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Review Article

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Climate change and insect biodiversity: recent advances in impacts, mechanisms, and management

Wajid Hasan
Krishi Vigyan Kendra, Jehanabad-804432, Bihar Agricultural University, Bihar, India
**Corresponding author e-mail:* entowajid@gmail.com
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ABSTRACT
Climate change is reshaping insect biodiversity, distribution, and ecological roles at an accelerating pace, with profound implications for agriculture, human and animal health, and ecosystem functioning. Rising temperatures, altered precipitation regimes, and more frequent extreme events are driving shifts in species ranges, modifying phenology, and altering population dynamics across many insect taxa. In numerous regions, generalist and thermophilic species are expanding poleward and to higher elevations, while specialists and cold-adapted taxa face range contractions and elevated extinction risk. These changes cascade through food webs, influencing pollination services, biological control, nutrient cycling, and the spread of vector-borne diseases. In agricultural landscapes, climate warming often increases voltinism, prolongs growing seasons, and reduces overwintering mortality of key pests, thereby intensifying crop damage and complicating integrated pest management. At the same time, climate-induced asynchrony between pests and their natural enemies, or between pollinators and host plants, can weaken long-established ecological interactions. Recent advances in genomics, long-term monitoring networks, species distribution modelling, remote sensing, and AI-assisted surveillance are improving our ability to detect and predict climate-driven changes in insect populations, yet substantial data gaps remain, particularly in tropical and under-sampled regions.
Keywords: Climate change; insect biodiversity; range shifts; phenology; agricultural pests; pollinators; integrated pest management

INTRODUCTION

Climate change and why insects matter

Insects are woven into nearly every terrestrial ecosystem. They pollinate crops and wild plants, recycle nutrients, regulate pest populations, and serve as food for birds, amphibians, reptiles, and mammals. At the same time, some insects are serious crop pests or vectors of disease. Because they are small, highly sensitive to temperature and moisture, and often complete many generations within a short time, insect populations respond quickly to environmental change. That is one reason they are often described as early indicators of ecological disturbance (University of Maryland, 2022; Yadav et al., 2025).

Over the last few decades, climate change has become one of the most important forces shaping insect ecology. Rising temperatures, irregular rainfall, prolonged droughts, floods, and heat waves are no longer occasional disturbances; they are increasingly part of the new environmental background in which insects develop, reproduce, disperse, and interact with plants and natural enemies. These shifts do not affect all insects in the same way. Some species appear to benefit, especially those that tolerate warmer conditions, reproduce rapidly, and exploit a broad range of host plants. Others, particularly specialists or insects confined to cooler habitats, may decline or disappear from areas where they once thrived (Yadav et al., 2024; Yadav et al., 2025; IntechOpen, 2026). This uneven response is what makes the topic both scientifically important and agriculturally urgent. Climate change is not simply reducing insect numbers everywhere; it is reorganizing insect communities, altering species interactions, and changing the balance between harmful and beneficial insects. In crop systems, this may mean more frequent outbreaks of certain pests, new invasions into previously unaffected regions, disruption of biological control, and greater uncertainty in pest forecasting. In natural ecosystems, it may mean changes in pollination, decomposition, and the stability of food webs (University of Maryland, 2022; Yadav et al., 2024; Yadav et al., 2025).

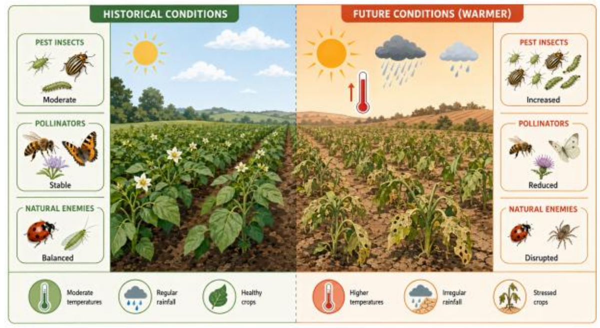
Changing distributions, phenology, and pest pressure

One of the clearest biological responses to climate change is the shift in insect distribution. As temperatures rise, many species are moving toward higher latitudes or elevations where conditions are more suitable. This pattern has already been reported across several insect groups and is especially important in the case of agricultural pests. Areas that were once too cool to support certain species may gradually become favorable, allowing pests to establish, survive winter, and complete more generations than before. This creates practical problems for farmers, extension workers, and pest management programs, because established risk maps and seasonal calendars may no longer reflect field reality (Yadav et al., 2025; IntechOpen, 2026).

Alongside distributional shifts, climate change is also affecting insect phenology, or the timing of recurring life-cycle events such as emergence, migration, oviposition, diapause, and overwintering. Warmer temperatures can accelerate development, shorten generation time, and increase voltinism in many pest species. In simple terms, some insects may now reproduce more often within a single season than they did under cooler conditions. When this happens in agricultural systems, the result can be a longer period of crop attack and greater cumulative damage. At the same time, altered rainfall and humidity may favour some pests while suppressing others, producing complex, region-specific responses that are difficult to predict without long-term monitoring (Yadav et al., 2024; Yadav et al., 2025). These changes do not occur in isolation. Insect responses are closely tied to plant physiology, crop phenology, and the performance of predators and parasitoids. A pest may increase under warmer conditions, but its natural enemy may not respond at the same rate. Likewise, pollinators may emerge earlier while flowering patterns shift differently under changing climate conditions. Such mismatches can weaken long-established ecological relationships. In agriculture, this may reduce the reliability of biological control and pollination, two ecosystem services that are essential for sustainable production. Therefore, the climate signal in entomology is not limited to insect abundance alone; it is visible in the timing, geography, and interaction networks of insect life (Yadav et al., 2024; Yadav et al., 2025).

Relevance to biodiversity, agriculture, and future research

The consequences of climate change for insect biodiversity extend well beyond individual species. When insect communities are reorganized, the effects are felt throughout ecosystems. Pollination may decline in some landscapes, herbivory may intensify in others, and decomposition or nutrient cycling may be altered in ways that affect soil processes and plant productivity. This is particularly concerning because insect populations are already under pressure from habitat fragmentation, pesticide exposure, invasive species, and land-use change. Climate change adds another layer of stress, and in many cases, it may amplify the effects of these existing pressures rather than acting alone (University of Maryland, 2022; Yadav et al., 2025).



From an agricultural perspective, the issue is especially significant. Insects influence food security in two opposite but equally important ways: as pests that reduce yield and quality, and as beneficial organisms that support pollination and natural suppression of crop enemies. Recent reviews have emphasized that warming temperatures, changing precipitation patterns, and altered host-plant quality can increase pest pressure, favor invasive insects, and complicate integrated pest management. For tropical and subtropical agriculture, including much of South Asia, these concerns are even more serious because insect development is already fast under warm conditions and farming systems are highly climate-sensitive (Yadav et al., 2024; IntechOpen, 2026; Yadav et al., 2025). At the same time, advances in entomological research are making it easier to study these changes with greater precision. Recent work highlights the growing use of genomic tools, environmental DNA, remote sensing, automated insect surveillance, and climate-linked distribution models to track shifts in insect populations and predict future risks. These methods offer new opportunities, but important gaps remain, especially in under-sampled tropical regions, in long-term field datasets, and in studies that connect biodiversity change with practical management outcomes (Advances, challenges, and future directions in entomological research, 2026; Yadav et al., 2025).

Against this background, the present review focuses on recent evidence regarding the effects of climate change on insect biodiversity and distribution, with special attention to implications for agriculture. It brings together current understanding of range shifts, phenological changes, population responses, and ecological interactions, while also considering emerging methods and management strategies. A clearer understanding of these patterns is essential not only for biodiversity conservation, but also for developing climate-resilient pest management and protecting the ecosystem services on which sustainable agriculture depends.

Global Patterns of Climate Change and Insect Responses

Warming climates and shifting insect ranges

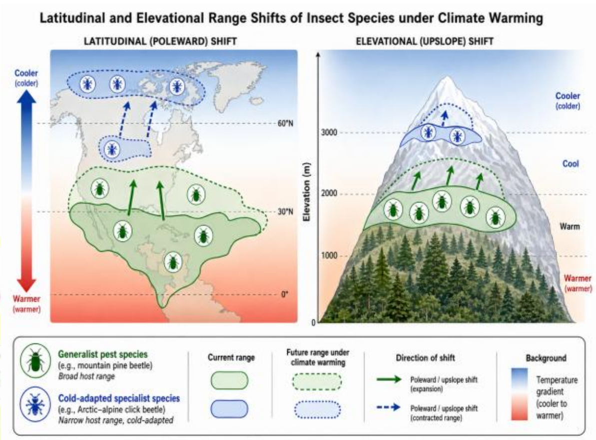
One of the most consistent responses of insects to climate change is a shift in geographic distribution. As regional temperatures rise, many species are moving toward higher latitudes and elevations in search of suitable thermal conditions. This trend has been documented in both natural and agricultural systems, and it is especially important for species whose survival, reproduction, and overwintering success are tightly controlled by temperature. In practical terms, regions that were once too cool for certain insects may now support their establishment, seasonal persistence, or even permanent residency. For entomologists and crop protection specialists, this means that pest problems are no longer confined to their traditional boundaries.

These range shifts are not uniform across all insect groups. Generalist herbivores, invasive species, and migratory pests often respond more quickly because they are better able to exploit new habitats and host plants. By contrast, species with narrow habitat requirements or limited dispersal capacity may fail to track changing climate zones and instead suffer local decline. Recent reviews indicate that warming tends to favour pest expansion in temperate and mid-to-high latitude regions more strongly than in the tropics, where many insects already live closer to their upper thermal limits (Deutsch et al., 2018; Jactel et al., 2025; Yadav et al., 2025). This distinction is important because it shows that climate change may create new pest risks in one region while increasing extinction pressure in another. In agricultural landscapes, the consequences of these distributional changes are already becoming more visible. Warming conditions can allow pests to colonize regions where crops are present, but pest pressure was once relatively low. This creates new vulnerabilities for farmers, particularly where local management practices, extension systems, and surveillance programs are built around older pest calendars. In some cases, climate change may also facilitate the spread of invasive insects through interaction with trade and transport networks, allowing pests to establish more easily once introduced into climatically suitable areas (Jactel et al., 2025; Skendžić et al., 2021). As a result, the geography of agricultural entomology is becoming increasingly dynamic.

Phenology, voltinism, and seasonal disruption

Alongside range shifts, changes in phenology are among the most widely observed responses of insects to climate change. Phenology refers to the timing of life-history events such as emergence, feeding, migration, diapause, mating, and reproduction. Because insect development is strongly temperature dependent, even modest warming can accelerate growth and shorten the time needed to complete a life cycle. In many species, this leads to earlier seasonal activity and, in some cases, a greater number of generations per year. For agricultural pests, this increase in voltinism can have major economic consequences because it extends the period over which crops are exposed to feeding damage.

A longer activity season can also alter the intensity and timing of infestations. Pests that previously caused one clear seasonal outbreak may begin to appear earlier, persist longer, or build multiple damaging peaks within a single cropping cycle. Reduced winter mortality further strengthens this trend in cooler regions, where warming allows more individuals to survive until spring. Reviews of agricultural insect responses repeatedly note that increased overwintering survival, advanced phenology, and additional generations are among the most important ways climate change increases pest risk (Skendžić et al., 2021; Yadav et al., 2024; Jactel et al., 2025). This has direct relevance for forecasting systems, as decision tools based on older thermal assumptions may underestimate future pest pressure.



However, phenological change is not simply a matter of "more insects for more months." The timing of insect life cycles is closely linked to host plant stages, floral resource availability, and the activity of predators and parasitoids. When these components respond differently to climate cues, ecological mismatches can emerge. A pollinator may become active before peak flowering, a herbivore may reach damaging density when a plant is unusually vulnerable, or a parasitoid may miss the developmental window of its host. Such mismatches can reduce pollination efficiency, weaken biological control, and destabilize trophic interactions in both natural and managed ecosystems (Yadav et al., 2025; Jactel et al., 2025). In this sense, phenological change is not only a timing issue but also a reorganization of ecological relationships.

Extremes, ecological stress, and uneven responses

Although gradual warming receives much attention, climate change is also intensifying short-term extreme events such as heat waves, droughts, heavy rainfall, and floods. These events can produce sudden and severe effects on insect populations. Some insects experience direct mortality when temperatures exceed physiological thresholds, while others suffer from desiccation, reduced fecundity, or disrupted mating and feeding behavior. At the same time, certain pest species may actually benefit from moderate drought or warmer nights if these conditions weaken host plants or reduce the effectiveness of natural enemies. This helps explain why climate change often produces highly uneven responses, even among insects living in the same agricultural landscape.

Water stress is particularly important in shaping insect performance. Drought can alter plant chemistry, reduce plant defences, and concentrate nutrients in ways that influence herbivore feeding. In some systems, stressed plants become more susceptible to attack, while in others, reduced plant quality limits herbivore growth. Heavy rainfall may physically suppress small exposed insects, but greater humidity can favour survival and reproduction in other taxa. Because of this complexity, the effect of climate change on insects is rarely determined by temperature alone; it is the interaction among heat, moisture, host quality, and species traits that shapes outcomes (Jactel et al., 2025; Skendžić et al., 2021; Yadav et al., 2024). Another increasingly important insight is that insect responses to climate change are not only ecological but also evolutionary. Recent work suggests that some pest species can adapt rapidly to warming through changes in life-history traits, potentially magnifying their agricultural impact beyond what simple statistical models predict. This means that future pest projections may be too conservative if they ignore the possibility of rapid adaptation in development rate, thermal tolerance, or reproductive performance (Benton et al., 2025). For agriculture, this is a serious concern because it implies that some pests may not merely persist under warming conditions but may become even more damaging over time.

Taken together, global patterns show that insect responses to climate change are widespread but highly variable. Warming generally promotes poleward and upward movement, earlier activity, longer damage seasons, and in many cases, greater pest pressure, especially in temperate cropping systems. Yet the same climate drivers can also increase stress, disrupt synchrony, and threaten vulnerable insect groups, including beneficial insects and biodiversity-rich specialist taxa. The emerging picture is therefore not one of a single universal response, but of broad ecological reorganization. Understanding that reorganization is essential for predicting future pest problems, conserving beneficial insects, and developing climate-resilient agricultural systems.

Impacts on Agricultural Pests and Beneficial Insects

Climate change and the biology of crop pests

Agricultural pests are among the most visible indicators of how climate change is reshaping insect ecology in crop systems. Temperature, moisture, and carbon dioxide levels directly affect pest survival, development, fecundity, and dispersal, and indirectly influence them through changes in host-plant quality and cropping patterns. As a result, rising temperatures and more variable rainfall are now recognized as major drivers of pest population dynamics and outbreak risk in many regions (Skendžić et al., 2021; Yadav et al., 2024).

One of the most consistent patterns is an increase in survival and reproduction for many pests in temperate and subtropical zones. Warmer winters reduce cold-induced mortality and allow more individuals to survive into the next growing season. Earlier springs and longer frost-free periods extend the time window for feeding, mating, and oviposition. In species whose development is strongly temperature dependent, higher mean temperatures can shorten generation time and increase voltinism, leading to more pest generations per year. Collectively, these factors can produce larger populations, earlier infestations, and more frequent or severe outbreaks, especially in crops such as wheat, rice, and maize, where pest dynamics have been linked closely to temperature regimes (Skendžić et al., 2021; Yadav et al., 2024; Skendžić, 2024).

The effects of elevated atmospheric CO_2 and altered precipitation patterns add further complexity. Increased CO_2 can change plant tissue chemistry by modifying carbon-to-nitrogen ratios and secondary metabolite profiles. In some cases, this may reduce herbivore performance, but in many situations it can lower plant nutritional quality, forcing pests to consume more foliage to meet their requirements. Drought stress and irregular rainfall can also weaken plant defenses or alter plant growth stages in ways that make crops more vulnerable to attack at critical times. Reviews of climate–pest interactions emphasize that these combined factors often lead to greater pest pressure and higher expected crop losses, particularly where climate change is accompanied by monoculture, reduced crop diversity, and simplified landscapes (Skendžić et al., 2021; Ajraf, 2025; Skendžić, 2024).

It is important to note that not all pests respond positively. In tropical regions where many insects already operate near their upper thermal limits, further warming may reduce performance or shift pests to higher elevations and latitudes. Yet even in these areas, extreme events and changed rainfall patterns can still favour certain pests over others, reshaping pest complexes in ways that complicate management. The overall picture from recent studies is that climate change tends to increase the unpredictability and, in many cases, the intensity of pest problems, even if some individual species decline (Skendžić et al., 2021; Yadav et al., 2024; Yadav et al., 2025).

Natural enemies, biological control, and ecological balance

Beneficial insects, predators, parasitoids, and other natural enemies are central to sustainable pest management. They help keep pest populations below damaging levels and reduce the need for chemical interventions. However, these beneficial species are subject to the same climatic drivers as pests, and they do not always respond in parallel. Differences in thermal tolerance, development thresholds, overwintering strategies, and resource requirements mean that climate change can easily disrupt the synchrony between pests and their natural enemies (Skendžić et al., 2021; Climate change impacts on pest and beneficial insects, 2025).

For example, a parasitoid may require specific temperature ranges to complete development and may time its life cycle to coincide with a particular life stage of its host. If warming accelerates host development more than parasitoid development, the host may “escape” parasitism by reaching less vulnerable stages before parasitoids are most active. Similarly, predators such as ladybird beetles or lacewings may be more sensitive to heat waves or drought than their prey, reducing their abundance or hunting efficiency just when pest populations are increasing. Over time, these mismatches can weaken the stabilising role of biological control in agroecosystems (Skendžić et al., 2021; Jactel et al., 2025; Climate change impacts on pest and beneficial insects, 2025).

Extreme weather events create additional challenges. Heavy rains and storms may wash away or physically damage fragile natural enemies, while heat waves can cause acute mortality, especially for species that lack behavioural or microhabitat options for thermal refuge. Repeated exposure to such extremes may push beneficial insects toward local decline, even if pests are partly able to exploit microclimatic shelters or resume activity quickly. In regions where farmers respond to increased pest pressure by intensifying insecticide use, beneficial insects face a double burden of climatic stress and chemical exposure. This can further tip the ecological balance in favour of pests and erode the long-term effectiveness of natural control (Skendžić et al., 2021; Volk et al., 2023; Climate change impacts on pest and beneficial insects, 2025). These trends highlight an important management message: climate change not only alters pests; it reshapes the whole pest–natural enemy complex. Strategies that focus solely on pests without considering natural enemies may produce short-term relief but undermine resilience in the long run. Climate-smart integrated pest management therefore needs to pay explicit attention to maintaining and enhancing populations of beneficial insects, for example, through habitat management, reduced chemical exposure, and the use of climate-resilient biological control agents (Skendžić et al., 2021; Jactel et al., 2025; Climate change impacts on pest and beneficial insects, 2025).

Pollinators under a warming and more variable climate

Pollinators occupy a special place at the intersection of climate change, biodiversity, and agriculture. Insect pollinators, bees, butterflies, hoverflies, moths, and others, support the reproduction of a large share of flowering plants and significantly contribute to yields and quality in fruits, vegetables, oilseeds, and seed crops. Any climate-driven change in their abundance, diversity, or activity patterns therefore has direct consequences for food security and ecosystem functioning (Volk et al., 2023; Indian Entomology, 2025; Journal IJECC, 2025).

Climate change affects pollinators through both direct and indirect pathways. Directly, increased temperatures, heat waves, and altered rainfall can influence foraging activity, mortality, reproductive success, and the incidence of pathogens or parasites. For example, high temperatures may restrict foraging in some bee species to cooler hours, reducing the time available for effective pollination. Extended droughts can reduce floral abundance and continuity, leaving pollinators with fewer and more scattered resources. At the same time, extreme weather events such as heavy storms can destroy nests or floral resources in a single episode, especially for ground-nesting and solitary bees (Volk et al., 2023; Journal IJECC, 2025).

Indirectly, climate change alters plant phenology and floral resource landscapes. If flowering shifts earlier or later than the activity period of key pollinators, mismatches may arise, reducing the number of visits per flower and, ultimately, fruit or seed set. Cropping patterns and varieties may also change in response to climate, further modifying the spatial and temporal distribution of floral resources. In many regions, these climate-related changes operate on top of existing stresses from habitat loss, pesticide exposure, invasive plants, and diseases. Recent work focusing on India and other climate-vulnerable regions underscores that climate change is now considered one of the major drivers of pollinator decline and pollination instability, with serious implications for smallholder agriculture and horticulture (Volk et al., 2023; Indian Entomology, 2025; Journal IJECC, 2025).

Despite these risks, it is also clear that not all pollinators are equally vulnerable. Some species show considerable plasticity in foraging behaviour, nesting choices, and seasonal activity, which may buffer them against moderate climatic shifts. There is evidence that certain pollinators can adjust their phenology or shift their ranges in ways that partially track changing climates, at least in the short to medium term. However, this adaptive capacity has limits, and the combined pressure of climate change and other anthropogenic stressors raises concerns about long-term resilience. For agriculture, this means that protecting pollinators under climate change will require both targeted conservation measures and broader efforts to create diverse, pesticide-reduced, and structurally complex landscapes that support pollinators across seasons and years (Volk et al., 2023; Indian Entomology, 2025; Journal IJECC, 2025; Hatfield & Lebuhn, 2024). Overall, climate change is pushing agricultural pest and beneficial insect dynamics into a more variable and uncertain regime. Many pest species are gaining advantages through higher survival and reproduction, while natural enemies and pollinators face a mix of stressors that may erode their capacity to provide ecosystem services. The challenge for entomology and agricultural science is to understand these interacting trends well enough to design management and policy responses that protect food production and biodiversity in the decades ahead.

Mechanistic bases: physiology, phenology, genetics, and behaviour

Physiological responses to a changing climate

The most immediate reason insects respond so strongly to climate change is that they are ectothermic animals. Their body temperature, metabolic rate, development, movement, and reproduction are closely tied to ambient environmental conditions, especially temperature and moisture. When temperatures rise within a favourable range, many insects develop faster, feed more actively, and complete their life cycles in less time, which can increase population growth and outbreak potential in agricultural settings. At the same time, once temperatures approach or exceed upper thermal limits, performance may decline sharply through heat stress, dehydration, reduced fecundity, or mortality.

Moisture and humidity are equally important, although they are often discussed less than temperature. Changes in rainfall patterns influence desiccation risk, egg survival, larval development, and habitat suitability, while drought can alter plant water status and indirectly affect herbivorous insects through changes in host quality. In some cases, moderate water stress may favour certain pests if plants become physiologically weakened, but severe drought or extreme heat can suppress insects that lack refuge or physiological tolerance. This is one reason climate change does not generate a single universal response across all species; instead, responses depend on where each species sits relative to its thermal and hydric limits. Recent work also emphasises that insect heat tolerance is more complex than previously assumed. It is shaped not only by maximum lethal temperatures but also by acclimation capacity, exposure duration, developmental stage, and microclimatic buffering. Eggs, larvae, pupae, and adults may differ greatly in tolerance, and short but repeated heat events can have lasting effects even when they do not cause immediate death. For agricultural entomology, this means that climatic risk cannot be estimated only from average seasonal warming; short-term temperature spikes and humidity stress may be equally important in determining future pest abundance and beneficial insect survival.

Phenology and seasonal timing

Phenology provides one of the clearest windows into how insects respond to a warming world. Seasonal events such as emergence, diapause termination, migration, mating, and oviposition are strongly influenced by temperature and, in many species, by photoperiodic cues. As warming alters the pace of seasonal development, insects may emerge earlier in spring, prolong their period of activity, or add extra generations within the same year. In agricultural systems, these shifts can increase crop vulnerability by extending pest pressure across longer parts of the growing season.

Yet phenological responses are not mechanically identical across taxa. Species differ in whether they are univoltine or multivoltine, whether they rely more heavily on temperature or photoperiod, and how diapause is regulated. Because of these differences, two insects sharing the same field or habitat may respond in very different ways to the same climatic trend. This helps explain why climate change often disrupts synchrony among pests, host plants, pollinators, and natural enemies rather than simply shifting all organisms forward at the same pace.

Phenological mismatch has major ecological and agricultural implications. If a pest reaches peak abundance when crops are in a particularly sensitive stage, damage may intensify even without a dramatic increase in overall pest numbers. If a parasitoid becomes active after its host has already passed the vulnerable stage, biological control may weaken. Likewise, if pollinators and flowering periods become out of step, crop pollination and seed production may decline. These examples show that climate change influences not only how many insects are present, but also whether they are active at the right or wrong time.

Genetics, plasticity, and behavioural adjustment

Not all insect responses to climate change are immediate physiological reactions. Many are shaped by phenotypic plasticity, adaptive evolution, and changes in behaviour. Plasticity allows insects to adjust traits such as development rate, diapause timing, feeding pattern, or habitat use without genetic change, giving them a short-term way to cope with variable conditions. Behavioural responses may include shifting activity to cooler hours of the day, using shaded microhabitats, changing migration timing, or altering host selection under climate stress. These adjustments can temporarily buffer populations against climatic extremes and help explain why some species persist despite substantial environmental change.

Over longer timescales, there is growing evidence that insects can also evolve in response to changing climates. Recent work suggests that life-history traits, thermal tolerance, and photoperiodic responses may undergo heritable shifts under continued warming, especially in species with large populations and short generation times. This evolutionary potential is particularly relevant for pest species, because even modest changes in development time, diapause regulation, or stress tolerance may significantly increase their agricultural impact. In other words, future pest risk may depend not only on current climatic suitability but also on the capacity of insects to adapt genetically to new thermal environments.

Behaviour also plays a central role in mediating climate responses. Insects that rely on pheromonal communication, host-finding cues, or finely timed mating behaviour may be affected when warming changes volatile release, wind patterns, humidity, or daily activity windows. Feeding behaviour can also shift under climate stress, either because insects need more resources to compensate for nutritionally altered plants or because plants become more or less suitable under elevated CO_2 and drought. These behavioural pathways are often overlooked, yet they can strongly influence pest severity, pollinator efficiency, and the stability of insect–plant interactions. Taken together, physiology, phenology, genetics, and behaviour provide the mechanistic foundation for understanding insect responses to climate change. Climate warming alters the basic environmental conditions under which insects survive and reproduce, but the outcome depends on species-specific tolerance, seasonal timing systems, plasticity, and adaptive capacity. This is why some insects expand, some decline, and many respond in complex or unpredictable ways. For both biodiversity conservation and agricultural management, a mechanistic understanding is essential because it allows more realistic forecasting than broad descriptive trends alone.

Emerging tools and modern approaches

Recent progress in entomology has made it possible to study climate-driven insect change with much greater precision than was possible a decade ago. Traditional field sampling, morphological identification, and seasonal observation remain essential, but they are now increasingly supported by molecular tools, artificial intelligence, remote sensing, automated traps, and spatial modeling. This shift is important because climate change affects insects across scales, from genes and physiology to landscapes and migration routes, and no single method can capture all of these dimensions.

A major advance has come from **molecular monitoring**. DNA metabarcoding allows researchers to identify multiple insect taxa from mixed samples rapidly, while environmental DNA, including airborne eDNA, offers a non-invasive way to detect insect presence from environmental material rather than from collected specimens alone. These methods are especially useful for biodiversity surveys, invasive species detection, and monitoring difficult-to-identify taxa, although they still depend heavily on reference libraries and careful interpretation of abundance patterns. In climate-change research, such tools can strengthen early warning systems by detecting shifts in species composition before those shifts become obvious in conventional surveys. At the same time, **AI-based monitoring** is rapidly transforming entomological research. Deep-learning systems can identify insects from images, classify movement and behavior, and process large volumes of acoustic or visual data much faster than manual methods. Smart traps, automated cameras, and acoustic sensors can now support near real-time monitoring of pest populations, pollinators, and vectors, making them highly relevant for climate-sensitive agricultural surveillance. These technologies are not flawless, since model accuracy depends on training data quality and taxonomic coverage, but they are increasingly valuable when combined with expert validation and conventional trapping.

Remote sensing, drones, and sensor networks are also becoming more important in climate-oriented entomology. Drones can help map crop condition, canopy stress, and pest hotspots, while distributed environmental sensors can capture local microclimates that strongly influence insect performance but are often missed by coarse weather data. This is especially useful because many insect responses depend on field-level temperature and humidity conditions rather than on regional averages alone. In agricultural landscapes, integrating drone observations with insect traps and predictive models opens the way for more targeted and climate-responsive pest management. Another important development is the increasing use of **integrated modelling frameworks**. Species distribution models, phenology models, and machine-learning approaches are being used to predict where insects may move, when outbreaks may occur, and which systems are likely to be most vulnerable under future climates. These models are particularly powerful when they combine biological traits, land use, host plant data, and climate projections, but their reliability still depends on good-quality long-term observations. As a result, the future of climate-change entomology will depend not only on new technologies themselves, but also on how well they are integrated with classical taxonomy, ecological knowledge, and field validation.

Table 1. Emerging tools in entomology relevant to climate-change research

S. No.	Tool/approach	Main use in entomology	Relevance to climate-change studies	Key limitation
1	DNA metabarcoding	Rapid identification of multiple taxa from mixed samples	Detects biodiversity shifts and early community turnover	Depends on strong reference databases
2	Environmental DNA (eDNA)	Non-invasive detection of species from environmental samples	Useful for monitoring rare, invasive, or difficult-to-sample insects	Presence data may not reflect true abundance
3	Airborne eDNA	Detection of terrestrial insects from air samples	Helps broad-scale biodiversity surveillance under changing environments	Still developing; not all species are consistently detected
4	AI-based image recognition	Automated identification from trap or field images	Supports real-time tracking of pest and pollinator dynamics	Accuracy varies across taxa and image conditions
5	Acoustic monitoring with AI	Detection of insects from sound signatures	Useful for continuous monitoring of activity patterns and distribution	Limited to taxa or contexts with usable acoustic signals
6	Drones and sensor networks	Crop surveillance, habitat mapping, microclimate recording	Links pest abundance with field-scale climatic conditions	Cost, regulation, and data-processing complexity
7	Machine-learning distribution models	Forecasting insect occurrence and spread	Predicts future range shifts and outbreak risk under climate scenarios	Sensitive to biased or sparse training data

Management, policy, and adaptation strategies

Climate change is making insect management more uncertain, but it is also making it clearer that conventional pest control alone is not enough. Static pest calendars, routine insecticide use, and narrowly targeted interventions are often poorly suited to a world in which insect phenology, distribution, and outbreak intensity are shifting from year to year. Recent work increasingly supports a move toward climate-smart pest management, where monitoring, forecasting, habitat management, and adaptive decision-making are combined rather than treated as separate activities. In this context, the goal is not only to suppress pests, but also to maintain ecological resilience, reduce risk, and protect beneficial insects under changing climatic conditions.

A key principle of adaptation is **dynamic surveillance**. Climate-driven pest responses are often detected first through changes in timing, distribution, or outbreak frequency, so regular monitoring becomes the foundation of any climate-resilient strategy. This includes trap networks, field scouting, phenology tracking, and climate-linked early warning systems that integrate weather data with insect development models. When such systems are linked with extension services and digital advisory tools, they can help farmers respond earlier and more precisely, reducing unnecessary pesticide use while improving control timing. Another major area of adaptation is **climate-smart IPM**. Integrated pest management remains the most widely recommended framework, but recent literature argues that it must be updated to account for climate variability, emerging pests, and more complex pest–natural enemy interactions. This means revising economic thresholds, adjusting sowing dates where appropriate, selecting climate-resilient crop varieties, conserving natural enemies, and integrating biological, cultural, and mechanical controls more deliberately. In a warming world, IPM is increasingly being framed not just as a pest-control strategy, but as part of broader climate-smart agriculture.

Pollinator and beneficial insect conservation must also become a formal part of adaptation planning. Habitat simplification and intensive chemical use can magnify climate stress on pollinators and natural enemies, especially when high temperatures and resource scarcity already reduce survival and activity. Measures such as flower-rich field margins, refugia, reduced insecticide pressure, diversified landscapes, and improved nesting resources can help buffer beneficial insects against climate variability while strengthening ecosystem services. These interventions are particularly important in crop systems that rely heavily on insect pollination or biological control. The policy-level adaptation requires more than farm-level changes. National and regional systems need stronger pest forecasting networks, better data sharing, support for long-term insect monitoring, and closer coordination between agriculture, biodiversity, and climate institutions. The literature also points to the need for policies that encourage ecological intensification, reduce overreliance on broad-spectrum insecticides, and invest in research on climate-resilient biological control, pollinator health, and predictive modelling. In countries with climate-vulnerable agriculture, these actions are especially important because insect-related losses can directly affect smallholder livelihoods and food security.

Table 2. Management and policy responses to climate-driven insect change

S. No.	Strategy	Main target	Practical application	Expected benefit
1	Climate-linked pest surveillance	Crop pests and invasive insects	Use traps, field scouting, and weather-linked alerts to detect shifting pest activity	Earlier intervention and reduced surprise outbreaks
2	Climate-smart IPM	Pests across major cropping systems	Revise thresholds, diversify control tactics, integrate climate information into decisions	More resilient and less pesticide-dependent pest management
3	Forecasting and predictive models	Seasonal and emerging pest risks	Combine climate data, phenology models, and crop information for risk prediction	Better timing of control measures and improved preparedness
4	Habitat management for beneficial insects	Pollinators and natural enemies	Maintain field margins, refugia, mixed vegetation, and nesting resources	Improves pollination and biological control under stress
5	Reduced broad-spectrum insecticide dependence	Beneficial insects and ecosystem health	Shift toward selective, need-based, and ecologically informed interventions	Lowers non-target damage and supports long-term resilience
6	Policy support for monitoring and extension	Farmers, researchers, and regulators	Invest in long-term monitoring, advisory networks, and data-sharing platforms	Strengthens regional adaptation capacity
7	Pollinator-focused adaptation planning	Pollinator-dependent crops	Protect floral resources, nesting habitats, and climate refugia	Supports yield stability and food security

CONCLUSION

Climate change is emerging as one of the most powerful forces reshaping insect life across natural and agricultural ecosystems. Its effects are already visible in shifting distributions, altered phenology, changes in abundance, and the reorganization of interactions among pests, pollinators, host plants, and natural enemies. The evidence reviewed across recent studies shows that these changes are not uniform: some insects, especially adaptable pest species, may expand and intensify under warmer and more variable conditions, while many beneficial or specialized insects face rising ecological stress and declining stability.

From an agricultural perspective, this transformation has serious implications for crop productivity, pest forecasting, and long-term food security. Climate change is increasing the likelihood of new pest outbreaks, extended damage periods, and geographic spread into previously lower-risk areas, while also threatening pollination services and the effectiveness of biological control. At the same time, the interaction between climate warming and agricultural intensification can further reduce insect abundance and species richness, particularly where natural habitat is limited, underscoring the need to view entomological change within broader landscape and farming contexts. This also highlights that insect responses to climate change are governed by underlying physiological limits, seasonal timing systems, behavioural flexibility, and, in some cases, adaptive evolutionary change. This mechanistic understanding is essential because it explains why insect responses differ so widely across taxa, regions, and production systems, and why simple generalisations often fail. For this reason, predictive entomology must increasingly combine physiology, ecology, genomics, and field-based monitoring rather than relying on distribution records alone.

Encouragingly, recent advances in DNA-based monitoring, artificial intelligence, remote sensing, smart surveillance, and predictive modelling are creating new opportunities to study and manage insect populations under changing climates. These tools, when linked with climate-smart integrated pest management and habitat-based conservation approaches, can improve early detection, guide timely interventions, and support the protection of beneficial insects that sustain agriculture. However, technology alone will not be enough unless it is embedded within long-term monitoring systems, strong extension networks, and policies that reduce ecological vulnerability at both farm and landscape scales. Overall, the entomological consequences of climate change are best understood not as isolated biological shifts, but as part of a larger ecological transition with direct implications for biodiversity conservation, agroecosystem resilience, and human well-being. Future success will depend on developing farming and conservation systems that are adaptive, knowledge-based, and ecologically grounded, so that both insect diversity and the services it provides can be sustained in an increasingly uncertain climate.

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