Journal of Advances in Microbiology

Volume 24, Issue 12, Page 103-118, 2024; Article no.JAMB.127744
ISSN: 2456-7116

Climate Change and Insect Ecology: Impacts on Pest Populations and Biodiversity

Sunita Yadav [a++], Satyabrata Sarangi [b++], Ali Assaba Mohammed Shafi [c++], Kartikey Pandey [d++*], Mamatha Thodusu [e#], Suraj Soni [f++] and Shradha Parmar [g++]

[a] Department of Entomology, Jawaharlal Nehru Krishi Vishwa, Vidyalaya, Jabalpur, India.
[b] Department of Entomology, College of Agriculture, OUAT, Bhubaneswar, Odisha, India.
[c] Department of Entomology, BAU, Sabour, Bhagalpur, India.
[d] Department of Plant Pathology, Jawaharlal Nehru Krishi Vishwa, Vidyalaya, Jabalpur, India.
[e] Department of Entomology, Uttara Banga Krishi Vishwa, Vidyalaya, West Bengal, India.
[f] Department of Entomology, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India.
[g] Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya, Gwalior, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jamb/2024/v24i12876

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/127744

Received: 04/10/2024
Accepted: 06/12/2024
Published: 10/12/2024

Review Article

[++] *Ph.D. Scholar;*
[#] *PG. Scholar;*
**Corresponding author: E-mail: kartikeyp03@gmail.com;*

Cite as: *Yadav, Sunita, Satyabrata Sarangi, Ali Assaba Mohammed Shafi, Kartikey Pandey, Mamatha Thodusu, Suraj Soni, and Shradha Parmar. 2024. "Climate Change and Insect Ecology: Impacts on Pest Populations and Biodiversity". Journal of Advances in Microbiology 24 (12):103-18. https://doi.org/10.9734/jamb/2024/v24i12876.*

ABSTRACT

Climate change is significantly altering the dynamics of insect populations, with wide-ranging implications for agriculture, biodiversity, and ecosystem services. Rising temperatures, shifts in precipitation patterns, and elevated atmospheric CO_2 levels are reshaping insect behavior, physiology, and distribution. These changes have led to altered pest population dynamics, with some species experiencing increased reproduction rates, extended breeding seasons, and expanded geographic ranges into previously cooler regions, intensifying agricultural damage. Conversely, many non-pest insects, such as pollinators and species with specialized habitats, face declines due to phenological mismatches, habitat loss, and reduced resilience to extreme weather events. These shifts threaten essential ecosystem services like pollination, nutrient cycling, and soil health, which are critical for food security and ecosystem stability. Despite efforts to mitigate these impacts through strategies like Integrated Pest Management (IPM), biocontrol, and habitat restoration, significant knowledge gaps remain in understanding the combined effects of multiple climate factors on insect ecology. Emerging technologies, including remote sensing, ecological modeling, and genomics, offer new avenues for studying insect responses to climate change, while citizen science and big data can enhance monitoring efforts. Addressing these challenges requires interdisciplinary collaboration between scientists, conservationists, and policymakers to develop adaptive management strategies that integrate climate resilience into conservation policies. Future research should focus on long-term studies to better predict the effects of climate change on insects and inform proactive measures to protect biodiversity. By leveraging a combination of technological innovations, policy frameworks, and community engagement, we can develop sustainable solutions to mitigate the adverse effects of climate change on insect populations and ensure the continued functioning of ecosystems that humans and other species rely on.

Keywords: Climate change; insect ecology; biodiversity; phenology; pest management; pollinators.

1. INTRODUCTION

1.1 Climate Change

Climate change refers to long-term alterations in temperature, precipitation, and other atmospheric conditions on Earth, primarily driven by human activities. Since the pre-industrial era, anthropogenic activities, particularly the burning of fossil fuels like coal, oil, and natural gas, have led to a sharp rise in carbon dioxide (CO_2) levels, surpassing 420 parts per million (ppm) in 2023 levels not observed in millions of years. This increase has contributed to an average global temperature rise of approximately 1.2°C since the late 19th century (Folland et al. 2001). Major contributors to climate change include not only fossil fuel combustion but also deforestation and land-use changes, which reduce the Earth's ability to absorb CO_2. Agriculture also plays a role by emitting methane (CH_4) from livestock and nitrous oxide (N_2O) from fertilizer application. As a result, climate change has far-reaching consequences, such as rising sea levels, ocean acidification, and an increase in the frequency of extreme weather events.

1.2 Importance of Studying the Effects of Climate Change on Insect Ecology

Insects are critical components of ecosystems, performing essential functions such as pollination, nutrient cycling, and serving as a food source for other animals. Pollinators like bees, butterflies, and moths are vital for the reproduction of nearly 75% of flowering plants, which include many of the crops humans rely on (Khalifa et al. 2021). Insects like ants and beetles play crucial roles as decomposers, breaking down organic material to maintain soil health. Insects are highly sensitive to environmental changes because they are ectothermic, meaning their body temperature and physiological processes are regulated by external temperatures. Even minor shifts in climate variables can significantly impact their life cycles, metabolism, and behavior. Warmer temperatures can accelerate insect development, leading to increased reproduction rates for some pest species, while extreme heat can push others beyond their thermal limits, causing declines or local extinctions. Phenological shifts, such as earlier emergence or mismatches between insects and their food sources, can disrupt ecological interactions, ultimately affecting agricultural productivity and ecosystem resilience (Singer & Parmesan 2010).

1.3 Scope and Objectives of the Review

The purpose of this review is to synthesize current knowledge on how climate change affects insect populations, with a focus on both pest species and broader biodiversity. Understanding these impacts is crucial as warmer temperatures, changing precipitation patterns, and extreme weather events are expected to alter insect behavior, physiology, and distribution. This, in turn, could lead to increased agricultural losses due to pest infestations and reduced pollination services vital for crop yields (Goulson et al. 2015). Shifts in climate may facilitate the spread of invasive species into new regions, threatening native ecosystems. The review will also explore the consequences for non-pest insect species, particularly those involved in pollination and nutrient cycling, whose decline could have cascading effects on ecosystem health. The objectives of this review include examining the direct and indirect impacts of climate change on insect ecology, identifying critical knowledge gaps, and suggesting strategies for managing these changes to protect both agricultural systems and biodiversity. By doing so, this review aims to provide a comprehensive overview of the challenges and potential solutions related to insect ecology in a rapidly changing climate.

2. CLIMATE CHANGE: KEY FACTORS AFFECTING INSECT ECOLOGY

2.1 Rising Temperatures

Rising global temperatures have profound effects on insect physiology, particularly because insects are ectothermic organisms whose body temperature and metabolic processes are closely tied to ambient temperatures (Table 1) (Chown & Gaston 1999). As temperatures increase, metabolic rates accelerate, often resulting in faster development, increased feeding rates, and higher reproductive output. For example, studies have shown that many insect species, including pests like the diamondback moth (*Plutellaxylostella*), exhibit increased reproductive rates and shortened generation times under warmer conditions. There are limits to this positive response, as excessively high temperatures can reduce survival rates, disrupt enzyme functions, and impair reproductive success. Temperatures beyond optimal thresholds can lead to heat stress, reducing fertility in insects such as fruit flies (*Drosophila spp.*) and significantly impacting population viability (Green et al.2019). Climate warming has driven many insect species to shift their geographic ranges to higher altitudes and latitudes in search of cooler habitats. The mountain pine beetle (*Dendroctonus ponderosae*), traditionally confined to lower altitudes, has expanded its range to higher elevations, where trees previously unaffected by this pest are now vulnerable. Shifts in the distribution of agricultural pests like the European corn borer (*Ostrinianubilalis*) are linked to rising temperatures, with potential consequences for crop production in regions that were previously pest-free. These range shifts not only increase the risk of pest outbreaks in new areas but also threaten endemic species that cannot migrate or adapt quickly enough to changing conditions (Macfadyen et al. 2018).

2.2 Changes in Precipitation Patterns

Climate change is also altering precipitation patterns, leading to shifts in rainfall distribution, with some regions experiencing increased rainfall while others face prolonged droughts. These changes have significant implications for insect life cycles, especially for species that are sensitive to moisture levels. Many insects, such as mosquitoes and dragonflies, rely on aquatic habitats for their larval stages, making them vulnerable to changes in water availability. For example, decreased rainfall and drying of ponds can reduce mosquito populations in some areas, while increased precipitation in others can lead to outbreaks due to expanded breeding habitats (Medlock & Vaux 2015). The availability of moisture also affects soil-dwelling insects and decomposers, such as ants and termites, which play critical roles in nutrient cycling. Drought conditions can reduce the activity of these species, thereby impacting soil health and ecosystem productivity. Conversely, excessive rainfall can cause flooding that washes away insect habitats, disrupts reproductive cycles, and leads to higher mortality rates.

2.3 Increased Frequency of Extreme Weather Events

The increasing frequency and intensity of extreme weather events such as heatwaves, droughts, floods, and storms pose additional challenges to insect populations (John et al. 2024). Drought conditions can lead to reduced

Table 1. Climate change: Key factors affecting insect ecology

Key Factor	Description	Impact on insect ecology	Examples
Temperature Rise	Increasing global temperatures due to greenhouse gas emissions.	Alters insect metabolism, reproductive cycles, and geographic distribution.	Expansion of malaria-transmitting mosquitoes (Anopheles spp.) to cooler regions.
Altered Precipitation Patterns	Changes in rainfall intensity and distribution.	Affects habitat availability, insect breeding, and survival rates.	Reduced mosquito breeding in drought-prone areas, increased breeding in flooded regions.
Changes in Phenology	Shift in the timing of life-cycle events such as emergence, mating, and migration.	Leads to mismatches with host plants or prey, impacting survival and reproduction.	Early emergence of butterflies affecting synchronization with nectar plants.
CO2 Concentration Increase	Elevated atmospheric CO2 levels influencing plant-insect interactions.	Changes in plant nutritional quality, affecting herbivorous insects.	Reduced nitrogen content in plants, leading to increased feeding by aphids.
Extreme Weather Events	Increased frequency of storms, droughts, and heatwaves.	Directly impacts insect mortality, disrupts ecosystems, and reduces population sizes.	Heatwaves causing mass mortality in pollinators like bees.
Habitat Loss and Fragmentation	Disruption of ecosystems due to climate-induced changes.	Limits the range of insects, disrupts migration paths, and reduces biodiversity.	Loss of wetlands affecting dragonfly populations.
Emergence of Novel Pests	Favorable conditions for invasive and pest species due to climate change.	Expands the range and survival of pests, causing increased crop damage.	Proliferation of fall armyworm (Spodoptera frugiperda) in new regions.
Microclimatic Variability	Localized climatic changes within ecosystems due to larger climate shifts.	Alters insect behavior and microhabitat preferences.	Changes in forest canopy temperature affecting beetle activity.
Impact on Natural Enemies	Climate change affecting the predators, parasitoids, and pathogens of insects.	Disrupts biological control, leading to pest outbreaks.	Reduced effectiveness of Cotesia spp. (a parasitoid wasp) in controlling caterpillars.
Oceanic and Aquatic Changes	Warming oceans and changing aquatic ecosystems.	Impacts aquatic insects and those dependent on freshwater habitats.	Decline in populations of mayflies and caddisflies in warming streams.

(Source: (Chown et al. 1999, Macfadyen et al. 2018, Sun et al. 2016, Agrell et al. 2004))

plant availability and water scarcity, which can lower survival rates for herbivorous insects and those reliant on plant hosts. For example, prolonged droughts have been linked to declines in grasshopper populations in semi-arid regions, as reduced vegetation limits food resources. On the other hand, floods can devastate soil-dwelling insects by saturating their habitats and reducing oxygen levels, which are critical for survival. Insects' ability to survive and recover from extreme events varies among species. Some insects, like aphids and locusts, can rapidly increase their populations following favorable conditions after a drought, leading to sudden outbreaks. For other species, recovery may take longer due to habitat loss and decreased reproductive rates after extreme events. The resilience of insect populations is also influenced by their life history traits, such as the ability to enter diapause or hibernation to survive adverse conditions (Danks 1978). Extreme weather can also disrupt mutualistic interactions, such as those between pollinators and flowering plants, which depend on synchronized timing.

2.4 Elevated Levels of Atmospheric CO_2

Rising atmospheric CO_2 concentrations have indirect but significant effects on insect ecology by altering plant physiology. Elevated CO_2 levels can increase the carbon-to-nitrogen ratio in plant tissues, leading to lower nutritional quality for herbivorous insects. This can force insects to consume more plant material to meet their nutritional needs, potentially increasing plant damage. Studies on soybean aphids (*Aphis glycines*) have shown that elevated CO_2 can enhance aphid reproduction, likely due to changes in plant chemistry that favor aphid growth (Sun et al. 2016). Not all insects respond uniformly; while some may thrive, others may experience reduced fitness and slower development rates due to poorer plant quality. In altering insect feeding behavior, increased CO_2 levels can affect the secondary metabolites in plants that serve as defense mechanisms against herbivory. Changes in the production of alkaloids, tannins, and other compounds can either enhance or reduce a plant's resistance to insect pests, leading to complex and species-specific outcomes. Elevated CO_2 has been observed to reduce the concentration of certain defensive compounds in cotton, making it more susceptible to pest attacks (Agrell et al. 2004). These interactions highlight the need for a nuanced understanding of how multiple factors associated with climate change interact to influence insect-plant dynamics.

3. IMPACTS ON INSECT PEST POPULATIONS

3.1 Alterations in Population Dynamics

Climate change has significantly altered the population dynamics of various insect pests, with many species exhibiting changes in abundance due to shifting environmental conditions. For example, studies have shown that rising temperatures and prolonged growing seasons have led to increases in the population densities of pests such as the spruce budworm (*Choristoneura fumiferana*) in North America, resulting in more frequent and severe outbreaks (Navarro et al. 2018). Warmer winters with reduced snow cover have increased the survival rates of pests like the pine processionary moth (*Thaumetopea pityocampa*), which has expanded its population in southern Europe. Not all pests benefit from climate change; for some species, the increased frequency of extreme weather events like heatwaves and droughts can suppress populations by exceeding their thermal tolerance limits. Climate change also affects the phenology of insect pests, often leading to shifts in life cycles that favor increased reproduction. Many insect pests such as the European corn borer (*Ostrinia nubilalis*) have shown an increase in voltinism (number of generations per year) in response to warmer temperatures (Liu et al. 2021). This change results in more frequent pest infestations, which can increase pressure on crops. Extended breeding seasons due to milder autumns and earlier springs allow pests like the green peach aphid (*Myzus persicae*) to reproduce for longer periods, thereby increasing their population densities and potential for crop damage. These phenological changes also disrupt traditional pest management strategies that were developed based on historical climate patterns.

3.2 Shifts in Pest Distribution

As global temperatures rise, many insect pests are expanding their geographic ranges toward higher latitudes and altitudes in search of suitable habitats. For example, the mountain pine beetle (*Dendroctonus ponderosae*) has shifted its range into previously colder areas of Canada and Alaska, where it now infests lodgepole and jack pines, causing widespread tree mortality (Coops et al. 2012). This northward expansion is facilitated by warmer winters, which reduce the beetle's cold-induced mortality rates. Agricultural pests such as the Colorado potato beetle (*Leptinotarsa decemlineata*) have been reported in regions where they were previously absent, threatening potato crops in northern Europe. Climate change has also accelerated the spread of invasive insect species by altering habitats and reducing natural barriers to dispersal. The Asian tiger mosquito (*Aedes albopictus*), which transmits diseases like dengue and Zika, has expanded into Europe and North America due to warmer temperatures and changes in precipitation patterns. Invasive agricultural pests, such as the fall armyworm (*Spodoptera frugiperda*), have also spread to Africa and Asia, threatening staple crops like maize and rice (Kumar et al. 2022). These invasions can lead to severe economic and ecological consequences, as native species often lack natural defenses against newly introduced pests.

3.3 Implications for Agriculture and Food Security

The increased prevalence and range expansions of insect pests due to climate change have dire implications for global agriculture (Fig. 1). Rising temperatures can enhance pest metabolism and feeding rates, leading to more significant damage to crops like wheat, rice, and maize. Warming has been linked to higher rates of infestation by the brown planthopper (*Nilaparvata lugens*) in rice fields in Asia, resulting in reduced yields. Climate-induced changes in pest populations can affect food security, particularly in developing countries where agricultural systems are more vulnerable to pest outbreaks (Kumar et al. 2022). As pest populations increase and expand into new areas, farmers may resort to more frequent pesticide applications to control infestations, potentially leading to increased pesticide resistance. For example, the corn earworm (*Helicoverpa zea*), which affects crops like maize and cotton, has developed resistance to multiple classes of insecticides due to intensive spraying. Climate change can exacerbate this issue by speeding up pest life cycles and increasing genetic variability, thereby enhancing the likelihood of resistance. Warmer temperatures may reduce the effectiveness of some biological control agents, further complicating pest management strategies (Hoelmer & Kirk 2005, Frank 2021, Karley et al. 2004).

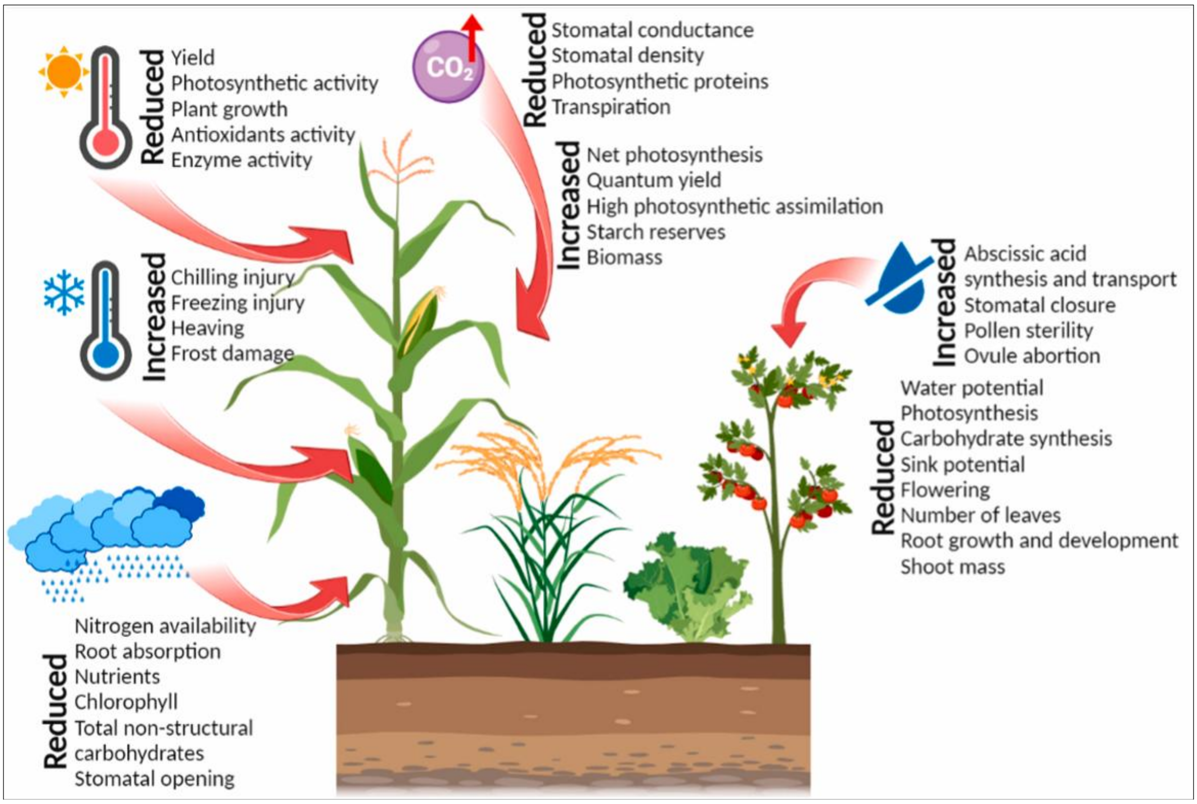

Fig. 1. Impact of climate change on crops
(Source:MDPI)

4. EFFECTS ON NON-PEST INSECT BIODIVERSITY

4.1 Vulnerable Insect Species and Their Habitats

Non-pest insect species, especially those with specialized ecological niches, are particularly vulnerable to the impacts of climate change (Table 2). For example, many pollinators, including bees, butterflies, and moths, are highly sensitive to temperature fluctuations and changes in precipitation patterns (Abrol & Abrol 2012). These insects rely on specific flowering plants that may also shift their blooming periods in response to warming temperatures, leading to phenological mismatches. Such mismatches can result in reduced food availability, which directly affects the survival and reproduction of pollinator populations. Aquatic insects, such as mayflies (*Ephemeroptera*), dragonflies (*Odonata*), and caddisflies (*Trichoptera*), are also at risk due to the sensitivity of freshwater ecosystems to temperature increases and altered water flow. Warmer water temperatures and changes in hydrological regimes can reduce the availability of suitable habitats, leading to declines in species that are already constrained by specific ecological requirements. In regions experiencing prolonged droughts or altered precipitation patterns, the loss of ephemeral ponds and streams could lead to local extinctions of moisture-dependent insects (Darke & Tallamy 2014). The decline in insect biodiversity is becoming increasingly apparent, with recent studies highlighting significant reductions in insect abundance and diversity across multiple ecosystems. Habitat loss, driven by changes in climate and land use, is a primary factor contributing to these declines. Species that are highly specialized, have narrow habitat ranges, or exhibit limited dispersal capabilities are at a greater risk of extinction. The distribution of alpine and polar insect species, such as certain bumblebees (*Bombus spp.*), is shrinking as temperatures rise and suitable habitats retreat to higher altitudes or latitudes. If these species are unable to migrate or adapt quickly enough to changing conditions, they may face localized extinctions (Littlefield et al. 2019).

4.2 Effects on Insect Interactions Within Ecosystems

Mutualistic relationships, such as those between pollinators and flowering plants, are particularly vulnerable to climate change-induced disruptions. Pollinators like bees rely on the availability of floral resources for nectar and pollen, while plants depend on these insects for pollination. As climate change causes shifts in the timing of flowering and insect emergence, these interactions may become unsynchronized. For example, in temperate regions, earlier springs may lead to the premature blooming of plants before their pollinators have emerged, reducing reproductive success for both plants and pollinators. This can result in cascading effects on plant communities and the ecosystems that depend on them (Atkinson et al. 2013). Climate change can also affect predator-prey and parasite-host interactions, leading to shifts in ecosystem dynamics. Warmer temperatures can accelerate the development and reproduction rates of some insect predators, but they may also cause declines in prey species, leading to potential imbalances. Shifts in temperature and humidity can influence the distribution and efficacy of parasitoids that control pest populations, thereby impacting biological control strategies. Changes in climate can affect the emergence patterns of parasitic insects, potentially leading to mismatches with their hosts, which could reduce the effectiveness of natural pest control and disrupt ecosystem stability (Welch & Harwood 2014).

4.3 Consequences for Ecosystem Services

Insects play crucial roles in ecosystem services, such as pollination, nutrient cycling, and soil health, which are essential for the functioning of terrestrial and aquatic ecosystems. Pollinators like bees, butterflies, and hoverflies are responsible for the pollination of approximately 75% of the world’s flowering plants and about 35% of global food crops. The decline of pollinator populations due to climate change and habitat loss poses a significant threat to food security, particularly for crops that are highly dependent on insect pollination, such as fruits, vegetables, and nuts. Insects also contribute to nutrient cycling by breaking down organic matter, thereby enriching soil and promoting plant growth (Yadav et al. 2021). Dung beetles, ants, and termites are critical for decomposing plant material and animal waste, which helps in nutrient recycling and soil aeration. Climate-induced changes in temperature and moisture can reduce the efficiency of these decomposers, negatively impacting soil health and agricultural productivity. For example, the activity of dung beetles may decrease under extreme heat

Table 2. Vulnerable insect species and their habitats

Insect Species	Habitat	Threats	Conservation Status	Key Conservation Efforts
Monarch Butterfly (*Danaus plexippus*)	Grasslands, meadows, and migratory routes in North America	Habitat loss, climate change, pesticide use, and reduced milkweed plants.	Vulnerable (IUCN)	Habitat restoration, planting milkweed, and reducing pesticide use.
Bumblebee (*Bombus spp.*)	Temperate grasslands, forests, and urban gardens	Habitat fragmentation, pesticide exposure, and climate change.	Declining populations	Pollinator-friendly practices, bans on harmful pesticides, and habitat conservation.
Indian Red Pierrot (*Talicada nyseus*)	Dry forests, scrublands, and gardens in South Asia	Habitat destruction, climate variability, and urbanization.	Locally threatened	Habitat preservation and urban greening initiatives.
Dragonfly (*Anax imperator*)	Freshwater habitats such as ponds, lakes, and marshes	Water pollution, habitat destruction, and climate-induced wetland loss.	Vulnerable in regions	Wetland conservation and restoration of aquatic habitats.
Goliath Beetle (*Goliathus spp.*)	Tropical forests in Africa	Deforestation and illegal collection for pet trade.	Endangered in wild	Anti-poaching laws and sustainable forest management.
Madagascan Sunset Moth (*Chrysiridia rhipheus*)	Madagascar’s forests	Habitat loss due to deforestation and invasive plant species.	Endangered	Protection of Madagascar’s unique forest ecosystems.
European Honeybee (*Apis mellifera*)	Forests, grasslands, and managed agricultural landscapes	Colony collapse disorder, pesticides, and diseases.	Declining populations	Promoting sustainable beekeeping and pesticide regulations.
Jewel Beetle (*Chrysochroa spp.*)	Tropical and subtropical forests	Logging, habitat loss, and climate change.	Locally threatened	Enforcement of logging restrictions and forest conservation.
Giant Swallowtail (*Papilio cresphontes*)	Woodlands and citrus groves in North and Central America	Habitat loss, pesticide use, and climate change.	Vulnerable in regions	Planting native host plants and limiting pesticide use.
Great Diving Beetle (*Dytiscus marginalis*)	Freshwater habitats across Europe and Asia	Water pollution, habitat destruction, and climate-induced droughts.	Locally declining	Wetland restoration and water quality management.

(Source: ((Abrol & Abrol 2012, Darke & Tallamy 2014, Littlefield et al. 2019))

conditions, reducing their effectiveness in nutrient cycling. The loss of keystone insect species can have cascading effects throughout ecosystems. Keystone species, such as bees and certain beetles, play irreplaceable roles in maintaining the structure of their ecosystems. The decline or extinction of such species can lead to a breakdown in ecosystem functions, reducing biodiversity and resilience to environmental changes (Oliver et al. 2015). The loss of honeybee populations due to climate-induced stressors like habitat loss and disease has already led to decreased pollination services, which could threaten agricultural systems worldwide. The reduction in insect diversity can affect other species that depend on insects as a food source, such as birds, amphibians, and small mammals. The decline of these predators could further disrupt food webs, leading to long-term ecological consequences. The cumulative effect of these changes underscores the need for immediate conservation efforts to protect insect biodiversity and the critical ecosystem services they provide.

5. MECHANISMS DRIVING CHANGES IN INSECT BEHAVIOR AND PHYSIOLOGY

5.1 Phenological Changes (Timing of Biological Events)

Climate change is driving significant shifts in the timing of biological events (phenology) for many insect species. As global temperatures increase, insects are emerging, mating, and migrating earlier in the year compared to historical averages (Musolin 2007). Butterflies in Europe have been observed to emerge up to 10 days earlier than they did several decades ago due to warming spring temperatures. Warmer temperatures have caused earlier migration in dragonflies and butterflies, leading to changes in their distribution and population dynamics. The accelerated phenology can have cascading ecological consequences, as insects may not align with the availability of critical resources like host plants and prey. Phenological mismatches occur when the life cycles of insects and their food sources become desynchronized due to climate change. For example, pollinators like bees may emerge before the flowering of their preferred plants, reducing the availability of nectar and pollen (Nicholls & Altieri 2013). Such mismatches can have severe consequences for insect fitness and ecosystem health, as they disrupt essential mutualistic interactions between pollinators and plants. In agricultural systems, early emergence of herbivorous pests, such as aphids (*Aphididae*), can lead to increased crop damage if their life cycle becomes unsynchronized with natural predators or biocontrol agents. These shifts not only affect individual species but can also alter the structure of entire ecosystems, as the timing of interactions between predators, prey, and competitors is disrupted.

5.2 Evolutionary Adaptations to Climate Change

In response to prolonged environmental stressors like rising temperatures and altered precipitation patterns, some insect species are undergoing genetic changes that enable them to adapt to their changing environments (Harvey et al. 2020). Evolutionary adaptations can include changes in developmental rates, thermal tolerance, and behavior to optimize survival under new condition. For example, the pitcher plant mosquito (*Wyeomyia smithii*) has evolved shorter diapause durations in response to warming climates, allowing it to reproduce earlier in the season. Genetic changes have been observed in the European corn borer (*Ostrinia nubilalis*), which has adapted to warmer temperatures by shifting its voltinism patterns, resulting in additional generations per year. Research has documented several case studies where insects have exhibited adaptive responses to climate change. The mountain pine beetle (*Dendroctonus ponderosae*) has developed increased cold tolerance, allowing it to expand its range into previously inhospitable northern regions (Sambaraju & Goodsman 2021). In the case of the fruit fly (*Drosophila melanogaster*), populations in warmer regions have shown genetic changes that enhance their heat shock protein expression, increasing their survival rates under heat stress. These examples highlight the capacity of some insects to adapt to rapid environmental changes, although the rate of adaptation may not be sufficient for species with longer generation times or more specialized ecological requirements.

5.3 Changes in Insect Physiology and Immunity

Insects are ectothermic, meaning their physiological processes are directly influenced by environmental temperatures. Rising temperatures can induce heat stress, which negatively impacts insect immunity and survival (Wojda 2017). Elevated temperatures can suppress the immune response in bees, making them more susceptible to pathogens like *Nosema* and viruses. Heat stress has been shown to reduce the hemocyte count and antimicrobial peptide production in insects like the tobacco hornworm (*Manduca sexta*), compromising their ability to fend off infections. In agricultural contexts, weakened insect immunity due to climate-induced stress can influence pest dynamics, potentially leading to more severe outbreaks. Climate change is also altering the thermal tolerance ranges of many insects, affecting their ability to survive in fluctuating environments (Colinet et al. 2015). Insects that can adjust their physiology through acclimatization may be better equipped to cope with extreme temperature changes. For example, some insects can enhance their thermal tolerance by producing heat shock proteins that protect cellular structures from damage during high temperatures. Not all species have the same capacity for acclimatization; studies have shown that tropical insects are more vulnerable to warming because they are adapted to narrow temperature ranges, making them less resilient to even modest increases in temperature. Thermal acclimatization can also involve behavioral changes, such as seeking cooler microhabitats or altering activity patterns to avoid heat stress (Enriquez-Urzelai et al. 2020). The availability of suitable microhabitats may decline as global temperatures continue to rise, limiting the effectiveness of these adaptive strategies. The interplay between physiological and behavioral responses highlights the complexity of predicting insect responses to climate change, especially given the variability in species' resilience and adaptive capacities.

6. MITIGATION STRATEGIES AND ADAPTIVE MANAGEMENT

6.1 Integrated Pest Management (IPM) in a Changing Climate

In climate change, Integrated Pest Management (IPM) plays a critical role in controlling insect pest populations in a sustainable manner. IPM focuses on combining multiple strategies, such as biological control, cultural practices, and chemical controls, to manage pest populations while minimizing environmental impacts (Table 3) (Tiwari 2024). As temperatures rise and pest ranges expand, the use of IPM becomes even more vital to prevent over-reliance on chemical pesticides, which can lead to resistance and negative effects on non-target species. Adjusting planting dates, employing crop rotation, and using pest-resistant crop varieties are strategies that can reduce pest pressures while enhancing resilience to climate variability. Biological control, which involves the use of natural predators, parasitoids, or pathogens, is a key component of IPM that can be adapted to address climate-driven changes in pest populations. For example, introducing or conserving natural enemies like ladybugs (*Coccinellidae*) and parasitic wasps can help suppress aphid outbreaks (Riddick et al. 2009). Habitat management, such as creating buffer zones and hedgerows, can support beneficial insect populations by providing refuges and alternative food sources. Developing and deploying pest-resistant crop varieties through traditional breeding and genetic engineering can reduce the need for chemical interventions. Crops that are genetically engineered to withstand pests, such as Bt cotton, have shown promise in reducing pesticide use and improving yields under changing climatic conditions.

6.2 Conservation Efforts to Protect Insect Biodiversity

Climate change poses a significant threat to insect biodiversity, necessitating robust conservation efforts to restore and protect critical habitats. Habitat restoration involves re-establishing native vegetation, enhancing water availability, and removing invasive species to create favorable conditions for native insects (Negash 2021). For example, restoring wetlands and riparian zones can benefit aquatic insects, which are particularly vulnerable to changes in water temperature and flow. Protecting key habitats, such as grasslands, forests, and pollinator corridors, is essential for supporting species with specialized ecological needs. Creating protected areas that are resilient to climate change can help conserve vulnerable species and maintain ecological functions. Targeted conservation strategies are required to protect species that are highly sensitive to climate change, such as certain pollinators, butterflies, and other insects with narrow habitat requirements. This can involve measures like assisted migration, where species are relocated to areas with more favorable climates, or captive breeding programs to prevent extinction (Lopez 2015). Enhancing ecosystem resilience by promoting biodiversity and maintaining ecosystem services is also critical. Increasing habitat connectivity through ecological corridors can facilitate species movement in response to shifting climate zones. Community-based

Table 3. Integrated Pest Management (IPM) in a changing climate

Component of IPM	Role in Pest Management	Impact of Climate Change	Adaptation Strategies
Cultural Practices	Altering farming techniques to disrupt pest lifecycles and habitats.	Changing climate affects pest population dynamics and crop suitability.	Adaptive crop rotations, adjusting planting schedules, and using climate-resilient crop varieties.
Biological Control	Using natural enemies (predators, parasitoids, pathogens) to control pests.	Climate-induced shifts in predator-prey relationships and distribution.	Enhancing conservation biological control by protecting natural habitats and ensuring year-round availability of hosts.
Chemical Control	Application of pesticides for immediate pest suppression.	Increased pest resistance due to frequent applications under favorable conditions.	Using climate-specific pesticide application timings and integrating precision application techniques.
Monitoring and Surveillance	Regular monitoring of pest populations and environmental conditions.	Faster pest outbreaks and unpredictable pest migrations.	Using AI and remote sensing technologies for real-time monitoring and predictive modeling.
Pest-Resistant Varieties	Developing crop varieties genetically resistant to pests.	Potential loss of resistance due to new pest strains evolving in warmer climates.	Breeding climate-resilient varieties with broad-spectrum resistance traits.
Physical and Mechanical Control	Direct physical removal or barriers to prevent pest access to crops.	Altered pest behavior due to extreme weather patterns.	Innovative methods like solar traps, climate-adaptive netting, and enhanced mechanical weeding.
Climate-Smart IPM Strategies	Adjusting IPM components to align with changing climatic conditions.	Increased unpredictability in pest emergence and behavior.	Developing region-specific IPM packages tailored to climate scenarios.
Use of Predictive Models	Forecasting pest outbreaks based on environmental and climatic data.	Complex interactions between climate factors and pest development cycles.	Leveraging big data and machine learning to improve pest forecasting accuracy.
Conservation of Ecosystem Services	Maintaining ecosystem balance to ensure natural pest control mechanisms remain functional.	Disruption of ecosystems, reducing the availability of natural enemies.	Restoring ecosystems and promoting biodiversity in agricultural landscapes.
Education and Training	Building farmer capacity to implement IPM practices effectively.	Farmers may lack awareness of climate-related pest challenges.	Conducting climate-focused IPM training programs and workshops.

(Source: (Tiwari 2024, Riddick et al. 2009))

conservation initiatives that involve local stakeholders can also play an essential role in protecting insect habitats and promoting sustainable land use practices.

6.3 Role of Policy and International Cooperation

Effective policy frameworks and international cooperation are essential for mitigating the impacts of climate change on insect biodiversity (Ortiz et al. 2021). Global initiatives like the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) aim to reduce greenhouse gas emissions and promote conservation efforts worldwide. The Paris Agreement, which seeks to limit global warming to well below 2°C, is critical for preventing the worst effects of climate change on ecosystems. International agreements such as the Aichi Biodiversity Targets emphasize the need to protect natural habitats and reduce the extinction risk for threatened species. Incorporating climate change into conservation planning is essential for protecting insect biodiversity in the long term. This includes integrating climate models into habitat management and restoration projects to account for future changes in temperature and precipitation (Battin et al. 2007). Policies should also support research on the impacts of climate change on insects, as well as the development of adaptive management strategies to safeguard biodiversity. National governments and conservation organizations must prioritize funding for research on climate adaptation, habitat protection, and species conservation to ensure that efforts are aligned with global biodiversity goals. Collaborating with local communities, NGOs, and the private sector can enhance the effectiveness of these policies and promote sustainable resource management (Florini & Pauli 2018).

7. FUTURE RESEARCH

7.1 Areas of Uncertainty and Knowledge Gaps

One of the most significant gaps in our understanding of the impact of climate change on insect populations is the lack of long-term studies. Most existing research focuses on short-term observations, which can miss the broader, cumulative effects of climate change on insect life cycles, behavior, and ecosystem interactions. Insects have complex life histories that are influenced by a range of environmental factors, including temperature, precipitation, and habitat availability. Long-term studies are essential to understand how these factors interact over time to affect population dynamics, migration patterns, and species survival (Clutton-Brock & Sheldon 2010). These studies can help predict the responses of both pest and beneficial insect species to ongoing environmental changes and inform adaptive management strategies. While substantial progress has been made in understanding the impacts of individual climate factors like temperature on insect physiology, there remains a significant knowledge gap in how multiple, interacting factors influence insect ecology. For example, increased atmospheric CO_2 levels can alter plant chemistry, affecting herbivorous insects, while rising temperatures simultaneously impact insect metabolism and phenology. The combined effects of these factors are complex and can vary across species, ecosystems, and regions, making it challenging to generalize findings. Interactions between abiotic stressors such as heatwaves, droughts, and changing precipitation patterns can exacerbate the vulnerability of insects to climate change (Harvey et al. 2020). Addressing these gaps will require integrative studies that consider multiple climate variables to better predict future impacts on insect populations and ecosystem services.

7.2 Emerging Technologies and Methodologies

Emerging technologies, such as remote sensing and ecological modeling, provide new opportunities for monitoring insect populations and their responses to climate change. Remote sensing allows researchers to track habitat changes, vegetation dynamics, and even insect swarms over large spatial scales, providing crucial data for assessing the impacts of climate change on insect distribution (Rhodes et al. 2022). Ecological models can integrate data from various sources to predict changes in insect populations and their interactions with ecosystems under different climate scenarios. These models are invaluable for exploring the potential range shifts of pests, pollinators, and other ecologically significant insects. Genomics is another powerful tool for understanding the genetic basis of insect adaptation to climate change. Advances in sequencing technologies have enabled researchers to study the genetic diversity, gene flow, and evolutionary responses of insect populations. Genomic studies on the mountain pine beetle (*Dendroctonus ponderosae*) have identified genes associated with cold tolerance, which has facilitated the beetle's range expansion into previously colder regions. Transcriptomics can reveal how insects regulate gene expression in response to environmental stressors, such as heat or drought (Shu et al. 2020). Integrating these technologies into climate change research can help identify adaptive traits and inform conservation strategies. Citizen science and the use of big data are emerging as essential tools for tracking insect populations over large geographic areas and extended periods. Public participation in biodiversity monitoring, facilitated by platforms like iNaturalist and the Global Biodiversity Information Facility (GBIF), has significantly increased the volume of data available on insect distributions and phenology. These large datasets can be analyzed using machine learning algorithms to detect patterns and predict changes in insect populations in response to climate variables (Domingues et al. 2022). For example, citizen scientists have contributed to the monitoring of pollinator declines in Europe, providing valuable data that would be difficult to collect solely through traditional scientific methods. Leveraging big data from citizen science initiatives can enhance our understanding of climate change impacts and inform conservation policies at regional and global levels.

7.3 Interdisciplinary Approaches

Addressing the challenges posed by climate change requires a collaborative, interdisciplinary approach. Entomologists, climatologists, and ecologists must work together to develop comprehensive models that incorporate biological, environmental, and socio-economic factors (Parham et al. 2015). For example, integrating climate models with ecological data on insect populations can help predict future changes in species distributions and identify vulnerable habitats that require conservation efforts. Collaborations with policy-makers are essential to translate scientific findings into actionable policies that protect insect biodiversity and ecosystem services. Interdisciplinary research can also facilitate the development of adaptive management strategies that address both local and global challenges. Understanding how climate change affects agricultural pests and pollinators can inform policies on sustainable agriculture, pesticide use, and habitat conservation (Decourtye et al. 2019). Collaboration between scientists and stakeholders can promote the adoption of integrated pest management (IPM) practices that are resilient to changing climatic conditions. By fostering interdisciplinary communication and partnerships, researchers can generate holistic solutions to mitigate the impacts of climate change on insects and the ecosystems they support.

8. CONCLUSION

Climate change poses profound and complex challenges to insect ecology, affecting both pest populations and non-pest species critical to ecosystems. Rising temperatures, altered precipitation patterns, and increased CO_2 levels are driving shifts in insect phenology, distribution, and behavior, often leading to mismatches with their food sources and habitats. The cascading effects on agriculture, biodiversity, and ecosystem services such as pollination and nutrient cycling are concerning. While adaptive strategies like Integrated Pest Management (IPM), habitat conservation, and technological advancements in monitoring offer hope, significant knowledge gaps remain, particularly regarding the combined effects of multiple climate stressors. Future research must prioritize long-term studies, leverage emerging technologies, and encourage interdisciplinary collaboration to develop effective mitigation strategies. By integrating science, policy, and community action, we can better protect insect biodiversity and ensure ecosystem resilience in the face of climate change.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Abrol, D. P., & Abrol, D. P. (2012). Climate change and pollinators. *Pollination biology: Biodiversity conservation and agricultural production*, 479-508.

Agrell, J., Anderson, P., Oleszek, W., Stochmal, A., & Agrell, C. (2004). Combined effects of elevated CO 2 and herbivore damage on alfalfa and cotton. *Journal of Chemical Ecology*, *30*, 2309-2324.

Atkinson, C. J., Brennan, R. M., & Jones, H. G. (2013). Declining chilling and its impact on temperate perennial crops. *Environmental and Experimental Botany*, *91*, 48-62.

Battin, J., Wiley, M. W., Ruckelshaus, M. H., Palmer, R. N., Korb, E., Bartz, K. K., & Imaki, H. (2007). Projected impacts of climate change on salmon habitat restoration. *Proceedings of the national academy of sciences*, *104*(16), 6720-6725.

Chown, S. L., & Gaston, K. J. (1999). Exploring links between physiology and ecology at macro-scales: the role of respiratory metabolism in insects. *Biological Reviews*, *74*(1), 87-120.

Clutton-Brock, T., & Sheldon, B. C. (2010). Individuals and populations: the role of long-term, individual-based studies of animals in ecology and evolutionary biology. *Trends in ecology & evolution*, *25*(10), 562-573.

Colinet, H., Sinclair, B. J., Vernon, P., & Renault, D. (2015). Insects in fluctuating thermal environments. *Annual review of entomology*, *60*(1), 123-140.

Coops, N. C., Wulder, M. A., & Waring, R. H. (2012). Modeling lodgepole and jack pine vulnerability to mountain pine beetle expansion into the western Canadian boreal forest. *Forest Ecology and Management*, *274*, 161-171.

Danks, H. V. (1978). Modes of seasonal adaptation in the insects: I. Winter survival. *The Canadian Entomologist*, *110*(11), 1167-1205.

Darke, R., & Tallamy, D. W. (2014). *The living landscape: Designing for beauty and biodiversity in the home garden*. Timber Press.

Decourtye, A., Alaux, C., Le Conte, Y., & Henry, M. (2019). Toward the protection of bees and pollination under global change: present and future perspectives in a challenging applied science. *Current opinion in insect science*, *35*, 123-131.

Domingues, T., Brandão, T., & Ferreira, J. C. (2022). Machine learning for detection and prediction of crop diseases and pests: A comprehensive survey. *Agriculture*, *12*(9), 1350.

Enriquez-Urzelai, U., Tingley, R., Kearney, M. R., Sacco, M., Palacio, A. S., Tejedo, M., & Nicieza, A. G. (2020). The roles of acclimation and behaviour in buffering climate change impacts along elevational gradients. *Journal of Animal Ecology*, *89*(7), 1722-1734.

Florini, A., & Pauli, M. (2018). Collaborative governance for the sustainable development goals. *Asia & the Pacific Policy Studies*, *5*(3), 583-598.

Folland, C. K., Rayner, N. A., Brown, S. J., Smith, T. M., Shen, S. S. P., Parker, D. E., ... & Sexton, D. M. H. (2001). Global temperature change and its uncertainties since 1861. *Geophysical Research Letters*, *28*(13), 2621-2624.

Frank, S. D. (2021). Review of the direct and indirect effects of warming and drought on scale insect pests of forest systems. *Forestry: An International Journal of Forest Research*, *94*(2), 167-180.

Goulson, D., Nicholls, E., Botías, C., & Rotheray, E. L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, *347*(6229), 1255957.

Green, C. K., Moore, P. J., & Sial, A. A. (2019). Impact of heat stress on development and fertility of Drosophila suzukii Matsumura (Diptera: Drosophilidae). *Journal of insect physiology*, *114*, 45-52.

Harvey, J. A., Heinen, R., Gols, R., & Thakur, M. P. (2020). Climate change-mediated temperature extremes and insects: From outbreaks to breakdowns. *Global change biology*, *26*(12), 6685-6701.

Harvey, J. A., Heinen, R., Gols, R., & Thakur, M. P. (2020). Climate change-mediated temperature extremes and insects: From outbreaks to breakdowns. *Global change biology*, *26*(12), 6685-6701.

Hoelmer, K. A., & Kirk, A. A. (2005). Selecting arthropod biological control agents against arthropod pests: can the science be improved to decrease the risk of releasing ineffective agents?. *Biological control*, *34*(3), 255-264.

John, A., Kaur, A., Bhat, K. A., Ganie, S. A., Nugroho, C., Handoko, I., & Wani, A. K. (2024). Adapting to climate extremes: Implications for insect populations and sustainable solutions. *Journal for Nature Conservation*, 126602.

Karley, A. J., Parker, W. E., Pitchford, J. W., & Douglas, A. E. (2004). The mid-season crash in aphid populations: why and how does it occur?. *Ecological Entomology*, *29*(4), 383-388.

Khalifa, S. A., Elshafiey, E. H., Shetaia, A. A., El-Wahed, A. A. A., Algethami, A. F., Musharraf, S. G., ... & El-Seedi, H. R. (2021). Overview of bee pollination and its economic value for crop production. *Insects*, *12*(8), 688.

Kumar, L., Chhogyel, N., Gopalakrishnan, T., Hasan, M. K., Jayasinghe, S. L., Kariyawasam, C. S., ... & Ratnayake, S. (2022). Climate change and future of agri-food production. In *Future foods* (pp. 49-79). Academic Press.

Kumar, R. M., Gadratagi, B. G., Paramesh, V., Kumar, P., Madivalar, Y., Narayanappa, N., & Ullah, F. (2022). Sustainable management of invasive fall armyworm, Spodoptera frugiperda. *Agronomy*, *12*(9), 2150.

Littlefield, C. E., Krosby, M., Michalak, J. L., & Lawler, J. J. (2019). Connectivity for species on the move: supporting climate-driven range shifts. *Frontiers in Ecology and the Environment*, *17*(5), 270-278.

Liu, K. Q., Wang, L. X., Zhang, T. T., Bai, S. X., Wang, K. Q., Wang, Z. Y., ... & Hutchison, W. D. (2021). Voltine ecotypes of the Asian corn borer and their response to climate warming. *Insects*, *12*(3), 232.

Lopez, J. (2015). Biodiversity on the brink: The role of assisted migration in managing endangered species threatened with rising seas. *Harv. Envtl. L. Rev.*, *39*, 157.

Macfadyen, S., McDonald, G., & Hill, M. P. (2018). From species distributions to climate change adaptation: knowledge gaps in managing invertebrate pests in broad-acre grain crops. *Agriculture, ecosystems & environment*, *253*, 208-219.

Medlock, J. M., & Vaux, A. G. (2015). Impacts of the creation, expansion and management of English wetlands on mosquito presence and abundance–developing strategies for future disease mitigation. *Parasites & vectors*, *8*, 1-13.

Musolin, D. L. (2007). Insects in a warmer world: ecological, physiological and life-history responses of true bugs (Heteroptera) to climate change. *Global Change Biology*, *13*(8), 1565-1585.

Navarro, L., Morin, H., Bergeron, Y., & Girona, M. M. (2018). Changes in spatiotemporal patterns of 20th century spruce budworm outbreaks in eastern Canadian boreal forests. *Frontiers in Plant Science*, *9*, 1905.

Negash, L. (2021). A Selection of African Native Trees: Biology, Uses, Propagation and Restoration Techniques. *Addis Ababa, Ethiopia*.

Nicholls, C. I., & Altieri, M. A. (2013). Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. *Agronomy for Sustainable development*, *33*, 257-274.

Oliver, T. H., Heard, M. S., Isaac, N. J., Roy, D. B., Procter, D., Eigenbrod, F., ... & Bullock, J. M. (2015). Biodiversity and resilience of ecosystem functions. *Trends in ecology & evolution*, *30*(11), 673-684.

Ortiz, A. M. D., Outhwaite, C. L., Dalin, C., & Newbold, T. (2021). A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. *One Earth*, *4*(1), 88-101.

Parham, P. E., Waldock, J., Christophides, G. K., Hemming, D., Agusto, F., Evans, K. J., ... & Michael, E. (2015). Climate, environmental and socio-economic change: weighing up the balance in vector-borne disease transmission. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1665), 20130551.

Rhodes, M. W., Bennie, J. J., Spalding, A., ffrench-Constant, R. H., & Maclean, I. M. (2022). Recent advances in the remote sensing of insects. *Biological Reviews*, *97*(1), 343-360.

Riddick, E. W., Cottrell, T. E., & Kidd, K. A. (2009). Natural enemies of the Coccinellidae: parasites, pathogens, and parasitoids. *Biological Control*, *51*(2), 306-312.

Sambaraju, K. R., & Goodsman, D. W. (2021). Mountain pine beetle: an example of a climate-driven eruptive insect impacting conifer forest ecosystems. *CABI Reviews*, (2021).

Shu, B., Wu, Y., Qu, M., Pu, X., Wu, Z., & Lin, J. (2020). Comparative transcriptomic analyses revealed genes and pathways responsive to heat stress in Diaphorina citri. *Gene*, *727*, 144246.

Singer, M. C., & Parmesan, C. (2010). Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy?. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1555), 3161-3176.

Sun, Y., Guo, H., & Ge, F. (2016). Plant–aphid interactions under elevated CO2: some cues from aphid feeding behavior. *Frontiers in plant science*, *7*, 502.

Tiwari, A. K. (2024). IPM Essentials: Combining biology, ecology, and agriculture for sustainable pest control. *Journal of Advances in Biology & Biotechnology*, *27*(2), 39-47.

Welch, K. D., & Harwood, J. D. (2014). Temporal dynamics of natural enemy–pest interactions in a changing environment. *Biological control*, *75*, 18-27.

Wojda, I. (2017). Temperature stress and insect immunity. *Journal of Thermal Biology*, *68*, 96-103.

Yadav, A. N., Kour, D., Kaur, T., Devi, R., Yadav, A., Dikilitas, M., ... & Saxena, A. K. (2021). Biodiversity, and biotechnological contribution of beneficial soil microbiomes for nutrient cycling, plant growth improvement and nutrient uptake. *Biocatalysis and Agricultural Biotechnology*, *33*, 102009.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/127744