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Understanding the physiological effects of climate change on agricultural pests

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ABSTRACT

The increase in global average surface temperatures due to anthropogenic activities and the resulting climate change affects ecosystems in various ways. Melting glaciers and rising sea levels, loss of biodiversity, increasing intensity and frequency of floods and storms, drought in some parts of the world, the inability to sustain agricultural activities, and the threat to food security have become multi-faceted and very difficult to solve. Climate change affects all living organisms and has negative effects on agricultural pests. Insects respond to temperature increases by expanding their geographical distribution, increasing their voltinism and changes in their phenology. Climate change may affect the interactions of insect species with other species at higher and lower trophic levels. These climate-induced impacts are highly complex and variable, sometimes increasing pest pressure or reducing pollination. The effects of climate change are already being seriously observed today, and these effects are expected to become even more severe in the coming years. With many climate projections, it is already possible to predict a number of negative scenarios that could happen in the future due to rising global temperatures. Despite growing efforts to combat the impacts of climate change through adaptation and mitigation strategies, scientists emphasise that humanity is only at the beginning of a long and complex journey. This study highlights the potential impacts of climate change on insect physiology. Selected studies on climate change and its effects on agricultural pests in recent years are brought together to present possible future scenarios.

Keywords: climate crisis, harmful insects, CO_2, biodiversity, temperature

INTRODUCTION

The World Meteorological Organisation (WMO) reported in its State of the Global Climate 2023 report that global average temperatures by the end of October 2023 were approximately 1.4 degrees above the pre-industrial period (1850-1900) average (WMO, 2023). According to a statement made on June 5, 2024, it was reported that there is an 80% probability that these temperatures will temporarily exceed 1.5 °C for at least one year between 2024 and 2028 (WMO, 2024). This report highlighted that short-term warming does not mean a permanent breach of the Paris Agreement's 1.5 °C target, that the next five years are likely to be the hottest on record, with at least one of them surpassing 2023, and that climate action plans must be implemented urgently (MGM, 2024). The report also stated that this year, Antarctic sea ice reached its lowest winter maximum recorded and that Swiss glaciers have lost around 10% of their remaining volume in the last two years. It has also been reported that Canada has seen record wildfires, with the burned area accounting for approximately 5% of the country's forested area. 2024 is set to be the warmest year on record (WMO, 2024).

The increasing global surface temperatures first cause fluctuations in the hydrological cycle and cause disruptions in the material cycle. It increases the intensity and frequency of events such as floods, storms, droughts, frosts and seasonal changes in precipitation. Accordingly, the effects of climate change appear in many ways, such as changing sea levels, disruption of agricultural and forestry activities, a decrease in biodiversity, and negative effects on organisms and human health. In addition, it is among the scenarios that societies with weak economic power will be affected by climate change and that there will be mass migrations due to climate change in the next century (Battisti and Larsson, 2023; Harvey et al., 2023; Mahanta et al., 2023; Razzaq et al., 2024).

With the development of technology after the industrial revolution, human life has been extended, human welfare and world population have increased very rapidly. As a result of all these, ecological events that we will encounter more frequently in the coming years, damage to agriculture and food security will affect wider masses (Türkeş, 2020). Today, 75% of the world's poor population lives in rural areas. In developing countries, 2.5 billion people earn their living from agriculture (IFPRI, 2024). Therefore, agriculture and food security are important. Changes in climate affect all living organisms. According to the Living Planet Report of WWF (2022), 68% of the average population of vertebrates such as birds, fish, reptiles, mammals and amphibians has disappeared since the 1970s, and 40% of insects have disappeared since 1998. The main reason for these extinctions is human activities. Many species are facing the threat of extinction due to human-induced habitat destruction, uncontrollable pesticide use in the agricultural sector, and pressure from changes in climate (Dattilo and Gonzalez-Tokman, 2024; Wiens and Zelinka, 2024). However, it is also known that instead of extinct animals, surviving creatures will migrate to new distribution areas with the adaptations they have developed. Especially the insect class will search for regions where there will be optimum conditions for them due to milder winters and will move towards more northern regions according to climate scenarios (IPCC, 2024). Among these insects, there will also be harmful insects. It is estimated that insects will migrate and harmful insects will expand their distribution areas due to climate change in the next century (Rodriguez-Casteneda and Hof, 2024). Despite all this, there is limited information on how this will happen and what precautions can be taken in this regard. In this study, the effects of global climate change on agricultural pests and their physiology are emphasised, and possible future scenarios are presented.

INCREASE IN GLOBAL SURFACE TEMPERATURE AVERAGES AND ITS EFFECTS ON INSECT PHYSIOLOGY

Three temperature zones are defined for insects. The first is the Optimum Zone, where development and reproduction occur at maximum levels. The second is the Suboptimum Zone, where the organism can complete its life cycle, but its biological activities are lower, below or above the optimum zone. The third is the Lethal Zone, which causes the death of the living being and is below or above the temperature values in the suboptimal zone (Fields, 1992). Figure 1 shows how optimum, suboptimal and lethal zone temperature values affect insects.

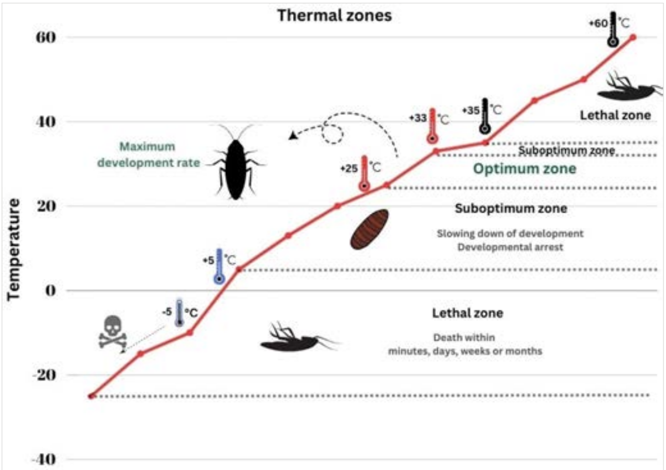

Figure 1. Optimum, suboptimum and lethal zone temperature (°C) values and their effects on insects (the figure was drawn by Evrim Sönmez)

It shows a steady development specific to many insect species at the optimum temperature. However, changes in winter temperatures, in particular, affect the insect's physiology, metabolism, reproductive capacity, feeding habits and, consequently, its distribution. In general, increasing temperatures accelerate the egg-laying rate, egg number and larval development stages of insects and shorten the adult life (Harvey et al., 2023; Rohner, 2024).

Today, increasing temperatures and the climate crisis are caused by greenhouse gases released into the atmosphere as a result of industrial and agricultural practices. 20% of the greenhouse gases released into the atmosphere after the industrial revolution are due to agricultural activities (Nihal, 2020). The use of synthetic fertilisers, overgrazing, excessive use of pesticides, excessive water use and energy consumption in agriculture release more and more of these gases into the atmosphere each year (Jacoby et al., 2024). Due to the greenhouse effect, global surface temperature averages increase each year, which causes us to face the climate crisis we are experiencing today. With the climate crisis, it is expected that certain parts of the world will be warmer and drier in the future, while it will be rainier in certain regions, and storms and floods will be more frequent and severe (Adler et al., 2022). Organisms can tolerate temperature increases by changing their metabolic activities, regulating their body temperature, or changing their microhabitat, although this varies depending on the species (Gonzalez-Tokman and Villada-Bedaya, 2024). Insects can exhibit physiological adaptations to increasing environmental temperatures depending on the species, including adjustments in metabolic activity, thermoregulation, and shifts in microhabitat preference (Nihal, 2020). Deviations from optimal temperature ranges can significantly influence insect metabolism, reproductive strategies, and feeding behaviours, thereby affecting population dynamics and geographic distribution. Within their thermal tolerance limits, rising temperatures generally lead to increased oviposition rates and egg production, accelerated larval development, and reduced adult lifespan. These physiological responses may, in turn, facilitate the expansion of insect species into previously uninhabited regions (Bhagarathi and Maharaj, 2023; Fu et al., 2024).

Generally, two types of behaviours are observed in insects depending on the temperature change. First, as the temperature increases, the biological response of the insect increases and this situation continues until the death limit. Second, up to a certain point, the increase in temperature increases the biological response of the insect, and then this response decreases (Eigenbrode and Adhikari, 2023; John et al., 2024). It is suggested that extreme fluctuations in temperature that may occur due to the climate crisis may change the distribution characteristics and migration routes of insects, which will bring about many pest control problems (Subedi et al., 2023). A warmer and wetter world is expected to have many direct and indirect effects on insects, their natural enemies and plants. In South Africa, an outbreak of the fall armyworm (*Spodoptera frugiperda*, JE Smith, 1797) (Lepidoptera: Noctudae) occurred in 2019 due to increased temperatures and rainfall. It was observed that when temperatures exceed 20 °C, several physiological parameters of the fall armyworm exhibit significant enhancement, reaching peak physiological activity at 32 °C. Elevated temperatures lead to a marked reduction in the duration of each developmental stage, while both the fecundity and oviposition period of female's increase. This acceleration in development results in a shortened pupal stage, ultimately contributing to an extended adult lifespan (Paredes-Sánchez et al., 2021; Fu et al., 2024). In addition, an epidemic of desert locusts (*Schistocerca gregaria*, Forsskål, 1775) (Orthoptera: Acrididae) started in East Africa (Eritrea, Somalia and Yemen) in 2019-2020, and excessive rainfall and humidity increased the reproduction, population and size of locusts, causing damage to a very large agricultural area (Ibrahim, 2024). These and similar examples give us clues about the harsher environmental conditions and food problems that will occur in the future. Rising temperatures and excessive rainfall due to the climate crisis also support the growth of vegetation that will feed the harmful insect population.

The temperature increase in ecosystems due to climate change leads to an increase in the survival rate of insects, a shortening of their developmental period due to the acceleration of their physiology, an improvement in their reproductive and adaptation abilities, an increase in voltinism, and a change in their migration behavior (Özpınar, 2023).

EXPLORING THE IMPACT OF RISING GLOBAL TEMPERATURES ON AGRICULTURAL PESTS: A SYNTHESIS OF RECENT FINDINGS AND FUTURE PROJECTIONS

Changes in insect mobility and migration dynamics affect agricultural production figures and cause major economic losses worldwide. It is expected that every additional 1 °C increase in temperature will cause the loss of 10-25% of agricultural products due to crop pests (Subedi et al., 2023; Del-Claro et al., 2024). Increasing global surface temperature averages due to climate change cause harmful insects to spread to higher latitudes and altitudes. The European corn borer (*Ostrinia nubilalis* Hübner, 1796) (Lepidoptera: Crambidae), spotted wing drosophila (*Drosophila suzukii*, Matsumura, 1931) (Diptera: Drosophilidae), and the Colorado potato beetle (*Leptinotarsa decemlineata* Say, 1824) (Coleoptera: Chrysomelidae) are likely to increase their range in many parts of Europe, colonise higher altitudes, and increase their annual generation numbers as a result of projected temperature increases (Kocmánková et al., 2011; Sario et al., 2023). Rising average temperatures, along with increasing atmospheric carbon dioxide (CO_2) concentrations, have been shown to positively influence the development and reproduction of many insect species, leading to higher pest populations in both agricultural and forest ecosystems. Moreover, elevated CO_2 levels can weaken the defense mechanisms of certain plant species, thereby creating a more favourable feeding environment for herbivorous pests. In addition, climate change-induced increases in wind intensity and severe storms can facilitate the long-distance dispersal of fungal pathogen spores through the atmosphere. This not only elevates the risk of disease outbreaks beyond local scales but also complicates disease management by enabling the emergence of plant pathogens in previously unaffected regions (Ainsworth and Long, 2021; Dixon, 2024).

On the other hand, rising global average temperatures, especially in temperate regions or in the already hot tropics, may cause some insect species to develop adaptations to survive at temperatures close to the lethal limit (Harvey et al., 2023; Nasution, 2023). The effects of climate change on pest species and the adaptations they develop are quite complex, so researchers should be very careful when generalising research results (Juroszek et al., 2020; Skendžić et al., 2021).

Increases in global average temperatures may cause three types of changes in insects (Figure 2) (Yasin et al., 2023; Boggs, 2024; Del-Claro et al., 2024; Rohner, 2024).

1. Expansion or retreat of geographical distribution areas or increased risk of pests entering the environment,
2. Changes in seasonal phenology resulting from earlier activation times in spring, disrupting the pest life cycle and natural predator/parasitoid synchrony,
3. Changes in population dynamics, which occur in the form of increased overwintering/diapause and survival rates, increased population growth rates, and increased number of generations.

Trophic dislocation: climate change-induced phenological asynchronies

Trophic dislocation refers to a phenological asynchrony that arises when organisms at different trophic levels within an ecosystem respond differently to environmental changes, particularly those driven by climate change. This mismatch can lead to significant ecological consequences, such as reduced food availability for insect or bird offspring, population declines, disruptions in food webs, and weakened ecosystem functioning. Trophic dislocation tends to have pronounced effects in seasonally synchronised systems, such as those between birds and insects, pollinators and flowering plants, or herbivores and grassland species (Aguila et al., 2021). Climate change, especially through rising temperatures and shifts in seasonal patterns, is altering the phenological timing of species in ecosystems. However, these changes do not occur uniformly across all species in terms of rate or direction. This discrepancy is particularly evident in the case of trophic mismatches observed between birds and insects. Many bird species have evolved to time their breeding periods to coincide with the peak abundance of insect populations, ensuring sufficient food supply for their chicks. Yet, under changing climate conditions, some insect species are now developing and reproducing earlier in the season, while migratory birds often maintain traditional patterns of arrival and reproduction. As a result, bird chicks may hatch after the peak availability of insect prey, leading to reduced breeding success and, over time, potential population declines. Similarly, trophic dislocations can also occur between parasitic or predatory insects and their hosts or prey. Such temporal mismatches may destabilise ecological balances, resulting in population explosions of some species and declines in others. Trophic dislocation is the disruption of synchrony between the activities of species at two or more interacting trophic levels (Taylor et al., 2018; Luna and Dattilo, 2024). As an example, the relationship between the winter moth (*Operophtera brumata* Linnaeus, 1758) (Lepidoptera: Geometridae), oak tree (*Quercus* spp.) and the great tit (*Parus major* L. 1758) bird can be given. Winter moth larvae feed on oak leaves and cause damage to the tree. Great tit larvae are also predators of the winter moth and feed on its larvae as well. Due to warmer winters, winter moth larvae emerged before the breeding season of great tits. The resulting loss of synchrony between species resulted in reduced chick size, weight and flight success in great tits (Buse et al., 1999). During the autumn and winter transition periods, it has been reported that warmer winter temperatures cause asynchronous shifts between two aphid species, *Drepanosiphum platanoidis* (Schrank, 1801) (Hemiptera: Aphididae) and *Periphyllus testudinaceus* (Fernie, 1852) (Hemiptera: Aphididae), and their associated braconid parasitoid wasps (Hymenoptera: Braconidae) (Senior et al., 2020). Similarly, it has been reported that favourable warm winters have extended the activity period of the parasitoid *Aphidius avenae* (Haliday, 1834) (Hymenoptera: Braconidae), making them more vulnerable to unpredictable cold events during winter (Alford et al., 2020). In addition, significant emergence mismatches have been observed between the braconid wasp genus Alabagrus (Braconidae) and the fern moths, as a result of rapid temperature increases (Morse, 2021).

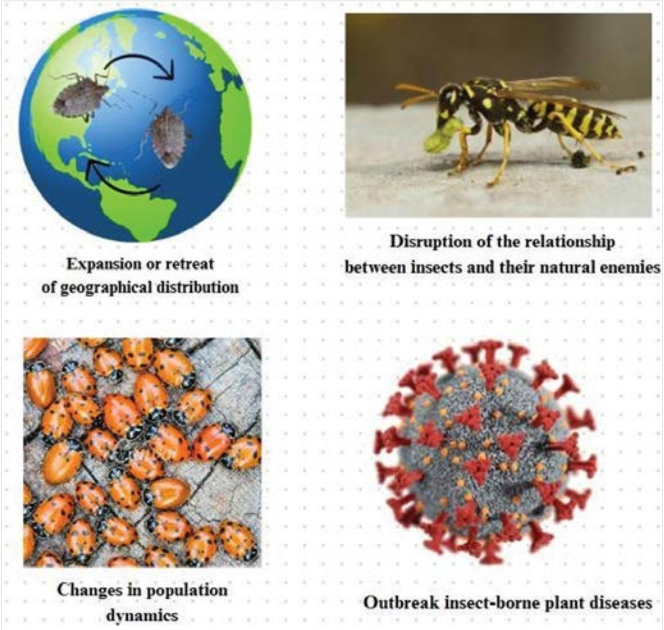

Figure 2. Effects of increasing global surface temperature on insects (the figure was drawn by Evrim Sönmez)

Climate-driven shifts in pest insect phenology, distribution, and vector-borne disease dynamics

Insects play a leading role in the transmission of many diseases, including bacteria, viruses, and phytoplasmas. These diseases are estimated to cause economic losses of more than $30 billion annually. The majority of viruses that cause disease in agricultural crops are single-stranded DNA viruses and messenger RNA viruses. The primary host-to-host transmission technique is usually sucking and puncturing, and insect vectors with mouthparts are effective in spreading these diseases. Climate change is increasing the frequency of insect-borne plant diseases due to the expansion of insect ranges and the increase in the number of insect vectors. The order Hemiptera feeds by sucking the sap of plants and is the primary vector of viral infections (Nassution, 2023). It includes the families Aphids (Aphididae), Leafhoppers (Cicadellidae), and Whiteflies (Aleyrodidae). Aphids are the largest group of vectors mentioned above, transmitting over 275 different types of viruses. Climate change may increase the prevalence of insect-borne plant diseases due to the expansion of habitats and the rapid reproduction of insect vectors. In Northern Europe, it has been found that the frequency of viral diseases in potatoes, especially in the early season, is increased due to early colonisation by virus-carrying aphids. Many insect species have developed many adaptations to environmental conditions. However, some species are very sensitive to temperature changes due to their physiology and metabolism (Juroszek et al., 2020; Meuti et al., 2024). Warmer, drier conditions increase the risk of insect pests, while warmer, more humid conditions increase the risk of pathogens (Dixon, 2024). For example, plant viruses and their insect vectors may be particularly affected by higher temperatures until upper temperature thresholds are reached (Trebicki, 2020; Gonzalez-Rete et al., 2024). Reynaud et al. (2009) reported that the incidence of maize streak disease caused by maize streak virus and the abundance of its vector, the aphid (*Cicadulina mbila* Naudé 1924) (Hemiptera: Cicadellidae), are closely related to temperature in tropical climate conditions. They showed that populations of both species increase rapidly above 24 °C, but temperatures of 30 °C and above may be detrimental to aphids and viruses (Juroszek and vonTiedemann, 2013). Therefore, while climate change is expected to increase the population of these pests within a certain temperature range, our knowledge about the upper temperatures is limited. Warmer average air temperatures in early spring, especially in temperate climates, may cause host plant life cycle stages to occur earlier in the season (Ali et al., 2024).

Many insect species living in temperate regions must undergo a period of diapause to complete their life cycle and survive the low temperatures of winter. Climate change, particularly the rise in average temperatures observed during spring in temperate regions, has led to shifts in plant phenology. This results in the earlier onset of key developmental stages in host plants, such as budburst, flowering, and leaf emergence. These phenological shifts, which affect both agricultural productivity and the structure of natural ecosystems, also directly influence the life cycles of phytophagous insect species that depend on these plants. Many insect species in temperate climates undergo a period of diapause to survive adverse environmental conditions, especially the low temperatures of winter. Diapause is a complex physiological state regulated by environmental cues such as photoperiod, temperature, and humidity, as well as the phenological status of the host plant. However, changes in temperature regimes due to climate change can disrupt the timing of diapause initiation or termination, reducing the ability of these organisms to synchronise with their environment. For instance, if plant development begins earlier in the season, insects in diapause may miss the optimal phenological stage of the host plant upon reactivation. This mismatch can result in reduced food availability, lower survival rates, and decreased reproductive success. In summary, climate change poses significant risks to insect pest populations and agricultural systems not only through direct temperature increases, but also by inducing phenological mismatches in plant–insect interactions.

While some of the existing insect species on earth are disappearing due to climate change and increasing average temperatures, some of them are changing their habitats and migrating to agricultural areas where they were not harmed before. Due to increasing temperatures and mild winters, the stink bug *Nezara viridula* (Linnaeus, 1758) (Hemiptera: Pentatomidae), which started to live in England, and the tomato moth *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae), one of the most important tomato pests of today, have expanded their distribution areas (Yaşar et al., 2021). *Helicoverpa zea* (Boddie, 1850) (Lepidoptera: Noctuidae), a major agricultural pest in North America, has recently been expanding its overwintering range further north due to rising soil temperatures during winter. This trend indicates the potential for this pest to exert pressure over a broader geographic area in the future. In a modelling study based on 40 years of soil temperature data, Lawton et al. (2022) projected that populations of *H. zea* would continue to expand in regions experiencing milder winters. The study emphasised that reduced winter mortality allows the species to overwinter successfully at higher latitudes. These findings strongly support the notion that a shift in winter mortality thresholds may enable *H. zea* to damage crops throughout the winter, maintain generational continuity, and pose a year-round threat to agricultural production. Outhwaite et al. (2022) found that insect abundance decreased by 7% and species richness decreased by 5% in natural habitats, especially in tropical regions. In areas that have lost their naturalness, such as agricultural areas, these decreases were 63% and 61%, respectively. Giant water bugs play an important role as top predators in wetland ecosystems by helping to control freshwater snails and mosquitoes. A study attempted to predict how climate change might affect the distribution of two Korean species of giant water bugs [*Appasus japonicus* Vuillefroy, 1864 (Hemiptera: Belostomatidae) and *Diplonychus esakii* Miyamoto and Lee, 1966 (Hemiptera: Belostomatidae)]. As a result of the projections, it was determined that *A. japonicus* could lose its habitat and move north, while *D. esakii* could expand its distribution area (Kim et al., 2024). Due to increasing average temperatures, optimum conditions for the Colorado potato beetle (*L. decemlineata*) (Wang et al., 2017) and nine other pest species [bean leaf beetle (*Ceratoma trifurcata* Forster, 1771) (Coleoptera: Chrysomelidae), Mexican bean beetle (*Epilachna varivestis* Mulsant, 1850) (Coleoptera: Coccinellidae), armyworm (*Pseudoletia unipuncta* Haworth, 1809) (Lepidoptera: Noctuidae), black cutworm (*Agrotis ipsilon* Hufnagel, 1766) (Lepidoptera: Noctuidae), corn earworm (*H. zea* Boddie, 1850) (Lepidoptera: Noctuidae), European corn borer (*Ostrinia nubilalis* Hübner, 1796) (Lepidoptera: Crambidae), stalk borer (*Papaipema nebris* Guenée, 1852) (Lepidoptera: Noctuidae), velvetbean caterpillar (*Anticarsia gemmatalis* Hübner, 1818) (Lepidoptera: Noctuidae), potato leafhopper (*Empoasca fabae* Harris, 1841) (Hemiptera Cicadellidae)] are expected to be in more northern regions and these pests are expected to move northward (Taylor et al., 2018). Numerous studies have demonstrated that pest species with high temperature tolerance are expanding their distributional ranges toward northern latitudes, regions where they were previously absent. These species have successfully established and reproduced in these new areas, posing emerging threats to local agricultural systems. This phenomenon indicates that the ecological impacts of climate change are not confined to warmer regions; rather, they are also generating new risk zones in areas that were previously relatively isolated from pest pressure. The northward expansion of pest distributions necessitates a comprehensive reevaluation of existing Integrated Pest Management (IPM) strategies, particularly from geographical, ecological, and phenological perspectives. In this context, it is of great importance to develop climate-based potential distribution maps for pest species, to expand early warning and monitoring systems, to ensure the adaptation of biological control agents to new environmental conditions, and to implement proactive measures in regions at risk. Furthermore, key questions such as how expanding pest species integrate into the vegetation and agroecosystems of newly colonised areas, how they interact with regional climatic conditions, and what changes they induce in natural enemy-community dynamics will be critical in shaping the effectiveness of future management strategies. Therefore, pest management under climate change should not be limited to narrowly focused chemical or biological control approaches; rather, it must be addressed through an integrated systems approach that incorporates spatial planning, agroecological adaptation, and climate projections. In conclusion, the northward expansion of agricultural pest insects is a direct manifestation of climate change, and this phenomenon necessitates the development of novel and complex management strategies to ensure sustainable agriculture and food security. Climate change is profoundly reshaping global agriculture and insect biodiversity, primarily through alterations in temperature regimes, precipitation patterns, and the frequency of extreme weather events (Del-Claro et al., 2024). Rising temperatures, in particular, are enabling numerous insect species to expand their geographical range beyond their historical thermal limits. As these species colonise new environments, their interactions with local ecosystems, especially their roles as vectors of plant and animal pathogens, are also shifting. Changes in vector dynamics, such as increased reproductive rates, shortened developmental cycles, and extended periods of activity, can enhance the efficiency of disease transmission. This poses not only a direct threat to agricultural production and food security but also complicates pest management strategies by introducing novel biotic stressors into previously unaffected regions. For instance, a study conducted by Plante et al. (2024) in strawberry fields in Eastern Canada revealed that rising temperatures led to a significant increase in aphid populations. Concurrently, the number of strawberry plants affected by phytoplasma-related diseases doubled.

They also suggested that pesticides used by farmers were ineffective in controlling aphid populations, probably due to changes in their microbiome. These findings clearly demonstrate that climate change not only intensifies pest populations but also amplifies the spread potential of the pathogens they carry. Therefore, the strong link between vector insect population dynamics and disease transmission underscores the need to reconfigure integrated pest management strategies with climate variables explicitly taken into account.

The increase in temperature causes the physiology of insects to accelerate, resulting in their development in a shorter period of time and an increase in their reproductivity. The number of offspring (generations) they produce in a year is also expected to increase (FAO, 2021; Gagnon and Bourgeois, 2024). For example, it is estimated that the number of generations of aphids (Hemiptera: Aphididae) will increase by 4 or 5 generations in a year with a 2 °C temperature increase (Harrington et al., 2001). In climate modeling studies with codling moth (*Cydia pomonella* Linnaeus, 1758) (Lepidoptera: Tortricidae), peach twig borer (*Anarsia lineatella* Zeller, 1839) (Lepidoptera: Gelechiidae) and oriental fruit moth (*Grapholita molesta* Busck, 1916) (Lepidoptera: Tortricidae), it was found that the biofixation dates of these pests could be shifted up to 28 days earlier, their lifespan could be shortened up to 19 days and 1.4 extra generations of these pests could be added by the end of the century (Jha et al., 2024). At the same time, increasing temperatures may also cause the wintering insects to have a shorter wintering period. The brown marmorated stink bug (*Halyomorpha halys* Carl Stål, 1885) (Hemiptera: Pentatomidae), which has a variety of potential hosts as a result of the climate crisis, is expected to spread to higher altitudes, produce more generations per year and be active earlier in the spring (Stoeckli et al., 2020). Habitat suitability for the oriental fruit fly (*Bactrocera dorsalis* Hendel, 1912) (Diptera: Tephritidae), mango fruit fly (*Ceratitis cosyra* Walker, 1849) (Diptera: Tephritidae) and tomato moth (*T. absoluta*) is predicted to increase moderately across the continent (Biber-Freudenberger et al., 2016), with pollen beetles (*Meligethes aeneus* Motschulsky, 1849) (Coleoptera: Nitidulidae) expected to invade crops earlier in the year (Junk et al., 2016).

It is predicted that a 1 °C temperature increase may affect the populations and spread of infectious disease-causing insects, and therefore, they may carry the diseases they carry to other geographies (Schneider et al., 2022). However, changes in the precipitation regime that can be seen alongside increasing temperatures are another problematic aspect of the climate crisis. For example, in 2019-2020, due to heavy rainfall in the Horn of Africa, extreme increases in desert locust (*S. gregaria*) populations were observed in Eritrea, Somalia and Yemen. Locusts are known to migrate with the winds, and where they will fly next depends on wind direction, speed and other weather parameters (Ibrahim, 2024). Climate change, increasing temperatures and changing rainfall patterns are expected to affect future migration routes of desert locusts (Guo et al., 2024).

Due to climate change, the agricultural sector has also developed many adaptations. Adaptations such as starting to irrigate crops earlier, changing planting dates and growing more than one crop per year may also affect pest populations in the future (FAO, 2021; IPPC, 2021). For example, irrigation of maize in Southeast Africa has allowed maize to be grown year-round but has also led to increases in insect vector populations. This has led to increased pressure of maize streak virus (MSV) (Geminiviridae) and pest insects in irrigated and subsequently rainfed crops (Shaw and Osborne, 2011). While some adaptation measures may unintentionally increase pest pressure, many climate-smart practices have the potential to reduce pest populations and disease transmission risk. Optimising planting times to avoid periods when pests are most active can reduce population levels by interrupting pest life cycles. Similarly, crop rotation reduces the persistence of certain pests and pathogens in the field by preventing them from consistently accessing their hosts. Effective irrigation planning that reduces plant stress can increase plant resistance to vector-borne diseases. Therefore, a comprehensive adaptation strategy should aim not only to cope with factors such as drought and heat but also to integrate pest and disease management into climate adaptation planning. This holistic approach supports both sustainable agricultural production and mitigates the increasing threat from climate-related pests (Ashfaq et al., 2024; Kabato et al., 2025).

Changing vegetation due to climate change also shapes the microclimate and may indirectly affect insects. Insect life cycles are often inextricably linked to the phenology of their host plants (Ma et al., 2024; Rohner, 2024). Therefore, changes in temperature, CO_2 and humidity levels may indirectly affect insects by altering the physiology and metabolism of the host plant. In addition, increases in average temperatures can disrupt the timing of important activities in the food chain due to their effects on plants and phytophagous insects (Luna and Dattilo, 2024). As a result of increasing temperatures and CO_2 concentrations, plants tend to store more sugar and starch in their leaves, and the carbon/nitrogen ratio of plants can change, which can change the metabolism and feeding habits of insects. At the same time, the resulting water stress causes plants to store more amino acids and sugars, and alcohol concentrations to increase. This results in plants becoming more susceptible to pest infestation (Ainsworth and Long, 2021; Shanker et al., 2022).

Effects of climate change on pest insects and their natural enemies

These environmental changes may disrupt the ecological dynamics between insect pests and their natural parasitoids or predators, potentially undermining the effectiveness of biological control strategies (Sanda, 2023; Boggs, 2024). High temperatures may also cause changes in the host-seeking behavior of predators and parasitoids, disruption of the relationships between the pest and its natural enemy, and lack of temporal overlap between host and predator insects (Sajjad et al., 2023). This leads to a decrease in the probability of parasitization and predation of the host. In a study on parasitoid-host interactions, it was determinded that the synchronization of the gall wasp parasitoid *Torymus sinensis* Kamijo, 1982 (Hymenoptera: Torymidae) was disrupted after the abnormally warm winter months of 2018 and chesnut gall wasp (*Dryocosmus kuriphilus* Yasumatsu, 1951) (Hymenoptera: Cynipidae) infestation increased (İpekdal, 2022). In the same study, it was determined that the pine cone sucking beetle (*Leptoglossus occidentalis* Heidemann, 1910) (Heteroptera: Coreidae) produced one to five generations from north to south in 2020, and that there was a significant increase in the number of generations in Turkey. It has been suggested that increasing temperatures and mild winters put biological control methods at risk in combating pests and may increase voltinism (İpekdal, 2022). The areas suitable for fall armyworm (*S. frugiperda*) distribution are expected to increase (Zacarias, 2020). There is a potential increase in two-spotted spider mite (*Tetranychus urticae* C. L. Koch, 1836) (Trombidiformes: Tetranychidae) outbreaks in some countries, and biological control measures by its predator, *Phytoseiulus persimilis* Evans, 1952 (Mesostigmata: Phytoseiidae), are not likely to improve this situation (Litkas et al., 2019). Bonsignore et al. (2019) reported that increasing temperatures have negative effects on host-parasitoid relationships and increase phenological asynchrony for some parasitoid species. They also suggested that gall wasp development time is extended (approximately 15 days) at higher altitudes (associated with a lower mean temperature of approximately 1.5 °C). These results highlight how parasitism on novel hosts depends on host phenology and, in the current study, was limited by the short duration of host presence in galls; this may explain the significant differences in cynipid gall wasp parasitism recorded at different altimeters. Viciriuc et al. (2024) reported that gall wasps were first detected in Romania in the western part of the country in 2015, but due to climate change, they spread to the northeast of the country 4 years later, in 2019.

Effects of climate change on forest pests

Rising temperatures cause the summer seasons to extend and insects to cause damage for longer periods. However, increasing temperatures and insect damage puts trees under water stress, negatively affecting the synthesis of protective substances such as resin, which are important defensive barriers. The water deficit in plants and trees, along with drought, also makes them vulnerable to their enemies (Skendžić et al., 2021; Bracalini et al., 2024). In studies conducted in Turkey, the future susceptibility of forests in the study area (Azdavay, Kastamonu) to the twelve-toothed pine bark beetle (*Ips sexdentatus* Börner, 1776) (Coleoptera: Curculionidae) was determined as 51.6% (Özcan, 2024), while the susceptibility of forests in Sarıçam (Kastamonu) was determined as 58% (Sivrikaya and Özcan, 2023). The European spruce bark beetle (*Ips typographus* Linnaeus, 1758) (Coleoptera: Scolytidae) is predicted to increase in late summer flight frequency and length. It is predicted that the insect will spread towards northern regions, with a second generation possible in southern Scandinavia and a third generation in the lowlands of central Europe (Jönsson et al., 2011).

With climate change, some forest pests are spreading to higher latitudes and altitudes; they can become invasive species in forested areas where they were not encountered before. For example, the pine processionary moth (*Thaumetopoea pityocampa* Denis and Schiffermüller, 1775) (Lepidoptera: Thaumetopoeidae), which causes serious damage to pine trees, has migrated further north in Europe due to mild winters (Battisti et al., 2006). Rising temperatures may be a factor encouraging the pine processionary moth, *T. pityocampa*, to feed and increase its population density during the winter months. In Europe, warmer winter temperatures have increased larval survival and distribution of the pine processionary moth, causing it to migrate into higher mountains and northwards (Battisti et al., 2006; Kiritani, 2006; 2013; Ali et al., 2024).

Effects of climate change on pollinator insects

In recent years, the impact of climate change on pollinator insects has become a hotly debated topic. 75% of cultivated crops require insects for pollination, and bees have an important place among the insects that provide pollination (Burkle and Jha 2024; Haq et al., 2024; Sajad et al., 2024). Especially, honeybees (*Apis mellifera* Linnaeus, 1758) (Hymenoptera: Apidae) are the most valuable pollinators in terms of agricultural production. Increasing temperatures can affect the development cycles of honeybees, which are an important source of income economically, by changing their physiology and behaviour. Honeybees are active when the hive temperature is between 29-33 °C. They are inactive when the colony or ambient temperature is below 10 °C or above 37 °C (Varalan and Çevrimli, 2023). Bee communities that encounter conditions other than optimum temperatures will quickly deplete their honey stocks, which can cause colonies to starve to death. In a study, it was observed that while there was no change in the mortality rate of bees when wintering temperatures were low, the dates of bees leaving the hive changed with increasing wintering temperatures. It was determined that the weight of the bees decreased due to their high metabolic rate and energy loss (Fründ et al., 2013). Increased temperature and changes in precipitation regimes due to climate change cause pollinator insects to have difficulty finding food, decreases in their populations or colony losses due to floods (Burkle and Jha, 2024). In addition, the increase in parasitic mites and infectious diseases such as *Varroa destructor* (Anderson and Truman, 2000) (Acari: Varroidae) within the colony can lead to the extinction of honey bee colonies. The Ministry of Agriculture and Forestry, Agricultural Economics and Policy Development Institute Directorate reported that honey production in Muğla decreased by 37.4% in 2021 compared to the previous year. They reported that this was due to the negative effects of the climate, forest fires that occurred in the region in the same year, and the decrease in the number of cochineal insects (Dactylopiidae), an insect needed for pine honey production (Burucu, 2022; 2024). In addition, increasing temperatures cause the flowering period to shorten, and honey producers to spend more effort searching for flowering plants for food. This situation both increases production costs and causes labour loss (Eigenbrode and Adhikari, 2023; Sajad et al., 2024).

EXPLORING THE INTERCONNECTIONS BETWEEN AGRO-ECOSYSTEMS AND CLIMATE CHANGE: IMPACTS AND FUTURE PROJECTIONS

Climate change is a major threat to agriculture. We have already passed the critical tipping point with the climate crisis. The increasing average temperatures will increase the spread of harmful insects, the incidence of diseases carried by them, and pose great risks to food safety (Plante et al., 2024). While climate change is reshaping insect biodiversity, its effects are much more complex. Phytophagy, which increases with increasing temperatures, will lead to a shortening of lifespan and developmental periods. Providing more generations in a year, more pests surviving, and the risk of transmitting more pathogens to hosts will also cause the disruption of natural ecosystems. These disruptions will also affect plant productivity, increase pesticide use, and cause more damage to the environment and living health through improper agricultural practices (Bhagarathi and Maharaj, 2023; Jasrotia et al., 2023; Sunil et al., 2023; Dixon, 2024).

Although all these effects of climate change have been studied using various insect models, the impact on plant-vector-pathogen interactions is still being understood. Gagnon and Bourgeois (2024) conducted a study using bioclimatic models to simulate the probability of a second generation of carrot beetles (*Listronotus oregonensis* LeConte, 1857) (Coleoptera: Curculionidae) in the current (1981-2010) and future (2041-2070) decades. They found that with increasing temperatures, the reproductive diapause of carrot beetles will be inhibited, causing them to increase in number and lay more eggs. They also reported a significant increase in the probability of developing a second generation from 24% to 37% and 62%-99% in the current and future years, respectively. It has been scientifically proven that some insect species have spread from Southern Europe to Northern Europe or from the southern regions to the north in our country. It is estimated that agricultural areas in the Northern Hemisphere will change 1000 km northwards in 100 years, and it is predicted that there may be major changes in the insect biodiversity in these areas (Ulusoy et al., 2022).

The climate crisis that has occurred due to the concentration of greenhouse gases released in the last 60 years has caused the biogeographic areas of all living organisms to gradually expand. The SSP5-8.5 scenario based on CMIP6 climate projections indicates that average temperatures in the Mediterranean Basin will exceed +2.5 °C by mid-century and that summer droughts will intensify (IPCC, 2021). For example, in recent years, it has been found that the geographical area of the Mediterranean fruit fly (*C. capitata* Wiedemann, 1824) (Diptera: Tephritidae) has expanded, and it causes damage to cherry, apple and pear trees at altitudes up to 1500 m in July-September (Özbek-Çatal et al., 2020). Model projections, in line with the warming trend, suggest that *C. capitata* could expand its range up to 1,800 meters in elevation in fruit-growing regions after 2050; and that the risk of damage to cherry and apple production could increase by 30% to 45% in the inland areas of the Black Sea region (Çalışkan-Keçe et al., 2024; FAO, 2024). It has been reported that the pine processionary moth has spread to altitudes higher than 1,200 m in recent years and that it migrates to high mountains and northwards due to higher winter temperatures in Europe. Similarly, degree-day-based projections involving *T. pityocampa* populations indicate that a +1 °C increase in winter temperatures in Europe could enable the species to shift northward by approximately 140 km (Battisti et al., 2006; Kiritani, 2006). The tomato moth (*T. absoluta*) has quickly established high populations in agricultural areas in many countries, becoming a major pest of tomatoes and is expected to expand its range in the future (Tabikha, 2022). The spotted stem borer (*Chilo partellus* Swinhoe, 1885) (Crambidae), belonging to the order Lepidoptera, was first identified as a potential pest of maize in India in the 1930s. It is now widespread in many countries and is expected to spread globally in the future. Similar models predict that suitable bioclimatic zones for *C. partellus* will expand from the Mediterranean region to Thrace, with initial colonisation expected to occur in the 2040s (Öztemiz & Akmeşe, 2018).

Invasive species negatively affect the biodiversity of newly entered ecological environments and cause epidemics in agricultural areas, resulting in serious agricultural product losses (Aulus-Giacosa et al., 2024; Cao and Feng, 2024). The increasing use of pesticides in agriculture and the potential for climate change to increase pest resistance to pesticides will be among the main threats to food security in the future (Jacoby et al., 2024). In a study using climate models, it was determined that the diamondback moth (*Plutella xylostella* L. 1758) (Lepidoptera: Plutellidae) has increased its wintering area by approximately 2.4 million km^2 worldwide in the last 50 years. Analysis of global datasets has shown that there is a link between pesticide resistance levels and the species' wintering range. Average pesticide resistance was found to be 158 times higher in wintering areas. It has been suggested that climate change may increase pesticide resistance by allowing the insect to spread throughout the year, which would cause major economic losses (Ma et al., 2021). These projections indicate that harmful insects will not only expand their geographic distribution but also trigger secondary outbreaks in higher-altitude agroecosystems. Therefore, integrating regional early warning systems with climate scenarios and restructuring IPM strategies according to subclimatic zones appears to be critical for ensuring sustainable food security.

Projections showing future models of some agricultural pests are given in Table 1.

Table 1. Future expectations of some pests depending on climate change scenarios

Time Spans	Insect Name	Future Expectations	Selected references
2070–2099	*Halyomorpha halys*, Carl Stål, 1885	It is expected to spread to higher altitudes and northern parts, produce more generations per year and be active earlier in the spring	Kistner, 2017; Stoeckli, et al.,2020; FAO, 2021; Powel et al. 2021; Afonin and Musolin, 2024
2050, 2100	*Spodoptera frugiperda* JE Smith, 1797	Habitat suitability is expected to increase partially	Zacarias, 2020; FAO, 2021; Fu et al., 2023; Adan et al. 2024; Karuppannasamy et al. 2024; Sumila et al. 2024; Yan et al. 2024
2050	*Schistocerca gregaria* Forsskål, 1775	It is expected that future migration routes will be affected and plague outbreaks will increase	FAO, 2021; Feng et al., 2024; Mitra et al., 2024; Pitafi, 2024
2001–2050, 2051–2100	*Ceratoma trifurcata*, Forster, 1771 *Epilachna varivestis*, Mulsant, 1850 *Pseudoletia unipuncta*, Haworth, 1809 *Agrotis ipsilon*, Hufnagel, 1766 *Helicoverpa zea*, Boddie, 1850 *Ostrinia nubilalis*, Hübner, 1796 *Papaipema nebris*, Guenée, 1852 *Anticarsia gemmatalis*, Hübner, 1818 *Empoasca fabae*, Harris, 1841	Insects are expected to move to northern regions where climate conditions are more favorable, and pest pressure is expected to increase overall	Taylor et al., 2018; FAO, 2021; Hayat et al., 2021; Skendžić et al., 2021; Li et al, 2024; Santos et al., 2024

Continued. Table 1

Time Spans	Insect Name	Future Expectations	Selected references
2041–2060	*Bactrocera dorsalis*, Hendel, 1912	Habitat suitability is expected to increase partially	Biber-Freudenberger et al.,2016; FAO, 2021; Dong et al. 2022; Ullah et al. 2023; Choudhary et al., 2025
	Thaumetopoea pityocampa, Denis and Schiffermüller, 1775	It is expected to migrate to more northern regions due to mild winters	Battisti et al., 2006 Kiritani, 2006; 2013; FAO, 2021; Bourougaaoui et al., 2024; Cao and Feng, 2024
2041–2060	*Ceratitis cosyra*, Walker, 1849	Habitat suitability is expected to increase partially	Biber-Freudenberger et al., 2016; FAO, 2021; Özbek-Çatal et al., 2020; Rao et al., 2024
	Operophtera brumata, Linnaeus, 1758	It is predicted that they will spread to more northern areas such as tundra, hatch earlier and therefore their predators and phenology will be disrupted.	Buse, 1999; Andersen et al. 2021; FAO, 2021; Vinstad et al 2022
2041–2060	*Tuta absoluta*, Meyrick, 1917	Habitat suitability is expected to increase partially	Biber-Freudenberger et al., 2016; FAO, 2021; Tabikha 2022; Yang et al., 2023; Zhao et al., 2023
2041–2060, 2061–2080	*Leptinotarsa decemlineata*, Say, 1824	It is expected to spread towards northern regions and increase its distribution areas, colonize higher altitudes and increase the number of annual generations	Kocmánková et al., 2011; Wang et al., 2017; FAO, 2021; Gao et al. 2022; Petrosyana et al. 2024
2100	*Cydia pomonella*, Linnaeus, 1758	It is expected that biofixation dates will shift to earlier, lifespan will shorten and extra generations will be added.	FAO, 2021; Guo et al., 2021; Jha et al., 2024
2021–2050, 2069–2098	*Meligethes aeneus*, Motschulsky, 1849	It is expected to invade crops earlier in the year.	Junk, et al., 2016
2011–2040, 2071–2100	*Ips* spp.	It is predicted that the frequency and length of late summer flight events will increase, colonising more northern areas and a third generation per year may be possible.	Jönsson et al., 2011; FAO, 2021; Özcan, 2024; Sivrikaya and Özcan, 2023
	Dryocosmus kuriphilus, Yasumatsu, 1951	Climate change is predicted to have negative effects on host-parasitoid relationships and may increase phenological asynchrony for some parasitoid species.	İpekdal, 2022; Bonsignore et al., 2023; Viciriuc et al., 2024
	Leptoglossus occidentali, Heidemann, 1910	It has been suggested that there is a significant increase in the number of generations in Turkey, that climate change puts biological control methods in the fight against pests at risk and may increase voltinism	Byeon et al., 2021; FAO, 2021; İpekdal, 2022; Lee et al., 2023
2041-2070	*Listronotus oregonensis*, LeConte, 1857	It is predicted that with increasing temperatures, reproductive diapause will be inhibited, resulting in an increase in their numbers and a greater number of eggs	FAO, 2021; Gagnon and Bourgeois, 2024

CONCLUSION AND RECOMMENDATIONS

Combating the climate crisis is a priority for all countries in the world in order to protect the ecosystem, prevent disruption of the food chain, and ensure sustainable plant production (Girona et al., 2023; John et al., 2024; Szmyt and Dering, 2024). Climate change is a multi-phase series of events, such as changes in annual precipitation, increasing temperatures, increases in the frequency and severity of natural disasters such as storms and floods, increases in the emissions of greenhouse gases such as CO_2, and increases in sea water levels. In addition to all these, improper agricultural practices, weeds and harmful insects, nematodes, viruses and bacteria also have a negative impact on agricultural activities. The negative impact of climate change affects crop production and food security worldwide. Climate change and pest risk (from insects, pathogens and weeds) are projected to increase in agricultural ecosystems, particularly in Arctic, boreal, temperate and subtropical regions (Jasrotia et al., 2023). It is predicted that all biomes worldwide will be affected by increasing temperatures, but the nature and extent of the impact will vary depending on the ability of natural ecosystems to adapt and evolve (Seidl et al., 2017; Gonzalez-Tokman et al., 2024; Müller et al., 2024). Plant protection will be necessary for countries to adapt to new climate scenarios (Almekinders et al., 2019). However, new regulations, international cooperation, capacity building and new research are needed. Future studies on this topic should take into account population growth, agricultural production, pesticide use, climate change and water availability. Pest risk analysis activities need to be intensified at national, regional and international levels, and climate change aspects need to be included in pest risk assessment. Observation and monitoring activities are important to detect the introduction of new pests or to monitor their status. National, regional and international surveillance and monitoring activities for plant health threats should be intensified. It is important to develop model templates for multilateral surveillance programs, particularly in developing countries. It is also critical to share information about changes in pest distributions, host ranges, and adaptations of pests and host plants on an international basis. National surveillance systems, such as diagnostic laboratories, should be established by national governments to rapidly counter potential biological invasions. The direct impact of climate change on ecological processes, chemical or biological control measures, natural enemies and pest control should be investigated much more comprehensively (Macfayden et al., 2018; Eigenbrode and Adhikari, 2023). Strategies for global climate change at national and international basis are shown in Figure 3.

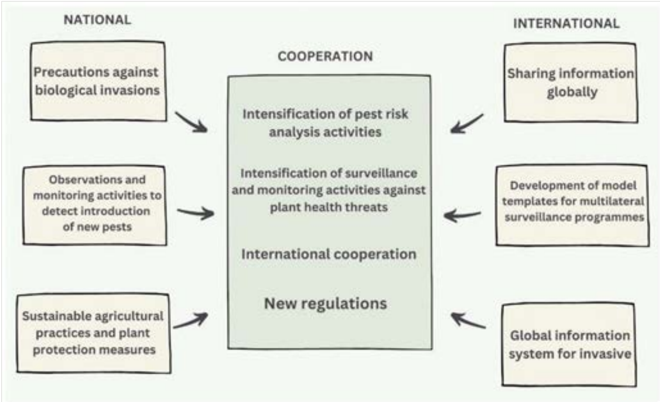

Figure 3. Strategies for global climate change on a national and international basis (the figure was drawn by Evrim Sönmez)

International cooperation is critical to the success of countries in adapting pest management strategies to climate change. International cooperation can be global or regional. Establishing a mechanism such as the global plant health research coordination can increase scientific cooperation and optimise resource use. By doing so, it could not only help advance science but also strengthen the scientific basis of international efforts to assess and manage the impact of climate change on plant health (Szmyt and Dering, 2024). Global forums with the support of international organisations for knowledge sharing can be extremely useful. The experience gained now in organising online meetings will help to promote long-distance contacts and interactions, saving considerable time and money. Preventive, curative, climate-resilient, sustainable agricultural practices and plant protection measures can help maintain current and future food security and help vulnerable regions cope with the changing climate scenario (Girona et al., 2023; Kar et al., 2024).

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