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The Impact of Climate Change on Agricultural Insect Pests: Non-linear Population Dynamics, Evolutionary Responses and Implications for Crop Production and Pest Management

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ABSTRACT

Climate change is altering insect pest behavior, distribution and crop damage worldwide. Rising temperatures, changing rainfall, elevated CO_2 and more frequent extreme weather events are driving these changes. This review synthesizes recent findings on climate driven changes in agricultural insect pest dynamics and their implications for crop protection. The findings show that pests are moving toward the poles and to higher elevations, completing more generations per year and causing greater crop damage. Temperate regions face the largest increases in pest pressure, while tropical species are more vulnerable to warming as they already live close to their thermal limits. Shifts in pest emergence timing often create mismatches with natural enemies, weakening biological control. Some insect species are evolving in response to climate change, but others cannot adapt fast enough. Non-linear responses, such as temperature thresholds for winter survival, mean that pest pressure can increase suddenly once critical limits are crossed. Crop losses from insect pests are projected to increase substantially with warming, threatening global food security. These losses are expected to hit smallholder farmers in developing countries the hardest. Climate smart pest management, which combines monitoring, predictive tools and ecological approaches, offers a way forward. However, significant gaps remain in understanding how multiple climate stressors interact and how pests evolve in response to warming. More research is needed, particularly in tropical regions where data are scarce.

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INTRODUCTION

Climate change is one of the most serious challenges facing global agriculture and food security today. The Earth's average temperature has risen by about 1.1°C since pre-industrial times (IPCC, 2021). Rainfall patterns are changing, extreme weather events like heatwaves, droughts and floods are happening more often and atmospheric CO_2 levels have exceeded 420 ppm (Folland et al. 2001). These changes affect how crops grow, where pests live and the balance between insects, their host plants and their natural enemies (Skendzic et al. 2021; Subedi et al. 2023).

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Insects are the most diverse group of animals on Earth and play many important roles in agriculture. Some insects are pests that damage crops, some are pollinators that help plants reproduce and others are natural enemies that keep pest populations under control (Li & Wiens, 2023). Because insects are cold-blooded, their body temperature and most of their physiological processes depend on the temperature of their surroundings (Chown & Gaston, 1999). This means even small changes in climate can affect their development, reproduction, survival and movement (Harvey et al. 2020).

When temperature rises, insect metabolism speeds up. This accelerates feeding and increases crop damage (Dukes et al. 2009). Warmer conditions also shorten development time, allowing pests to complete more generations each year (Skendzic et al. 2021; Altermatt, 2010). Many pests are now expanding their geographic ranges toward the poles and to higher elevations, reaching areas where they were previously unable to survive (Grunig et al. 2020; Thakur et al. 2025). This is especially true in temperate regions, where milder winters allow more pests to survive and build up populations (Bale & Hayward, 2010; Schneider et al. 2021).

The economic impact is already huge. Bradshaw et al. (2016) estimated that damage from invasive pests exceeded US $423 billion worldwide. Studies project that crop losses from insect pests will increase by 10-25% for each degree of warming (Deutsch et al. 2018). Under 2°C warming, yield losses due to pests could reach 18% for wheat, 32% for rice and 23% for maize (Subedi et al. 2023). These losses threaten global food security, especially in developing countries where smallholder farmers are most vulnerable (Kumar et al. 2022).

Climate change does not only affect pest biology directly. It also disrupts ecological interactions. The timing of pest emergence and crop growth is shifting, often creating mismatches between pests and their natural enemies (Renner & Zohner, 2018; Tougeron et al. 2020). This weakens biological control and can lead to pest outbreaks (Harvey et al. 2020). In addition, elevated CO_2 changes plant chemistry, reducing plant defenses and making crops more vulnerable to attack (DeLucia et al. 2012; Guo et al. 2012). Changes in rainfall, especially drought, also stress plants and make them more susceptible to pests (Netherer et al. 2019).

The combined effects of these changes are complex and often non-linear. Grunig et al. (2020) found that pest pressure does not increase gradually with temperature. Instead, there is an inflection point around -3°C in minimum winter temperature. Below this threshold, winter mortality keeps pest populations low. Above it, conditions become suitable for pests to establish and thrive. Once this threshold is crossed, pest pressure increases rapidly. This non-linear response means that some regions may face sudden and unexpected pest problems.

Insects are also responding through evolutionary changes. Some species are adapting to warmer conditions through genetic changes in thermal tolerance and development time (Broo et al. 2018; Sambaraju & Goodsman, 2021). Others show phenotypic plasticity, adjusting their behavior or physiology to cope with stress (Gibert et al. 2019). However, not all species can adapt fast enough. Species with narrow temperature ranges, limited dispersal, or small populations are most at risk (Lande & Shannon, 1996; Harvey et al. 2020). Understanding these evolutionary responses is important for predicting future pest problems.

Although many studies have examined climate change and insect pests, most have focused on single aspects such as range shifts, phenological changes, or physiological responses in isolation. Few have attempted to bring together the full range of ecological and evolutionary responses, including non-linear outbreak dynamics, trophic disruptions, evolutionary adaptation and their combined implications for crop production and pest management within a single framework. Moreover, previous studies have often concentrated on temperate regions, with less attention to tropical agricultural systems where pest pressures are already high and data are scarce. This review addresses these gaps by synthesizing evidence across multiple response types and geographic regions, with a particular focus on identifying non-linear thresholds, evolutionary constraints and the practical implications for climate smart pest management. By doing so, this review aims to provide a more integrated understanding of how climate change is reshaping agricultural pest systems and to highlight priority areas for future research and policy action.

The objectives of this review are:

1. To examine how climate change (temperature, rainfall, CO_2 and extreme weather) drives changes in agricultural insect pest biology and ecology;
2. To identify non-linear pest responses, thermal thresholds and range expansion patterns;
3. To analyze how climate change disrupts ecological interactions such as phenological synchrony and biological control;
4. To assess the evidence for evolutionary adaptation in pest species and its limits;
5. To evaluate the implications for crop production and food security; and
6. To outline adaptive pest management strategies.

RESEARCH METHODOLOGY

Literature Search Strategy

The literature search was conducted using Web of Science, Scopus, PubMed and Google Scholar for papers published between January 2000 and June 2026. The search was limited to this period to capture the most recent and relevant research on climate change and insect pests, as the majority of studies on this topic have emerged over the past two decades. Search terms including "climate change," "global warming," "insect pest," "agricultural pest," "range expansion," "voltinism," "thermal threshold," "phenology," "trophic interactions," "IPM," and "RCP scenarios" were used during the search for literature. Specific pest species such as *Helicoverpa armigera*, *Spodoptera frugiperda* and *Nilaparvata lugens* were also used as search terms.

The initial database search yielded the following number of records:

Web of Science (n = 78)

Scopus (n = 92)

PubMed (n = 45)

And Google Scholar (n = 60)

Giving a total of 275 potential papers.

Screening Process and Study Selection

Duplicate records were identified and removed manually by checking author names, titles and publication years. After removing duplicates, 210 unique records remained. The screening process was conducted in two stages. First, titles and abstracts were reviewed against pre-defined inclusion and exclusion criteria.

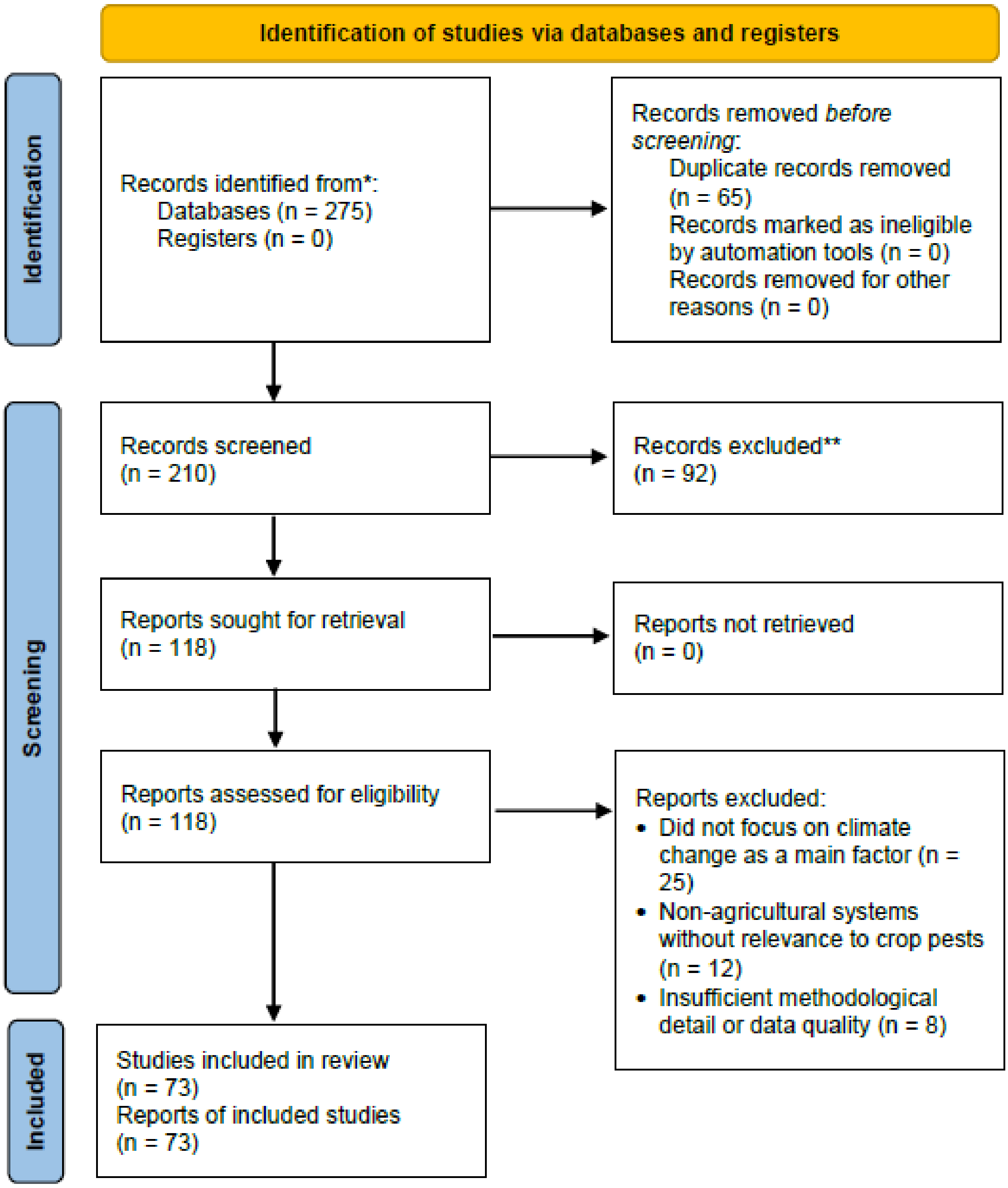

Figure 1. Flowchart of studies selected for systematic review

Studies were included if they examined direct effects of climate on insect physiology, development, or behavior; geographic range shifts or distribution changes; phenological shifts and trophic mismatches; evolutionary responses to climate change; crop yield impacts; or pest management adaptations.

Studies were excluded if they did not focus on climate change as a main factor, or if they examined non-agricultural systems without relevance to crop pests. This initial screening reduced the number of records to 118. Second, the full texts of the remaining 118 papers were read and assessed for methodological quality and relevance.

Studies were included only if they presented original data, clear methods and findings relevant to the review objectives. Both peer-reviewed journal articles and review papers were considered. Original research articles provided primary data on pest responses, while review papers were used to identify additional references and to provide broader context. Studies from all geographic regions were included, covering temperate, tropical and subtropical agricultural systems. No geographic restrictions were applied to ensure a comprehensive global perspective. After full-text screening, 73 articles met all inclusion criteria and were incorporated into the final review. A flow diagram illustrating the literature selection process is presented in Figure 1 above.

Data Extraction and Synthesis

From each study, information was recorded about climate variables, pest species, geographic region, response variables and main findings. The extracted data were grouped by theme and consistent patterns were identified across studies.

RESULTS

Direct Effects of Climate Factors on Insect Pests

Climate change is reshaping insect ecology through a series of interconnected environmental changes that influence pest development, survival, distribution, and interactions with host plants and natural enemies. These ecological responses can increase pest pressure, reduce crop productivity, and threaten global food security, particularly when combined with rapid changes in temperature and precipitation patterns. At the same time, the resulting agricultural impacts highlight the need for integrated and adaptive pest management strategies that strengthen crop resilience under changing climatic conditions. Figure 2 below provides a conceptual overview of the major pathways through which climate change affects insect ecology and the subsequent consequences for agricultural production and food systems.

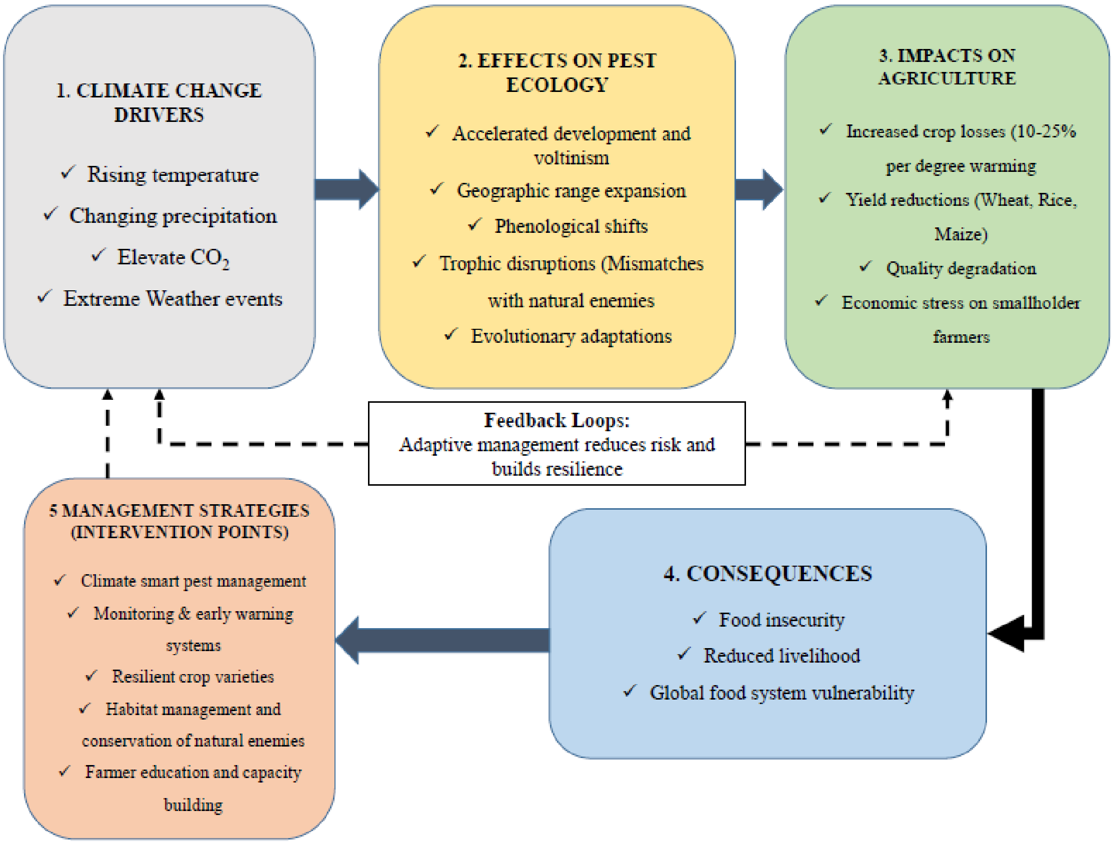

Figure 2. Conceptual Model of Climate Change Impacts on Agricultural Insect Pests and Food Security

Temperature Effects on Development, Reproduction and Survival

Temperature is the most important climate factor for insects. Development rates increase with temperature up to a certain point, then decline sharply at high temperatures (Rebaudo & Rabhi, 2018). When temperatures rise, insect metabolism speeds up. Each 2°C increase can raise metabolic rates by 10-25%, which means insects eat more and cause more crop damage (Dukes et al. 2009). Warmer temperatures also shorten development time, allowing pests to complete more generations each year (Skendzic et al. 2021). The cotton bollworm (*H. armigera*) is a good example. In many agricultural areas, it now produces more generations per year because of warmer growing seasons (Sharma, 2014). Similar patterns of increased voltinism have been reported for the European corn borer, codling moth and tobacco caterpillar across different regions (Altermatt, 2010; Stoeckli et al. 2012; Srinivasa Rao et al. 2015).

But not all insects respond the same way. Tropical insects often live near their upper temperature limit already. Even small increases in temperature can be harmful to them (Deutsch et al. 2008). Temperate insects may benefit from warming, but extreme heat events can kill them (Gonzalez-Tokman et al. 2020). However, few studies have examined tropical pest responses directly, so considerable uncertainty remains about how these species will fare under future warming. A study by Deutsch et al. (2018) found that global crop losses to insect pests will increase by 10-25% for each degree of temperature rise. Under 2°C warming, projected yield losses due to pests are 18% for wheat, 32% for rice and 23% for maize.

Precipitation Impacts on Pest Population Dynamics

Rainfall changes affect pests in different ways. Moderate drought often makes pest problems worse because stressed plants produce fewer defensive chemicals and are easier for insects to attack (Netherer et al. 2019). Aphids and whiteflies, which suck sap from plants, do well on drought-stressed crops (Sconiers & Eubanks, 2017). Heavy rain can wash away small insects like aphids. But high humidity also creates good conditions for other pests (Pathak et al. 2012). In tropical regions, heavy rain can stop pests from migrating. For example, in southern China, heavy rain during the pre-flood season makes it hard for the white-backed planthopper to migrate eastward (Chen et al. 2019). Long-term data on precipitation effects are scarce for most pest species, making it difficult to draw firm conclusions about rainfall-driven changes in pest dynamics.

Elevated CO_2 and Plant-Pest Interactions

Higher CO_2 levels change how plants grow. They increase the carbon-to-nitrogen ratio in plant tissues. This makes plants less nutritious for insects that eat them. To get enough nitrogen, insects have to eat more plant material, which means more crop damage (DeLucia et al. 2012). Elevated CO_2 can also reduce plant defenses. It suppresses jasmonic acid, a hormone plants use to defend against insects. Guo et al. (2012) found that elevated CO_2 reduced tomato resistance to cotton bollworm. Aphids often do better under elevated CO_2 (Rehman & Kumar, 2018). Most studies on CO_2 effects have been conducted in controlled environments, and whether these findings translate to field conditions remains uncertain.

Extreme Weather Events and Insect Mortality

Heatwaves, droughts, floods and storms are becoming more common. Heatwaves can kill insects directly when temperatures go above their lethal limits. They can also reduce fertility at temperatures below lethal levels. This is called "thermal fertility limits" (Walsh et al. 2019). Heat stress can also weaken insect immune systems, making them more vulnerable to disease (Wojda, 2017).

Extreme events also have indirect effects. Drought-stressed trees are more easily attacked by bark beetles (Netherer et al. 2019). Heatwaves can make pests and their natural enemies emerge at different times (Harvey et al. 2020). But some species are resilient and can survive extreme events, then increase rapidly when conditions improve. There is disagreement in the literature about whether extreme events will reduce pest populations or trigger outbreaks, as outcomes depend on the relative sensitivities of pests and their natural enemies (Harvey et al. 2020).

Climate change influences insect pests through multiple climatic drivers that often interact rather than acting independently. Although temperature has received the greatest attention, changes in precipitation, atmospheric CO_2 concentration and the increasing frequency of extreme weather events also shape pest population dynamics in different ways across ecosystems. Bringing these factors together provides a broader perspective on how different climatic variables influence insect biology in temperate and tropical regions. Table 1 summarizes representative examples from the literature and highlights the diversity of pest responses under changing climatic conditions.

Table 1: *Summary of Climate Change Effects on Insect Pest Biology Across Major Biomes*

Climatic Parameter	Region	Impact on Pest Populations	Key Examples	References
Rising mean temperature during development season	Temperate and Tropical	Accelerated development, increased feeding, more generations per year	Cotton bollworm (*Helicoverpa armigera*) shows more generations in warmer years	Skendzic et al. 2021; Sharma, 2014; Altermatt, 2010
Increasing minimum winter temperature	Temperate	Higher overwintering survival, range expansion poleward	Mountain pine beetle expanded into Canada; Southern green stink bug moved 85 km north in Japan	Bale & Hayward, 2010; Tougou et al. 2009; Schneider et al. 2021
Increasing maximum summer temperature (heat waves)	Temperate and Tropical	Heat stress, mortality, reduced fertility, disruption of host-parasitoid synchrony	Diamondback moth and its parasitoid show differential heat tolerance	Harvey et al. 2020; Gonzalez-Tokman et al. 2020; Walsh et al. 2019
Changing precipitation patterns	Tropical	Mixed effects: heavy rain limits migration; drought increases sap-feeding pests	White-backed plant hopper migration hindered by heavy rain; aphids increase under drought	Chen et al. 2019; Netherer et al. 2019; Sconiers & Eubanks, 2017
Extreme weather events	Temperate and Tropical	Population crashes, outbreaks, habitat destruction	Locust outbreaks after cyclones; bark beetle outbreaks after drought	Meynard et al. 2020; Netherer et al. 2019; Harvey et al. 2020
Elevated atmospheric CO_2	Global	Changes plant nutrition, reduces plant defenses, alters herbivore feeding	Elevated CO_2 reduces tomato resistance to cotton bollworm; aphids increase on legumes	DeLucia et al. 2012; Guo et al. 2012; Rehman & Kumar, 2018

Non-Linear Pest Responses and Threshold Effects

Temperature Inflection Points and Accelerated Pest Pressure

Pest responses to temperature are not always gradual. Grunig et al. (2020) found an important inflection point at about -3°C in the minimum temperature of the coldest month. Below this temperature, winter mortality keeps pest populations low. Above it, conditions become suitable for pests to establish and thrive. When this threshold is crossed, pest pressure increases rapidly. Similar thresholds have been identified for other pests in Europe and Asia, though the exact temperature varies among species (Schneider et al. 2021; Musolin et al. 2010). This means pest range expansion is not smooth. It can happen suddenly when critical temperature limits are crossed. Agricultural areas near these thermal boundaries face rapid changes in pest risk.

Overwintering Survival Thresholds

Winter survival is a key factor controlling pest populations in temperate regions. Insects survive harsh winter conditions by entering diapause, a state of suspended development. The starting or ending of diapause is usually triggered by changes in temperature and daylight length. But as the climate warms, these natural signals become unreliable. Insects may go into diapause too soon or wake up too late, leaving them vulnerable to starvation, cold snaps, or missing the window when their host plants are available. Milder winters allow more pests to survive (Bale & Hayward, 2010). The cotton bollworm and European corn borer both show higher survival in warmer winters, leading to earlier outbreaks (Schneider et al. 2021).

The relationship between winter temperature and survival has clear thresholds. For some species, a 1°C drop in January temperature can increase winter mortality by about 15% (Musolin et al. 2010). So small changes in winter temperatures can have big effects. Uncertainties remain about how warming will affect diapause timing, particularly because photoperiod cues may become mismatched with temperature cues.

Voltinism Shifts and Generation Number Changes

Voltinism means the number of generations a species completes per year. Warmer temperatures increase voltinism in many pests. Species that used to have one or two generations a year can now have three or more (Altermatt, 2010). Examples include the codling moth in central Europe (Stoeckli et al. 2012), the European corn borer in northern Europe (Grunig et al. 2020) and the cotton bollworm in many regions (Sharma, 2014). Srinivasa Rao et al. (2015) found that the tobacco caterpillar in India will likely have 1-2 more generations in the future. Development time will be reduced by 18-22%. This shorter time between generations means pests can grow faster and cause more damage. The magnitude of voltinism change varies among species, with those having flexible diapause responses showing the largest increases (Liu et al. 2021).

Outbreak-Breakdown Cycles under Temperature Extremes

Temperature extremes can cause both outbreaks and breakdowns of insect populations. Harvey et al. (2020) defined outbreaks as rapid increases in insect numbers that harm resources. Breakdowns are population crashes that lead to local extinction.

Herbivore outbreaks are often temporary. In one scenario, the herbivore loses its natural enemies because the enemies are more sensitive to temperature extremes. The herbivore then overeats its food plant and crashes. This is a "boom-bust" cycle. In another scenario, if herbivores are more sensitive to extremes than their enemies, their collapse causes dependent enemies to decline too. These cycles can disrupt ecosystems (Harvey et al. 2020). Whether outbreaks or breakdowns occur depends on which trophic level is more temperature-sensitive, a relationship that is poorly understood for most pest systems.

Geographic Range Shifts and Invasive Species Expansion

Poleward and Altitudinal Migrations

As temperatures rise, many insects are moving toward the poles and to higher elevations. More than 1,700 species globally have shifted their ranges pole ward at about 6.1 km per decade. Mountain species are moving upslope at about 6.1 meters per decade (Thakur et al. 2025).

In Europe, butterflies have expanded their ranges northward by 150-200 km in recent decades (Thakur et al. 2025). Bumblebees have lost ground at their southern range edges without expanding northward at the same rate. This means their ranges are getting smaller. For high-elevation specialists, moving upslope eventually leads to habitat loss because mountain tops are limited. The rate and direction of range shifts vary considerably among species, with high-dispersal species moving faster than those with limited mobility (Parmesan, 2006).

Invasive Species Establishment in Novel Regions

Climate change helps invasive species by making new areas suitable for them. Warmer winters, longer growing seasons and changed rainfall patterns help non-native insects survive and reproduce (Hulme, 2017). The Asian tiger mosquito, which spreads dengue and chikungunya, has moved into temperate regions because of milder winters and more rainfall (Yadav et al. 2024). The fall armyworm, originally from the Americas, has invaded Africa and Asia since 2016. It causes 20-50% yield losses in maize (Kumar et al. 2022). The mountain pine beetle has moved into colder areas of Canada and Alaska, killing many trees (Coops et al. 2012). However, the role of biotic interactions in mediating invasion success under climate change remains poorly understood (Hulme, 2017).

Regional Case Examples of Range Expansion

Several regional examples show these patterns clearly.

1. The southern green stink bug in Japan moved its northern limit northward by about 85 km over 45 years. January temperature and the number of cold days were the main factors controlling its range (Tougou et al. 2009).
2. The pine processionary moth has expanded both northward and to higher elevations in Europe because of warmer winters (Battisti et al. 2006).
3. The oak processionary moth likes warm microclimates and has spread where oak trees grow along roads (De Boer and Harvey 2020).

4. The coffee berry borer has moved to higher elevations in East Africa as rising temperatures allow it to survive above 1,500 meters (Jaramillo et al. 2011). These case studies consistently identify warming as the primary driver, though expansion rates vary from a few kilometers to over 100 kilometers per decade depending on species traits and local conditions.

One of the most visible biological consequences of climate change is the movement of insect species beyond their historical geographic boundaries. As climatic barriers become less restrictive, many economically important pests are establishing populations in regions where they were previously absent, creating new challenges for crop protection and biosecurity. Examining representative examples from different continents illustrates that range expansion is occurring across diverse pest groups and agricultural systems. A compilation of the key invasive and expanding pest species together with the climatic drivers and agricultural consequences reported in previous studies are presented in Table 2.

Table 2: *Geographic Range Shifts and Invasive Pest Species under Climate Change*

Pest Species	Common Name	Native Range	Expansion Area	Key Driver	Impact	References
Spodoptera frugiperda	Fall armyworm	Tropical Americas	Africa, Asia, Australia	Warming temperatures, wind patterns	20-50% maize yield losses; >$3 billion annual damage	Kumar et al. 2022; Maino et al. 2021
Tuta absoluta	Tomato leaf miner	South America	Europe, Africa, Asia	Warmer temperatures, multiple generations	>50% postharvest tomato losses	Desneux et al. 2010; Grunig et al. 2020
Dendroctonus ponderosae	Mountain pine beetle	Western North America	Canada, Alaska (northward)	Warmer winters, reduced cold mortality	Massive tree mortality; >57 billion CAN dollars economic impact	Carroll et al. 2006; Sambaraju & Goodsman, 2021; Coops et al. 2012
Nezara viridula	Southern green stink bug	Tropical regions	Japan (85 km northward)	Milder winter temperatures	Increased crop damage in new regions	Tougou et al. 2009; Musolin et al. 2010
Aedes albopictus	Asian tiger mosquito	Southeast Asia	Europe, North America	Warmer winters,	Vector for dengue, Zika,	Yadav et al. 2024;

				increased precipitation	chikungunya	Skendzic et al. 2021
Hypothenemus hampei	Coffee berry borer	Central Africa	Higher elevations in East Africa (>1500 m)	Increased minimum night temperatures	Coffee production losses in highland areas	Jaramillo et al. 2011
Bemisia tabaci	Tobacco whitefly	Tropical/subtropical	Expanded in East/Central Africa	Climate suitability improvement	Vector for cassava viral diseases; pandemic in Africa	Kriticos et al. 2020; Sarwar, 2020
Leptinotarsa decemlineata	Colorado potato beetle	Southwestern US/Mexico	Europe, Asia (northward)	Warmer winters, longer growing seasons	Potato crop damage in new temperate regions	Popova, 2014; Bale & Hayward, 2010

Disruption of Trophic Interactions and Ecological Networks

Phenological Mismatches between Pests and Natural Enemies

Climate change disrupts the timing between pests and their natural enemies. Different species respond differently to temperature cues. If pests emerge earlier than their enemies, they may escape control and have population booms (Renner & Zohner, 2018).

Aphid populations often peak earlier than their parasitoids under warming, leading to uncontrolled outbreaks (Tougeron et al. 2020). In East African mountain farms, warming lets maize stem borers move to higher altitudes. But their parasitic enemies do not follow, so biological control fails above 1200 meters (Mwalusepo et al. 2015).

Parasitoids often have narrower temperature ranges than their hosts (Agosta et al. 2018). Parasitoid development lags behind pest reproduction as temperatures rise. This weakens natural pest control (Harvey et al. 2020). The magnitude of phenological mismatch varies across systems, and it is unclear whether natural enemies will adapt to the new timing over time.

Plant Defense Responses under Climate Stress

Drought and heat stress weaken plant defenses. Stressed plants produce fewer defensive chemicals and are more vulnerable to attack (Netherer et al. 2019). Elevated CO_2 can also reduce plant resistance by changing hormone pathways (Guo et al. 2012).

Heat stress can slow both primary and secondary metabolism in plants, weakening their defenses against insects (Bita & Gerats, 2013). Plant hormones like salicylate and jasmonic acid help plants respond to stress. But how these responses interact with climate change is still not well understood (Dar et al. 2015). The magnitude of defense suppression varies across plant species and stress types, and field-based evidence remains limited.

Trophic Cascade Effects in Agroecosystems

Changes at one level of the food chain affect other levels. When herbivores are better adapted to temperature extremes than their enemies, they may have outbreaks (Harvey et al. 2020). When enemies are more sensitive, pest control fails.

In one experiment, warming increased herbivore biomass more than plant biomass, while parasitoid biomass did not change (de Sassi & Tylianakis, 2012). The result was communities dominated by herbivores. Higher trophic levels are generally more negatively affected by climate change (Voigt et al. 2003). However, some studies have found parasitoids to be equally or more tolerant than their hosts, so the outcome depends on the species involved (Hance et al. 2007).

Vector-Borne Disease Transmission Dynamics

Climate change affects insects that spread plant diseases. Whiteflies spread over 200 plant viruses and do well in warm, dry conditions (Sarwar, 2020). Thrips spread Tomato spotted wilt virus more effectively at higher temperatures (Jones & Barbetti, 2012). Aphids reproduce more in warm springs and survive better in mild winters, which increases virus spread (Skendzic et al. 2021).

Kriticos et al. (2020) showed that climate change made conditions better for the tobacco whitefly in East and Central Africa. This contributed to a pandemic of cassava diseases. Climate suitability for this insect improved significantly in affected areas over 39 years. The relationship between temperature and disease transmission is not always linear, and the effects of extreme heat on vector survival and virus replication remain uncertain.

Evolutionary Responses and Adaptive Constraints

Phenotypic Plasticity and Acclimatization

Insects can adjust to environmental changes through phenotypic plasticity. This means they change their traits without genetic changes. Plastic responses include changing diapause timing, foraging behavior, or reproduction rates under different temperatures (Chakraborty et al. 2025; Gotthard et al. 2025). This flexibility can help populations survive temporarily while genetic adaptation catches up.

Acclimatization, or hardening, happens when brief heat exposure makes insects more tolerant to later heat (Colinet et al. 2015). Heat hardening can improve survival in later heatwaves. But there are limits. Energy spent on stress responses may reduce reproduction. Plasticity is only effective within certain temperature ranges (Gibert et al. 2019). The extent to which plasticity can buffer populations against long-term warming is debated, with some studies suggesting limited scope for adjustment beyond certain thresholds.

Genetic Adaptations in Thermal Tolerance and Life History Traits

Some insects show genetic adaptation to warming. In Drosophila flies, there are clines in gene frequencies related to temperature regulation across different latitudes (Broo et al. 2018). Laboratory selection experiments have produced rapid evolution in thermal tolerance, development rate and stress resistance within just a few generations (Broo et al. 2018).

The mountain pine beetle has evolved greater cold tolerance, which helps it spread northward (Sambaraju & Goodsman, 2021). Fruit flies in warmer areas have genetic changes that increase heat shock protein expression (Broo et al. 2018). The European corn borer has adapted to warmer temperatures by changing its voltinism patterns (Liu et al. 2021). However, adaptation to one stressor can reduce tolerance to another, creating trade-offs that limit overall adaptive capacity (Harvey et al. 2020).

Limits to Evolutionary Adaptation

Not all species can adapt quickly enough. Small or isolated populations often lose genetic diversity, which limits their ability to adapt (Lande & Shannon, 1996). When multiple stressors act together, the problem gets worse.

Adapting to one stressor can reduce tolerance to another (Harvey et al. 2020). For example, selection for heat resistance reduced reproductive output under nutritional stress. Pesticide resistance sometimes reduces cold tolerance. These trade-offs make pest responses hard to predict. Predicting which species will adapt and which will not remain a major challenge, as current models can not accurately capture these complex trade-offs.

Crop Yield Impacts and Food Security Implications

Yield Losses under Climate-Driven Pest Pressure

Climate change increases crop losses from insect pests. Deutsch et al. (2018) estimated that each degree of warming will increase global crop losses by 10-25%. Under 2°C warming, projected losses are 18% for wheat, 32% for rice and 23% for maize (Subedi et al. 2023). In Africa and Asia, fall armyworm causes 20-50% yield losses in maize (Kumar et al. 2022). In Asia, rice planthopper outbreaks can cause 10-60% losses in bad years (Skendzic et al. 2021). In wheat, aphid infestations and Hessian fly outbreaks are increasing under warmer winters (Subedi et al. 2023). Projections vary across studies depending on climate scenarios and assumptions, and the extent to which elevated CO_2 may offset some losses through increased crop productivity remains uncertain.

Regional Vulnerabilities and Smallholder Impacts

The impacts are not the same everywhere. Temperate regions will see bigger increases in pest pressure than tropical regions (Deutsch et al. 2018). But tropical regions, where many developing countries are, already have serious problems. Smallholder farmers are hit hardest. The fall armyworm invasion has hurt maize farmers in sub-Saharan Africa. Surveys show household income losses up to 30% (Kumar et al. 2022). Higher input costs and lower yields make poverty worse and reduce farmers' ability to cope with future problems (Subedi et al. 2023). Whether adaptive management strategies can substantially reduce these losses is uncertain and likely depends on local conditions and the effectiveness of extension services.

Quality Degradation of Agricultural Produce

Pests not only reduce yields but also lower crop quality. The tomato leaf miner damages fruits directly. Postharvest losses often exceed 50% in tomato-growing areas of Africa and the Mediterranean (Desneux et al. 2010). Fruit flies like *Bactrocera dorsalis* cause blemishes, early fruit drop and shorter shelf life in mango, guava and citrus. This leads to export rejections (Sorahia et al. 2025). In apple and pear orchards, codling moth infestations lead to more pesticide sprays, which affects food safety (Sorahia et al. 2025). Crop quality losses have received less research attention than yield losses, so the full economic impact of climate change on agriculture may be underestimated.

DISCUSSION

This review shows that climate change is fundamentally changing how insect pests behave in agricultural systems. Rising temperatures speed up pest development, increase the number of generations per year and allow pests to move into new areas (Skendzic et al. 2021; Bebber et al. 2013). These changes are not always gradual. Often, they show threshold responses, especially when winter temperatures cross certain limits. Once thresholds are crossed, pest pressure can increase quickly (Grunig et al. 2020; Schneider et al. 2021).

Temperate regions are seeing the most dramatic changes (Deutsch et al. 2018). As cold constraints decrease, pests that were once limited to warmer areas are moving northward and to higher elevations (Parmesan, 2006; Thakur et al. 2025). This exposes agricultural regions to pests they have not dealt with before, creating new challenges for farmers (Macfadyen et al. 2018). Trophic disruptions make things worse. When pests and their natural enemies emerge at different times, biological control weakens (Renner & Zohner, 2018; Damien & Tougeron, 2019). This is especially concerning because many pests are already evolving in ways that may make them more resilient (Harvey et al. 2020; Hoffmann & Sgrò, 2011).

Researchers use two main approaches to predict pest distributions: physiological models and species distribution models (Grunig et al. 2020; Venette et al. 2010). Physiological models use lab data on development thresholds to define the fundamental niche (Kearney & Porter, 2009). Species distribution models use occurrence records to define the realized niche (Elith & Leathwick, 2009).

Grunig et al. (2020) found good agreement between these approaches for current conditions. But they diverged under future scenarios. Physiological models predicted broader niches than species distribution models. This suggests that species distribution models may underestimate potential range expansion. However, species distribution models may better capture biotic interactions that physiological models miss (Sinclair et al. 2010).

There are many sources of uncertainty: future emission scenarios, climate model projections, missing data on pest physiology and incomplete occurrence records (Bradshaw et al. 2024; Kriticos et al. 2020). Despite these uncertainties, the direction of change is consistent across studies: pest pressure will increase with warming (Deutsch et al. 2018; Yan et al. 2017).

Asymmetric responses happen because species differ in their temperature limits, development rates and phenological sensitivity (Colinet et al. 2015). Parasitoids and predators often have narrower temperature ranges than their herbivorous hosts, making them more vulnerable (Harvey et al. 2020; Hance et al. 2007).

Life stage differences also matter (Bowler & Terblanche, 2008). Eggs and pupae are immobile and cannot escape extreme temperatures. Adults may find cooler microclimates. Heat exposure at one life stage can affect later stages (Potter et al. 2011). These stage-specific vulnerabilities create complex population responses that are hard to predict (Kingsolver et al. 2011). Traditional pest management approaches, developed under stable climate conditions, are becoming less effective (Skendzic et al. 2021; Dass & Murugesan, 2026). Calendar-based spray schedules and fixed treatment thresholds no longer work when pest phenology is shifting (Heeb et al. 2019).

Adaptive integrated pest management strategies are needed (Subedi et al. 2023). These should use real-time climate monitoring, predictive modeling and flexible decision-making (Tonnang et al. 2017). Climate-smart pest management emphasizes ecological approaches: habitat management, conservation of natural enemies and resistant varieties. Climate-smart pest management refers to an approach that integrates climate information and projections into pest management decision-making to build resilience of farms and landscapes to changing pest threats (Heeb et al. 2019; Dass & Murugesan, 2026).

New technologies offer opportunities. Remote sensing, drones and automated traps improve monitoring (Sorahia et al. 2025; Subramanian et al. 2021). Artificial intelligence helps predict outbreaks. Genetic tools like CRISPR and RNA interference offer new control methods. But these technologies must be accessible and affordable for smallholder farmers (Ali et al. 2023; Haque et al. 2018; Kumar et al. 2022).

Several important gaps remain. Long-term monitoring data are lacking in many regions, especially in tropical areas where biodiversity is highest. Without consistent data, it is hard to detect trends and attribute causes. Understanding interactions between multiple stressors is a challenge. Temperature, CO_2, precipitation and land use change interact in complex ways. Most studies examine single factors in isolation. More research on combined effects is needed. Predictive models need improvement. Current models often simplify assumptions about pest biology. Incorporating evolutionary adaptation, natural enemy dynamics and host plant responses would improve accuracy.

The increasing complexity of climate-driven pest outbreaks indicates that conventional pest management alone will not be sufficient under future climatic conditions. Effective adaptation requires integrating ecological principles, technological innovations and climate information into pest management programmes. Rather than relying on a single intervention, resilient agricultural systems depend on complementary strategies that improve monitoring, prevention and rapid response. The following table summarizes the major adaptive pest management approaches that have been proposed to enhance agricultural resilience in a changing climate.

Table 3: *Adaptive Pest Management Strategies under Climate Change*

Management Component	Strategy	Climate Adaptation	Examples	References
Integrated Pest Management (IPM)	Climate-smart IPM	Use real-time climate and pest data; flexible decision-making	Adjust planting dates; use resistant varieties; dynamic thresholds	Heeb et al. 2019; Dass & Murugesan, 2026; Subedi et al. 2023
Biological Control	Conservation and augmentation of natural enemies	Protect natural enemy habitats; ensure year-round host availability	Hedgerows, floral diversity, parasitoid releases	Skendzic et al. 2021; Harvey et al. 2020
Monitoring and Surveillance	Remote sensing, drones, automated traps	Real-time pest detection; predictive modeling	MODIS/Landsat for locust tracking; pheromone traps	Subramanian et al. 2021; Rano et al. 2022; Sorahia et al. 2025
Predictive Modeling	Machine learning, AI, species distribution models	Integrate climate projections; forecast outbreaks	CLIMEX, MaxEnt for pest suitability; CNN for pest identification	Tonnang et al. 2017; Ali et al. 2023; Grunig et al. 2020
Genetic Approaches	CRISPR/Cas9, RNA interference	Develop pest-resistant, climate-resilient crop varieties	Bt crops; gene editing for tolerance	Haque et al. 2018; Chen et al. 2024
Chemical Control	Targeted pesticide application	Climate-specific timing; reduce resistance	Precision spraying; biopesticides	Lankinen et al. 2024; Dass & Murugesan, 2026
Habitat Management	Crop diversification, push-pull systems	Enhance ecosystem resilience; reduce pest pressure	Push-pull in East Africa against stemborers; intercropping	Han et al. 2022; Subedi et al. 2023
Policy and Quarantine	Strengthen biosecurity; international collaboration	Climate-adaptive quarantine measures; early detection networks	EPPO, FAO, IPPC; ISPMs; regional pest risk analysis	Szyniszewska et al. 2024; Bradshaw et al. 2024; Sorahia et al. 2025

CONCLUSION

Climate change is reshaping insect pest dynamics in many ways: faster development, more generations, range expansion, trophic disruption and evolutionary adaptation. Non-linear responses mean pest pressure can increase suddenly when temperature thresholds are crossed. Temperate regions face particularly rapid changes as cold constraints decrease.

Crop losses to insect pests are expected to increase substantially with warming, threatening global food security. Developing regions and smallholder farmers are most vulnerable. Trophic disruptions and phenological mismatches weaken biological control, making pest problems worse.

Some insects are evolving in response to climate change, but others cannot adapt fast enough. Species with narrow temperature ranges, limited dispersal, or small populations are most at risk. Generalist species with broad tolerance are likely to benefit.

Recommendations for Policy and Practice

Based on the findings of this review, this review recommends:

1. Strengthen monitoring networks: Invest in long-term pest surveillance, especially in understudied regions. Citizen science can help fill gaps.
2. Improve predictive models: Integrate climate projections, pest physiology, natural enemy dynamics and host plant responses. Use ensemble approaches to handle uncertainty.
3. Promote climate-smart IPM: Develop adaptive pest management that uses real-time monitoring, flexible decision-making and ecological approaches. Support farmer education and extension.
4. Invest in research: Prioritize studies on multi-stressor interactions, evolutionary responses and tropical ecosystems. Support long-term experiments and observations.
5. Strengthen international collaboration: Transboundary pests need coordinated surveillance and response. Share data, resources and expertise across regions.
6. Support smallholder farmers: Provide access to monitoring tools, forecasting services and adaptive management training. Develop affordable, appropriate technologies.
7. Integrate pest management into climate adaptation: National climate adaptation plans should include pest management. Agricultural policies should support climate-resilient practices.

REFERENCES

Agosta, S. J., Joshi, K. A., & Kester, K. M. (2018). Upper thermal limits differ among and within component species in a tritrophic host-parasitoid-hyperparasitoid system. *PLoS One*, *13*(6), e0198803. https://doi.org/10.1371/journal.pone.0198803

Ali, A., Hussain, T., Tantashutikun, N., Hussain, N., & Cocetta, G. (2023). Application of smart techniques, Internet of Things and data mining for resource use efficient and sustainable crop production. *Agriculture*, *13*(2), 397. https://doi.org/10.3390/agriculture13020397

Altermatt, F. (2010). Climatic warming increases voltinism in European butterflies and moths. *Proceedings of the Royal Society B: Biological Sciences, 277*(1685), 1281–1287. https://doi.org/10.1098/rspb.2009.1910

Bale, J., & Hayward, S. (2010). Insect overwintering in a changing climate. *Journal of Experimental Biology, 213*(6), 980–994. https://doi.org/10.1242/jeb.037911

Battisti, A., Stastny, M., Buffo, E., & Larsson, S. (2006). A rapid altitudinal range expansion in the pine processionary moth produced by the 2003 climatic anomaly. *Global Change Biology, 12*(4), 662–671. https://doi.org/10.1111/j.1365-2486.2006.01124.x

Bebber, D. P., Ramotowski, M. A., & Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change, 3*(11), 985–988. https://doi.org/10.1038/nclimate1990

Bita, C., & Gerats, T. (2013). Plant tolerance to high temperature in a changing environment: Scientific fundamentals and production of heat stress-tolerant crops. *Frontiers in Plant Science, 4*, 273. https://doi.org/10.3389/fpls.2013.00273

Bowler, K., & Terblanche, J. S. (2008). Insect thermal tolerance: What is the role of ontogeny, ageing and senescence? *Biological Reviews, 83*(3), 339–355. https://doi.org/10.1111/j.1469-185X.2008.00046.x

Bradshaw, C. J., Leroy, B., Bellard, C., Roiz, D., Albert, C., Fournier, A., & Courchamp, F. (2016). Massive yet grossly underestimated global costs of invasive insects. *Nature Communications, 7*(1), 12986. https://doi.org/10.1038/ncomms12986

Bradshaw, C., Eyre, D., Korycinska, A., Li, C., Steynor, A., & Kriticos, D. (2024). Climate change in pest risk assessment: Interpretation and communication of uncertainties. *EPPO Bulletin, 54*, 4–19. https://doi.org/10.1111/epp.12985

Broo, J., Mahoney, J., Bokor, J., & Hahn, D. (2018). Drowsy *Drosophila*: Rapid evolution in the face of climate change. *The American Biology Teacher, 80*(4), 272–277. https://doi.org/10.1525/abt.2018.80.4.272

Carroll, A. L., Régnière, J., Logan, J. A., Taylor, S. W., Bentz, B. J., & Powell, J. A. (2006). *Impacts of climate change on range expansion by the mountain pine beetle* (Mountain Pine Beetle Initiative Working Paper 2006-14). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre.

Chakraborty, A., Sgrò, C. M., & Mirth, C. K. (2025). Untangling plastic responses to combined thermal and dietary stress in insects. *Current Opinion in Insect Science, 68*, 101328. https://doi.org/10.1016/j.cois.2024.101328

Chen, F., Chen, L., Yan, Z., Xu, J., Feng, L., He, N., & Liu, C. (2024). Recent advances of CRISPR-based genome editing for enhancing staple crops. *Frontiers in Plant Science, 15*, 1478398. https://doi.org/10.3389/fpls.2024.1478398

Chen, H., Chang, X. L., Wang, Y. P., Lu, M. H., Liu, W. C., Zhai, B. P., & Hu, G. (2019). The early northward migration of the white-backed planthopper is often hindered by heavy precipitation in southern China during the preflood season in May and June. *Insects, 10*(6), 158. https://doi.org/10.3390/insects10060158

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. https://doi.org/10.1111/j.1469-185X.1999.tb00182.x

Colinet, H., Sinclair, B. J., Vernon, P., & Renault, D. (2015). Insects in fluctuating thermal environments. *Annual Review of Entomology, 60*, 123–140. https://doi.org/10.1146/annurev-ento-010814-021017

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*(1), 161–171. https://doi.org/10.1016/j.foreco.2012.02.011

Damien, M., & Tougeron, K. (2019). Prey-predator phenological mismatch under climate change. *Current Opinion in Insect Science, 35*, 60–68. https://doi.org/10.1016/j.cois.2019.07.002

Dar, T. A., Uddin, M., Khan, M. M. A., Hakeem, K. R., & Jaleel, H. (2015). Jasmonates counter plant stress: A review. *Environmental and Experimental Botany, 115*, 49–57. https://doi.org/10.1016/j.envexpbot.2015.02.010

Dass, K., & Murugesan, R. (2026). Ecological shifts under climate change: Understanding pest responses and agricultural vulnerability. *Journal of Agrometeorology, 28*(1), 126–138. https://doi.org/10.54386/jam.v28i1.3272

De Boer, J. G., & Harvey, J. A. (2020). Range-expansion in processionary moths and biological control. *Insects, 11*(5), 267. https://doi.org/10.3390/insects11050267

de Sassi, C., & Tylianakis, J. M. (2012). Climate change disproportionately increases herbivore over plant or parasitoid biomass. *PLoS One, 7*(7), e40557. https://doi.org/10.1371/journal.pone.0040557

DeLucia, E. H., Nabity, P. D., Zavala, J. A., & Berenbaum, M. R. (2012). Climate change: Resetting plant-insect interactions. *Plant Physiology, 160*(4), 1677–1685. https://doi.org/10.1104/pp.112.204750

Desneux, N., Wajnberg, E., Wyckhuys, K. A., Burgio, G., Arpaia, S., Narvaez-Vasquez, C. A., & Pizzol, J. (2010). Biological invasion of European tomato crops by *Tuta absoluta*: Ecology, geographic expansion and prospects for biological control. *Journal of Pest Science, 83*(3), 197–215. https://doi.org/10.1007/s10340-010-0321-6

Deutsch, C. A., Tewksbury, J. J., Huey, R. B., Sheldon, K. S., Ghalambor, C. K., Haak, D. C., & Martin, P. R. (2008). Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences, 105*(18), 6668–6672. https://doi.org/10.1073/pnas.0709472105

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., & Naylor, R. L. (2018). Increase in crop losses to insect pests in a warming climate. *Science, 361*(6405), 916–919. https://doi.org/10.1126/science.aat3466

Dukes, J. S., Pontius, J., Orwig, D., Garnas, J. R., Rodgers, V. L., Brazee, N., & Harrington, R. (2009). Responses of insect pests, pathogens and invasive plant species to climate change in the forests of northeastern North America. *Canadian Journal of Forest Research, 39*(2), 231–248. https://doi.org/10.1139/X08-171

Elith, J., & Leathwick, J. (2009). Species distribution models: Ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics, 40*(1), 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Folland, C. K., Rayner, N. A., Brown, S. J., Smith, T. M., Shen, S. S. P., Parker, D. E., Macadam, I., Jones, P. D., Jones, R. N., Nicholls, N., & Sexton, D. M. H. (2001). Global temperature change and its uncertainties since 1861. *Geophysical Research Letters, 28*(13), 2621–2624. https://doi.org/10.1029/2001GL012877

Gibert, P., Debat, V., & Ghalambor, C. K. (2019). Phenotypic plasticity, global change and the speed of adaptive evolution. *Current Opinion in Insect Science, 35*, 34–40. https://doi.org/10.1016/j.cois.2019.06.007

Gonzalez-Tokman, D., Cordoba-Aguilar, A., Dattilo, W., Lira-Noriega, A., Sanchez-Guillen, R. A., & Villalobos, F. (2020). Insect responses to heat: Physiological mechanisms, evolution and ecological implications in a warming world. *Biological Reviews, 95*(3), 802–821. https://doi.org/10.1111/brv.12588

Gotthard, K., Berger, D., & Rohner, P. (2025). Life history evolution of insects in response to climate variation: Seasonal timing versus thermal physiology. *bioRxiv*. https://doi.org/10.1101/2025.02.05.636251

Grunig, M., Calanca, P., Mazzi, D., & Pellissier, L. (2020). Inflection point in climatic suitability of insect pest species in Europe suggests non-linear responses to climate change. *Global Change Biology, 26*(11), 6338–6349. https://doi.org/10.1111/gcb.15313

Guo, H., Sun, Y., Ren, Q., Zhu-Salzman, K., Kang, L., Wang, C., & Ge, F. (2012). Elevated CO_2 reduces the resistance and tolerance of tomato plants to *Helicoverpa armigera* by suppressing the JA signaling pathway. *PLoS One, 7*(7), e41426. https://doi.org/10.1371/journal.pone.0041426

Han, P., Lavoir, A. V., Rodriguez-Saona, C., & Desneux, N. (2022). Bottom-up forces in agroecosystems and their potential impact on arthropod pest management. *Annual Review of Entomology, 67*(1), 239–259. https://doi.org/10.1146/annurev-ento-060121-060505

Hance, T., van Baaren, J., Vernon, P., & Boivin, G. (2007). Impact of extreme temperatures on parasitoids in a climate change perspective. *Annual Review of Entomology, 52*, 107–126. https://doi.org/10.1146/annurev.ento.52.110405.091333

Haque, E., Taniguchi, H., Hassan, M. M., Bhowmik, P., Karim, M. R., Śmiech, M., & Islam, T. (2018). Application of CRISPR/Cas9 genome editing technology for the improvement of crops cultivated in tropical climates. *Frontiers in Plant Science, 9*, 617. https://doi.org/10.3389/fpls.2018.00617

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. https://doi.org/10.1111/gcb.15377

Heeb, L., Jenner, E., & Cock, M. J. (2019). Climate-smart pest management: Building resilience of farms and landscapes to changing pest threats. *Journal of Pest Science, 92*(3), 951–969. https://doi.org/10.1007/s10340-019-01083-y

Hoffmann, A. A., & Sgrò, C. M. (2011). Climate change and evolutionary adaptation. *Nature, 470*(7335), 479–485. https://doi.org/10.1038/nature09670

Hulme, P. E. (2017). Climate change and biological invasions: Evidence, expectations and response options. *Biological Reviews, 92*(3), 1297–1313. https://doi.org/10.1111/brv.12282

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jaramillo, J., Muchugu, E., Vega, F. E., Davis, A., Borgemeister, C., & Chabi-Olaye, A. (2011). Some like it hot: The influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. *PLoS One, 6*(9), e24528. https://doi.org/10.1371/journal.pone.0024528

Jones, R. A., & Barbetti, M. J. (2012). Influence of climate change on plant disease infections and epidemics caused by viruses and bacteria. *CABI Reviews, 2012*, 1–33. https://doi.org/10.1079/PAVSNNR20127022

Kearney, M., & Porter, W. (2009). Mechanistic niche modelling: Combining physiological and spatial data to predict species' ranges. *Ecology Letters, 12*(4), 334–350. https://doi.org/10.1111/j.1461-0248.2008.01277.x

Kingsolver, J. G., Woods, H. A., Buckley, L. B., Potter, K. A., MacLean, H. J., & Higgins, J. K. (2011). Complex life cycles and the responses of insects to climate change. *Integrative and Comparative Biology, 51*(5), 719–732. https://doi.org/10.1093/icb/icr015

Kriticos, D. J., Darnell, R. E., Yonow, T., Ota, N., Boykin, L. M., Sutherst, R. W., & De Barro, P. J. (2020). Improving climate suitability for *Bemisia tabaci* in East and Central Africa correlates with increased prevalence of whiteflies and cassava diseases. *Scientific Reports, 10*(1), 22049. https://doi.org/10.1038/s41598-020-79149-6

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. https://doi.org/10.3390/agronomy12092150

Lande, R., & Shannon, S. (1996). The role of genetic variation in adaptation and population persistence in a changing environment. *Evolution, 50*(1), 434–437. https://doi.org/10.1111/j.1558-5646.1996.tb04504.x

Lankinen, A., Witzell, J., Aleklett, K., Furenhed, S., Karlsson Green, K., Latz, M., & Grenville-Briggs, L. (2024). Challenges and opportunities for increasing the use of low-risk plant protection products in sustainable production: A review. *Agronomy for Sustainable Development*, *44*(2), 21. https://doi.org/10.1007/s13593-024-00957-5

Li, X., & Wiens, J. J. (2023). Estimating global biodiversity: The role of cryptic insect species. *Systematic Biology*, *72*(2), 391–403. https://doi.org/10.1093/sysbio/syac069

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. https://doi.org/10.3390/insects12030232

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 and Environment*, *253*, 208–219. https://doi.org/10.1016/j.agee.2016.08.029

Maino, J. L., Schouten, R., Overton, K., Day, R., Ekesi, S., Bett, B., & Reynolds, O. L. (2021). Regional and seasonal activity predictions for fall armyworm in Australia. *Current Research in Insect Science*, *1*, 100010. https://doi.org/10.1016/j.cris.2021.100010

Meynard, C. N., Lecoq, M., Chapuis, M.-P., & Piou, C. (2020). On the relative role of climate change and management in the current desert locust outbreak in East Africa. *Global Change Biology*, *26*(7), 3753–3755. https://doi.org/10.1111/gcb.15137

Musolin, D. L., Tougou, D., & Fujisaki, K. (2010). Too hot to handle? Phenological and life-history responses to simulated climate change of the southern green stink bug *Nezara viridula*. *Global Change Biology*, *16*(1), 73–87. https://doi.org/10.1111/j.1365-2486.2009.01914.x

Mwalusepo, S., Tonnang, H. E. Z., Massawe, E. S., Okuku, G. O., Khadioli, N., Johansson, T., & Le Ru, B. P. (2015). Predicting the impact of temperature change on the future distribution of maize stem borers and their natural enemies along East African mountain gradients using phenology models. *PLoS One*, *10*(6), e0130427. https://doi.org/10.1371/journal.pone.0130427

Netherer, S., Panassiti, B., Pennerstorfer, J., & Matthews, B. (2019). Acute drought is an important driver of bark beetle infestation in Austrian Norway spruce stands. *Frontiers in Forests and Global Change*, *2*, 39. https://doi.org/10.3389/ffgc.2019.00039

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, *37*, 637–669. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100

Pathak, H., Aggarwal, P. K., & Singh, S. (2012). *Climate change impact, adaptation and mitigation in agriculture: Methodology for assessment and applications*. Indian Agricultural Research Institute.

Popova, E. N. (2014). The influence of climatic changes on range expansion and phenology of the Colorado potato beetle (*Leptinotarsa decemlineata*, Coleoptera, Chrysomelidae) in the territory of Russia. *Entomological Review, 94*(5), 643–653. https://doi.org/10.1134/S0013873814050017

Potter, K. A., Davidowitz, G., & Arthur Woods, H. (2011). Cross-stage consequences of egg temperature in the insect *Manduca sexta*. *Functional Ecology, 25*(3), 548–556. https://doi.org/10.1111/j.1365-2435.2010.01807.x

Rano, S. H., Afroz, M., & Rahman, M. M. (2022). Application of GIS on monitoring agricultural insect pests: A review. *Reviews in Food and Agriculture, 3*(1), 19–23. https://doi.org/10.26480/rfna.01.2022.19.23

Rebaudo, F., & Rabhi, V. B. (2018). Modeling temperature-dependent development rate and phenology in insects: Review of major developments, challenges and future directions. *Entomologia Experimentalis et Applicata, 166*(8), 607–617. https://doi.org/10.1111/eea.12693

Rehman, S. A., & Kumar, R. (2018). Scenario of insect pests under changing climatic situations. *International Journal of Chemical Studies, 6*(3), 77–81. https://doi.org/10.22271/chem/2018/6(3)/77-81

Renner, S. S., & Zohner, C. M. (2018). Climate change and phenological mismatch in trophic interactions among plants, insects and vertebrates. *Annual Review of Ecology, Evolution and Systematics, 49*, 165–182. https://doi.org/10.1146/annurev-ecolsys-110617-062535

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*. https://doi.org/10.1079/PAVSNNR202116018

Sarwar, M. (2020). Insects as transport devices of plant viruses. In *Applied Plant Virology* (pp. 381–402). Elsevier. https://doi.org/10.1016/B978-0-12-818654-1.00027-X

Schneider, L., Comte, V., & Rebetez, M. (2021). Increasingly favourable winter temperature conditions for major crop and forest insect pest species in Switzerland. *Agricultural and Forest Meteorology, 298*, 108315. https://doi.org/10.1016/j.agrformet.2020.108315

Sconiers, W. B., & Eubanks, M. D. (2017). Not all droughts are created equal? The effects of stress severity on insect herbivore abundance. *Arthropod-Plant Interactions, 11*(1), 45–60. https://doi.org/10.1007/s11829-016-9464-6

Sharma, H. C. (2014). Climate change effects on insects: Implications for crop protection and food security. *Journal of Crop Improvement, 28*(2), 229–259. https://doi.org/10.1080/15427528.2014.881205

Sinclair, S. J., White, M. D., & Newell, G. R. (2010). How useful are species distribution models for managing biodiversity under future climates? *Ecology and Society*, *15*(1), 8. https://doi.org/10.5751/ES-03089-150108

Skendzic, S., Zovko, M., Zivkovic, I. P., Lesic, V., & Lemic, D. (2021). The impact of climate change on agricultural insect pests. *Insects*, *12*(5), 440. https://doi.org/10.3390/insects12050440

Sorahia, D., Lokesh, M., Das, A., Kumari, N., Roy, T., Singh, V., Gawaria, J., & Mehla, S. (2025). Examining the emergence of insect pests under changing climate: A comprehensive review. *Journal of Advances in Biology and Biotechnology*, *28*(9), 1750–1765. https://doi.org/10.9734/jabb/2025/v28i93020

Srinivasa Rao, M., Swathi, P., Rama Rao, C. A., Rao, K. V., Raju, B. M. K., Srinivas, K., & Maheswari, M. (2015). Model and scenario variations in predicted number of generations of *Spodoptera litura* Fab. on peanut during future climate change scenario. *PLoS One*, *10*(2), e0116762. https://doi.org/10.1371/journal.pone.0116762

Stoeckli, S., Hirschi, M., Spirig, C., Calanca, P., Rotach, M. W., & Samietz, J. (2012). Impact of climate change on voltinism and prospective diapause induction of a global pest insect—*Cydia pomonella* (L.). *PLoS One*, *7*(4), e35723. https://doi.org/10.1371/journal.pone.0035723

Subedi, B., Poudel, A., & Aryal, S. (2023). The impact of climate change on insect pest biology and ecology: Implications for pest management strategies, crop production and food security. *Journal of Agriculture and Food Research*, *14*, 100733. https://doi.org/10.1016/j.jafr.2023.100733

Subramanian, K. S., Pazhanivelan, S., Srinivasan, G., Santhi, R., & Sathiah, N. (2021). Drones in insect pest management. *Frontiers in Agronomy*, *3*, 640885. https://doi.org/10.3389/fagro.2021.640885

Szyniszewska, A. M., Akrivou, A., Björklund, N., Boberg, J., Bradshaw, C., Damus, M., Gardi, C., Hanea, A., Kriticos, J., Maggini, R., Musolin, D. L., & MacLeod, A. (2024). Beyond the present: How climate change is relevant to pest risk analysis. *EPPO Bulletin*, *54*(S1), 20–37. https://doi.org/10.1111/epp.12986

Thakur, P., Mehla, S., Raghuram, P., Kumar, R., Kumar, V., Sharma, R., & Rana, A. (2025). Ecological and evolutionary responses of insects to climate change: A review. *International Journal of Environment and Climate Change*, *15*(12), 163–179. https://doi.org/10.9734/IJECC/2025/V15I125154

Tonnang, H. E. Z., Hervé, B. D. B., Biber-Freudenberger, L., Salifu, D., Subramanian, S., Ngowi, V. B., & Borgemeister, C. (2017). Advances in crop insect modelling methods—Towards a whole system approach. *Ecological Modelling*, *354*, 88–103. https://doi.org/10.1016/j.ecolmodel.2017.03.015

Tougeron, K., Brodeur, J., Le Lann, C., & van Baaren, J. (2020). How climate change affects the seasonal ecology of insect parasitoids. *Ecological Entomology*, *45*(2), 167–181. https://doi.org/10.1111/een.12792

Tougou, D., Musolin, D. L., & Fujisaki, K. (2009). Some like it hot! Rapid climate change promotes shifts in distribution ranges of *Nezara viridula* and *N. antennata* in Japan. *Entomologia Experimentalis et Applicata, 130*(3), 249–258. https://doi.org/10.1111/j.1570-7458.2008.00818.x

Venette, R., Kriticos, D., Magarey, R., Koch, F., Baker, R., Worner, S., & Pedlar, J. (2010). Pest risk maps for invasive alien species: A roadmap for improvement. *BioScience, 60*(5), 349–362. https://doi.org/10.1525/bio.2010.60.5.5

Voigt, W., Perner, J., Davis, A. J., Eggers, T., Schumacher, J., Bahrmann, R., & Sander, F. W. (2003). Trophic levels are differentially sensitive to climate. *Ecology, 84*(9), 2444–2453. https://doi.org/10.1890/02-0266

Walsh, B. S., Parratt, S. R., Hoffmann, A. A., Atkinson, D., Snook, R. R., Bretman, A., & Price, T. A. (2019). The impact of climate change on fertility. *Trends in Ecology and Evolution*, *34*(3), 249–259. https://doi.org/10.1016/j.tree.2018.12.002

Wojda, I. (2017). Temperature stress and insect immunity. *Journal of Thermal Biology, 68*, 96–103. https://doi.org/10.1016/j.jtherbio.2016.12.002

Yadav, S., Sarangi, S., Shafi, A. A. M., Pandey, K., Thodusu, M., Soni, S., & Parmar, S. (2024). Climate change and insect ecology: Impacts on pest populations and biodiversity. *Journal of Advances in Microbiology*, *24*(12), 103–118. https://doi.org/10.9734/JAMB/2024/V24I12876

Yan, Y., Wang, Y. C., Feng, C. C., Wan, P. H. M., & Chang, K. T. T. (2017). Potential distributional changes of invasive crop pest species associated with global climate change. *Applied Geography, 82*, 83–92. https://doi.org/10.1016/j.apgeog.2017.03.011