertilizers and crop rotation (Rafiei et al., 2023; Çakmakçı et al., 2023). Nature-based agriculture can reduce greenhouse gas emissions by preventing the conversion of forest lands and reducing fossil fuel consumption by about 30 to 70 percent, increasing soil fertility through the use of organic fertilizers, planting legumes, crop rotation, reducing summer fallow, and conservation tillage, as well as through the absorption of carbon dioxide by soil and plants (Sarabian and Nikpour, 2009).

New principles of agricultural pest management not only adjust the timing of crop planting with climate change; they sometimes change cropping systems. Overall, the use of new crops that are more suitable for new conditions (considering markets) leads to resilience against climate changes. These changes, in turn, require a set of strategies in pest control to achieve sustainable crops under climate changes (Ilk and Abajo, 2020).

4 Discussion

Climate change, characterized by rising temperatures, enhanced atmospheric CO_2 concentrations, and changing precipitation, has a large impact on insect. Such climatic changes facilitate the expansion of geographic distributions of pest species, improve their overwintering survival, and allow more generations to be completed in a year. Moreover, climate change disturbs the synchrony between plants and pests and changes interspecific interactions among insects. This could, in turn, increase the likelihood of migratory invasive pest species and a greater prevalence of insect-borne plant diseases. Agricultural systems will, therefore, be more vulnerable to economic losses due to reduced crop yields and food security for human populations. For successful adaptation to these detrimental effects, adaptive management strategies need to be devised. It includes the refinement of integrated pest management (IPM) practices based on the changing environmental conditions (Zhang, 2025). Additionally, thorough monitoring of climate trends and pest populations is a key component for the timely detection and response to changes in pest populations. Predictive modeling tools are used to forecast future pest dynamics under various climate scenarios. By utilizing all these approaches in crop management practices in every part of the world, some of the negative effects attributable to climate-induced changes in insect pest populations can be mitigated. These challenges require an approach that involves incorporation of scientific research into practical implementation across diverse agricultural settings around the world. Collaboration among researchers, scientists, policy makers, and farmers in developing robust solutions that can help address evolving threats by climate-driven shifts within insect populations, while assuring sustainable food production systems resilient against future environmental uncertainties.

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