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Review article

Ecological shifts under climate change: Understanding pest responses and agricultural vulnerability

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ABSTRACT

Climate change profoundly affects agricultural insect pests by altering their biology, distribution, and interactions within agroecosystems, threatening global food security. Rising temperatures, elevated atmospheric CO₂, and shifting precipitation patterns accelerate pest development, expand geographic ranges, and increase voltinism, intensifying crop damage. These shifts disrupt traditional pest management frameworks, as phenological mismatches among pests, host plants, and natural enemies weaken biological control. Moreover, abiotic stresses compromise the performance of biocontrol agents, such as entomopathogenic fungi, necessitating climate-specific strain selection. Adaptive integrated pest management (IPM) strategies that incorporate real-time monitoring, predictive modeling, precision agriculture technologies, and emerging tools such as CRISPR and sterile insect techniques are essential for climate-resilient agriculture. Sustainable approaches that leverage natural products and minimize reliance on chemical pesticides further support ecosystem health. This review synthesizes current knowledge on climate-driven pest dynamics, range expansions, and tritrophic disruptions based on literature searched in Web of Science, Scopus, PubMed, and Google Scholar from January 2000 to November 2025 using Boolean strings. This review proposes a comprehensive climate-adaptive IPM framework to safeguard agricultural productivity amid ongoing environmental change.

Keywords: Agriculture, Climate Action, CO₂, Environment, Food Security, Insects.

Climate change disrupts global agriculture by altering insect pest phenology, distribution, and population dynamics at rates faster than crops or natural enemies can adapt (Sharma *et al.*, 2017; Subedi *et al.*, 2023). An increase in atmospheric CO₂ levels, higher temperatures, and changes in precipitation patterns are interconnected factors that radically transform insect pest biology and distribution (Skendžić *et al.*, 2021a). The interactions among these climatic drivers, taken individually, go beyond mere resource access, invoking more complex physiological and behavioural changes across pest populations that stretch the traditional conceptualisation of agricultural ecology. The complex triadic relationships among crop-insect pests and the environment are vital to agricultural production (Alotaibi, 2023). With changes in climate parameters, these interactions become unpredictable, eroding decades of pest management experience. The stability that

enabled predictive models and seasonal management calendars to operate correctly is crumbling, and a fundamental re-evaluation of the approach to shaping and executing pest management strategies is needed. Poikilothermic insects can respond more quickly and strongly to changes in the weather than the plants they live on or their natural predators. This phenomenon is because insects have short generation times and high reproduction rates (Lehmann *et al.*, 2020). This phenological incompatibility between pest life cycles, crop susceptibility periods, and the life cycles of natural enemies jeopardises the effectiveness of existing integrated pest management approaches and the health of the natural biological services that support sustainable agriculture (Fig. 1).

Globally, people are already experiencing the effects of climate-driven pest dynamics. Significant infestations in major

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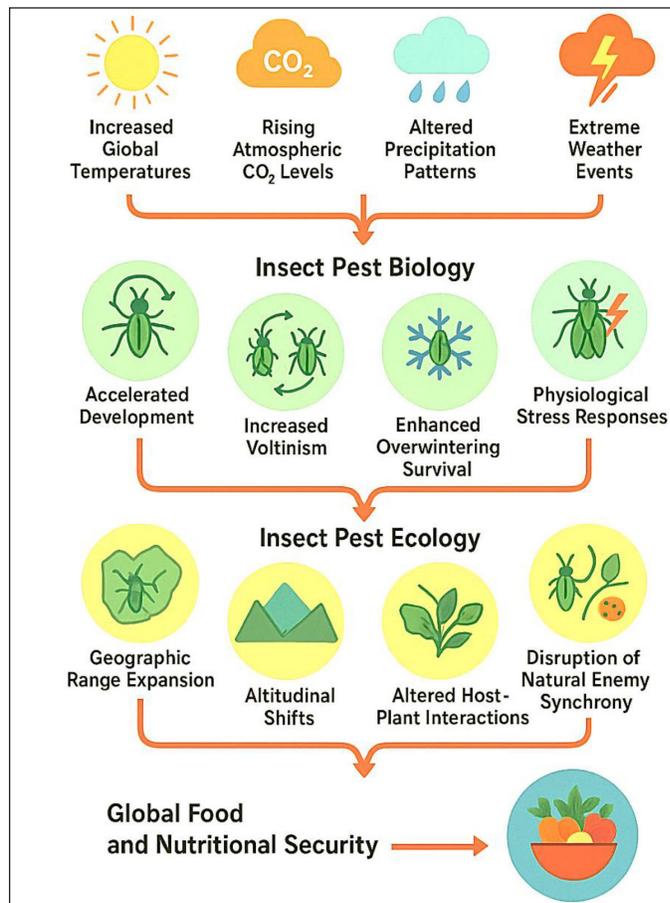


Fig. 1: Conceptual model of climate change impacts on agricultural insect pests and food security.

grain-producing countries, such as China, the United States, and France, are causing substantial crop losses due to the expansion of pests driven by climatic factors (Shrestha, 2019). We can view these trends as indicators of broader projections that suggest an increase in average global temperatures of 2.0 to 6.0°C (Knutti *et al.*, 2008), by the twenty-first century. This rise will likely have widespread impacts on insect populations, affecting their geographic distribution and the economic sustainability of agricultural systems (Alotaibi, 2023). Every degree rise in temperature could cause 10-25% more crop damage from insect pests, further risking food security in areas already vulnerable (Skendžić *et al.*, 2021b; Sunitha *et al.*, 2024). Understanding how climate change fundamentally alters the biology and ecology of insect pests is essential for developing adaptive management strategies that can effectively sustain crop production and food security in an increasingly variable global climate (Thakur & Rawat, 2014; Suresh *et al.*, 2018; Deb & Bharpoda, 2017; Saha *et al.*, 2018). This review addresses these gaps through four integrated objectives: (1) synthesize direct climate effects on pest biology using thermal thresholds and degree-day models; (2) quantify range expansions and voltinism shifts under RCP 2.6-8.5 scenarios; (3) evaluate tritrophic disruptions and yield implications; and (4) propose a climate-adaptive IPM framework integrating predictive modelling, precision tools, and emerging technologies including CRISPR and sterile insect techniques.

REVIEW METHODOLOGY

Literature was systematically searched in Web of Science, Scopus, PubMed, and Google Scholar from January 2000 to November 2025 using Boolean strings such as (“climate change” OR “global warming”) AND (“insect pest*” OR “agricultural pest*”) AND (“range expansion” OR “voltinism” OR “thermal threshold*” OR “tritrophic” OR “IPM” OR “RCP*”). Additional targeted searches included species-specific terms (e.g., “*Helicoverpa armigera*,” “*Spodoptera frugiperda*”) and management keywords (“climate-adaptive IPM,” “CRISPR pest resistance”)

DIRECT EFFECTS OF CLIMATE VARIABLES ON INSECT PEST BIOLOGY

Temperature serves as the primary environmental factor influencing insect development, survival, and reproductive success. With each degree Celsius of warming, potential yield losses from insect pests are estimated to increase by 10–25% (Shrestha, 2019; Pavunraj *et al.*, 2024). The direct effects of temperature on metabolic rates, developmental duration, and generational intervals in pest species have delineated essential thermal thresholds that define the geographical and seasonal limits of pest populations. The relationship between temperature and development rate is so consistent across insect taxa that predictive models can be used to estimate generation times under various climatic conditions. Developmental thresholds,

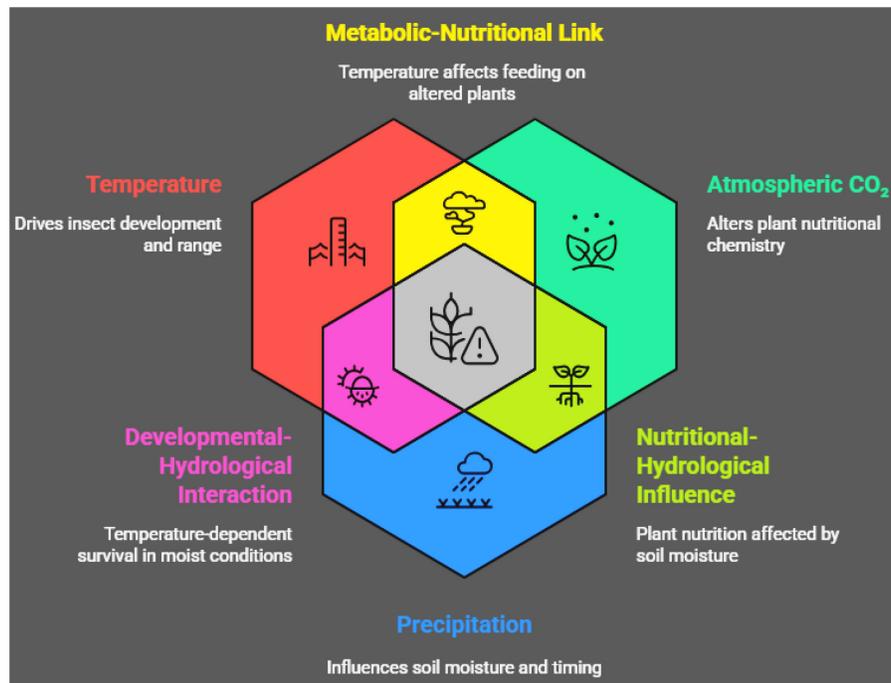


Fig. 2: Interplay of climate variables on insect pest dynamics.

or base temperatures below which insects cease to develop, vary by pest species and life stage. Most agricultural insects have base temperatures ranging from approximately 8 to 14°C and upper lethal temperatures between 37 and 43°C (Barteková & Praslička, 2006; Manideep & Saravanan, 2025). Extended growing seasons resulting from reduced winter chilling durations enable several generations of previously uninvolved pest species to complete an additional life cycle within a year. This shift significantly alters pest management calendars and dramatically enhances the cumulative potential for harm throughout the farming year (Shrestha, 2019).

High levels of atmospheric CO₂ lead to direct changes in plant nutritional chemistry, particularly affecting the carbon-to-nitrogen ratio. This alteration creates complex cascades of effects on herbivore populations by influencing their feeding efficiency and plant defence systems (Trębicki *et al.*, 2017a). Generally, elevated CO₂ levels reduce the nitrogen availability in plant tissues, compelling herbivores to consume more plant material to fulfil their nutritional requirements. This increased consumption can enhance the feeding rate and growth rate of particular species. However, this compensatory feeding behaviour is specific to particular pairings and varies across insect-plant associations; some pests may experience lower fecundity and slower growth on high-CO₂ plants when plant defence compound concentrations are elevated (Fig. 2). Changes in precipitation patterns disrupt the timing coordination between pest emergence and the optimal phenology of host plants, creating both critical vulnerability windows for crops during pest outbreaks and periods of diminished pest pressure during times of asynchrony (Skendžić *et al.*, 2021a). Variations in precipitation regimes also affect soil moisture conditions, which, in turn, influence the survival of overwintering immatures and the dynamics of pathogen transmission by altering humidity and the viability of fungal spores in field microhabitats (Monisha *et al.*, 2025) (Table 1).

SHIFTS IN GEOGRAPHIC DISTRIBUTION AND RANGE EXPANSION

Global warming is one of the significant factors that have caused fundamental changes in the geographic boundaries of pest suitability by lifting cold-stress constraints on pests that once had restricted distributions to low latitudes and low elevations (Skendžić *et al.*, 2021c). Physiological research has identified key inflexion points in the climatic tolerance of insect pests. One of the most affected nonlinear reactions occurs when the minimum temperatures in the coldest month exceed a threshold of about -3°C (Grünig *et al.*, 2020). There is a critical threshold below which mortality during winter severely limits pest population survival. However, beyond this point, conditions become conducive to the establishment of pest populations at high and sustained levels in regions once deemed hostile. Such a non-linear response indicates that expansion of pest ranges will not be gradual but will be characterised by abrupt, marked geographic reorganisation as the critical temperature limit is crossed. The consequences of agricultural zones located close to such thermal boundaries are far-reaching, as even modest temperature changes can transform inappropriate environments into exceptionally suitable ones within a single growing season (Grünig *et al.*, 2020).

Underlying many geographic range projections using maximum entropy algorithms, species distribution models suggest significant expansion in the geographic scales of key crop pests across a selection of total future time (RCP) scenarios and multiple future time horizons (Ning *et al.*, 2017). An example of this is the onion maggot (*Delia antiqua*), which is found mainly in temperate regions but has a limited subtropical distribution, and is projected to extend northward in Europe, North America, and Asia in 2050 and 2080 (Ning *et al.*, 2017). Likewise, invasive

Table 1: Direct effects of climate variables on insect pests.

Temperature Change Parameter	<i>Helicoverpa armigera</i>	<i>Nilaparvata lugens</i>	<i>Diabrotica virgifera</i>	<i>Spodoptera frugiperda</i>	References
Thermal Threshold	11.34-14.83°C (eggs-larvae)	Lower threshold varies; thermal tolerance -42.5°C	Varies by region; typically, 10-12°C	12.12-13.01°C (larvae); 13.06°C (pupae)	(Barteková & Praslička, 2006)
Degree-Day Requirement	625 days/°	Reduced ~18%	Variable by location and strain	391.61 ± 1.42 degree-days	(Barteková & Praslička, 2006)
Development (+1°C incre)	Accelerates 5-12%	Accelerates; nymph reduced 18.5% at +3°C	Accelerates significantly	Fastest development at 30°C (optimal)	(Skendžić <i>et al.</i> , 2021b)
Fecundity Impact	Increased 20-25°C	Increased 29.5% under CO ₂ +temp.	Generally, increases until thermal maximum	Reduced at extreme temperatures; optimal 26-30°C	(Skendžić <i>et al.</i> , 2021b)
Overwintering Survival	Enhanced warmer regions	Enhanced previously unsuitable regions	Extended survival in warmer winters	Expanded potential range under warming	(Adamec & Kučerová, 2013)
Geographic Range Exp.	Rapidly invading Central	Rapidly invading Central/North America; \$78 billion annual crop exposure in the USA.	Expanding range of cooler regions as temperatures increase	Invaded Africa (2016), expanding through Asia; 20-30 generations possible under warming	(Sharma 2014; Skendžić <i>et al.</i> , 2021c)
Additional Generation	2-3°C warming	+0.5-1 generation under elevated conditions	+1 generation per 2-3°C warming	Can reach 3-4 generations in warmed tropical/subtropical regions	(Ziter <i>et al.</i> , 2012; Skendžić <i>et al.</i> , 2021c)
Upper Lethal	~42-44°C	42.5°C (ULT ₅₀)	~40-42°C (estimated)	38-42°C depending on acclimation	(Skendžić <i>et al.</i> , 2021b)

Table 2: Shifts in geographic distribution and range expansion

Pest Species	Current Range	RCP 2.6 (2030s)	Vulnerable Regions	Key Limiting Factors	References
<i>Delia antiqua</i>	East Asia, North America, Western Europe, Caspian/Black Sea	Limited expansion	Temperate crop regions	Minimum coldest month temperature	(Ning <i>et al.</i> , 2017)
<i>Chrysomya bezziana</i>	Sub-Saharan Africa, parts of the Arabian Peninsula	Sub-Saharan, Arabian Peninsula stable	Livestock-dependent regions	Extreme heat stress (>42°C)	(Grünig <i>et al.</i> , 2020)
<i>Plutella xylostella</i>	Global temperate/subtropical distribution	Expanded northern range	Brassica-growing regions worldwide	Winter survival, minimum temperatures	(Maino <i>et al.</i> , 2021a)
<i>Helicoverpa armigera</i>	Africa, Asia, Mediterranean	Slight northward shift	Grain legume, vegetable crops	Thermal development thresholds	(Sharma, 2014)
<i>Spodoptera frugiperda</i>	Tropical Americas (now pantropical)	Africa: sub-Saharan stable	Cereals, legumes, and vegetables globally	Heat stress thresholds (38-42°C)	(Maino <i>et al.</i> , 2021a)
<i>Tuta absoluta</i>	South America (native), Mediterranean invasion	Mediterranean stable to expanding	Solanaceae crops (tomato, pepper)	Minimum temperature constraints	(Grünig <i>et al.</i> , 2020)

and migratory Lepidoptera (e.g., cereal stem borers: *Chilo* species, *Sesamia* species), as well as pod-boring species (e.g., *Helicoverpa armigera*, *Maruca vitrata*, *Spodoptera frugiperda*), are expected to exhibit faster poleward expansion. It implies that previously cold-farming areas are becoming climatically favourable for permanent settlement (Sharma, 2014). Such projected expansions of ranges not only increase geographic distributions of pests but are also an indication of a relocation of the species into agricultural lands where the farmers might lack prior experience in dealing with

them and where the natural complex of enemies within a region might be undeveloped, hence leading to compounded and new management issues (Skendžić *et al.*, 2021c). Table 2 shows how the geographic ranges of major agricultural insect pests are likely to change under different climate change scenarios (RCP 2.6, 4.5, and 8.5). For most species, warmer temperatures cause them to move northward or into new temperate, Mediterranean, and Asian areas. As conditions improve, pests such as *Delia antiqua*, *Helicoverpa armigera*, and *Tuta absoluta* may become more common in Europe,

Table 3: Population dynamics and changes in voltinism.

Region	Pest Species	Current Year	RCP 4.5 (2050)	Degree-Day Accumulation	Key Limiting Temperature	References
California Central Valley	<i>Spodoptera litura</i>	4-5	5-6	625-900	Base temp: 12-14°C; Optimum: 25°C	(Kumar & Bhattacharya 2019)
California (Coastal)	<i>Cydia pomonella</i>	1-2	2-3	900-1100	Winter chill requirement: 200-400 hrs	(Ziter <i>et al.</i> , 2012; Srinivasa Rao <i>et al.</i> , 2015)
California (Southern)	<i>Helicoverpa armigera</i>	3-4	4-5	625	Base temp: 11.3-14.8°C; Upper limit: 42-44°C	(Barteková & Praslička, 2006)
Japan (Rice paddies, Central)	<i>Chilo suppressalis</i>	2	2-3	400-500	Base temp: 10-12°C; Winter mortality critical	(Yamamura <i>et al.</i> , 2006)
Japan (Rice paddies, Southern)	<i>Nilaparvata lugens</i>	3-4	4-5	Reduced 18% under elevated CO ₂ + heat	Thermal max: 42.5°C; Base: 10-12°C	(Skendžić <i>et al.</i> , 2021c)
North America (Northern US/Southern Canada)	<i>Diabrotica virgifera</i>	1	1-2	900-1200	Base temp: 10-12°C; Diapause breaks at >200°C-days	(Govindan & Hutchison, 2020)
North America (Central US Corn Belt)	<i>Helicoverpa zea</i>	2-3	2-3	391-625 (2-3 cycles)	Base: 12-14°C; Overwintering survival: -3°C threshold	(Skendžić <i>et al.</i> , 2021a)
East Africa (lowland maize)	<i>Chilo partellus</i>	2-3	3-4	500-700	Altitude expansion: >1200 m risk increasing	(Mwalusepo <i>et al.</i> , 2015)
East Africa (highland maize, >1500 m)	<i>Busseola fusca</i>	1	1-2	Temperature-limited historically	Cooler elevation: altitude limit shifting	
Tropical/Subtropical regions	<i>Spodoptera frugiperda</i>	4-5	4-5	391 ± 1.42	Can reach 3-4 in favourable warmed zones	(Maino <i>et al.</i> , 2021b)

North America, and Central Asia. Extreme heat stress, low winter temperatures, and crop availability are among the most important limiting factors. Climate change is expected to make pests more easily invade, spread to more places, and have more negative effects on different types of farming worldwide (Murugesan, 2024).

POPULATION DYNAMICS AND VOLTINISM CHANGES

The nature of global warming significantly alters the dynamics of insect populations, increasing the rate of development (i.e., the number of generations formed in a given year) (Skendžić *et al.*, 2021c). Degree-day models, which sum thermal units above a species-specific base temperature threshold, are effective at forecasting how temperature changes translate into additional pest generations (Ziter *et al.*, 2012). Research on various pest species in California and other areas has consistently shown that, with warmer temperatures, the number of generations per year is increasing (Table 3). Although variable predictions are obtained at specific geographic locations and climate conditions, a sound conclusion is that all significant pest species will exhibit augmented voltinism (Ziter *et al.*, 2012). For example, Srinivasa Rao *et al.*, (2015) estimated that the tobacco caterpillar, *Spodoptera litura*, on peanut crops in India would have 1-2 additional generations in the future, with generation time reduced by 18-22% under baseline conditions, based on a climate model. These shortened development times shrink the timeframe within which any pest can be detected and acted upon, while at the same time allowing rapid population

expansions to exceed traditional control limits easily.

Increased overwintering survival is a key driver of population growth, especially in temperate zones, where severe winter conditions have previously hindered pest establishment (Skendžić *et al.*, 2021c). Lower death rates during winter months allow pest populations to live at higher densities and initiate reproduction earlier in the spring, effectively lengthening the growing season during which the population can develop. Higher winter temperatures have also been reported to benefit poikilothermic insects that are at higher risk of freezing, with minimum temperatures showing inflexion points near full mortality and considerable population persistence (Schneider *et al.*, 2021). The long autumn reproductive periods allow more reproductive cycles to occur before dormancy sets in. Thus, the equilibrium population densities are higher going into winter, and hence the founding populations are larger coming out of the spring. These overwintering interactions, along with lower mortality to cold stress, contribute to population doubling times across more temperate farming areas once marked by strong winter population regulation (Schneider *et al.*, 2021).

The combined impact of high rates of development acceleration, improved overwinter survival, higher population growth rates, and phenological reorganisation forms a synergistic rather than additive driver of higher pest pressure. Geographic areas close to the modern thermal limits of pest suitability, especially in temperate zones and highland agricultural sites, are the most

Table 4: Tritrophic interactions and natural enemy disruption.

Interaction Type	Climate Change Effect	Specific Impact on Tritrophic System	Consequence for Pest Management	References
Phenological Synchrony	Differential thermal requirements and life-cycle shifts across trophic levels	Mismatches between pest emergence, host plant vulnerability, and natural enemy activity	Reduced the effectiveness of biological control and increased pest pressure during critical crop stages	(Mwalusepo <i>et al.</i> , 2015)
Natural Enemy Thermal Niches	Narrower thermal niches and less flexible responses in parasitoids/predators compared to hosts	Parasitoid development lags behind pest reproduction; reduced predation pressure.	Asymmetrical host-parasitoid interactions, ecological windows for pest escape, and deteriorated biological control.	(Romo & Tylianakis, 2013)
Entomopathogenic Fungi Efficacy	Temperature, humidity, and UV radiation constraints	Conidial depletion, inactivation, loss of virulence/infectivity; strain-specific thermal tolerances	Reduced field efficacy of fungal biocontrol agents, necessity for climate-specific strain selection	(Membang <i>et al.</i> , 2021; Quesada-Moraga <i>et al.</i> , 2024)
Plant-Insect-Pathogen Chemistry	Elevated CO ₂ and temperature alter plant biochemistry (C: N ratios, defence compounds)	Changes in herbivore feeding, pathogen infection rates, and volatile organic compound profiles (affecting natural enemy host-finding)	Variable effects on herbivore performance, potential collapse of biological control services due to multi-trophic disruptions	(Dyer <i>et al.</i> , 2013; Trębicki <i>et al.</i> , 2017b)
Cross-Protection	Combined exposure to insecticide and temperature stressors	Pest populations develop broad-spectrum stress tolerance (e.g., insecticide-enhanced thermotolerance)	Compromised efficacy of conventional pest management, accelerated evolution of multi-stressor tolerance	(Bueno <i>et al.</i> , 2023)

dramatic in population dynamics, where critical temperature thresholds that facilitate year-round pest settlement are crossed (Schneider *et al.*, 2021). The underlying causes of these changes are the fact that the predictive nature of integrated pest management systems has traditionally operated on the premise of a constant, seasonally predictable population dynamic to inform decision-making thresholds and timing of management (Skendžić *et al.*, 2021c).

TRITROPHIC INTERACTIONS AND NATURAL ENEMY DISRUPTION

Climate change disrupts the temporal synchronisation of herbivorous pests and their host plants with natural enemies, due to differences in thermal requirements and developmental plasticity (Skendžić *et al.*, 2021b). Changes in phenology due to temperature variations tend to advance at different rates across trophic levels, resulting in mismatches in which pest hatching is no longer linked to critical host plant susceptibility periods and in the relative abundance of natural enemies (Table 4). In East African mountain agroecosystems, warming increases the geographic distribution of maize stem borers to higher altitudes and, at the same time, desynchronizes them with parasitic complexes, leading to the loss of effective biological control above 1200 meters of elevation despite high pest populations (Mwalusepo *et al.*, 2015). Such phenological incongruities are a root cause of tritrophic instability, in which pest

populations become more resistant to natural enemy control during critical periods when host plants are not at the appropriate stage of defensive development, or when natural enemy populations are not at the appropriate stage of development.

Natural predators, mainly parasitic, often have a much more specific thermal niche and less adaptive phenological responses compared to their herbivorous hosts, which is why pest populations are exposed to a narrower ecological niche. The degree of host-parasitic relationships is becoming increasingly metrical in warmer environments, with parasitic growth often lagging behind pest reproduction as temperatures rise. Experimental research shows that high temperature and drought do not interact to reduce the effectiveness of parasitism. The combined stress factors have the lowest emergence success and offspring production, although both temperature and parasitic attack show positive relationships (Romo & Tylianakis, 2013). This decreased parasitic efficacy has cascading effects on pest control, thereby altering the top-down regulatory forces that maintain biological control in agroecosystems. Equally, field experiments on urban heat islands reveal that phenological mismatches between scale insect pests and their parasitic groups lead to increased pest densities on trees warmed by 2-2.5°C, providing unambiguous evidence that tritrophic synchrony warping translates directly into high pest densities (Frank *et al.*, 2020).

Persistence and infectivity of entomopathogenic fungi are environmentally limited during climatic stresses, and temperature, humidity, and UV radiation pose several abiotic impediments to the effectiveness of biological control (Quesada-Moraga *et al.*, 2024). Environmental competence- the capacity of fungal strains to endure, survive, and remain infectious in host environments with different climatic conditions pertains basically to the level of humidity, where excessive dryness leads to conidial inactivation and poor performance in the field. Whereas UV radiation and humidity are the most significant limiting factors in epigeal (above-ground) habitats, temperature is the most important factor limiting the efficacy of fungi in hypogean (below-ground) habitats with low light levels. Strain-specific temperature tolerances also complicate the implementation of biocontrol because fungal isolates differ significantly in germination, mycelial development, and sporulation rates across the temperature ranges (13-37°C) encountered in agroecosystems, with some isolates tolerant only of 20-29°C (Membang *et al.*, 2021). This environmental limitation of fungal biocontrol agents requires the conscious selection of strains well adapted to the expected climatic conditions in the regions where they are intended to be used (Quesada-Moraga *et al.*, 2024).

IMPLICATIONS FOR CROP PRODUCTION AND YIELD SECURITY

Climate change poses a threat to global crop production through cascading effects on insect pest populations and mechanisms of crop resilience. The aggregate strain of heightened pest pressure and abiotic climatic stress results in compounding yield losses that undermine food security in susceptible areas. The loss in crop yields due to insect pests is estimated to rise significantly under climate change, with only rising temperatures contributing to 10-25% losses in major cereals (Junaid & Gokce, 2024). This is a radical change from past losses caused by pests, making it even more difficult for farmers to support productive systems. Currently, insect pests contribute between 13.6 and 38% of annual crop losses worldwide, and climate change is likely to increase pest pressure and limit crop resistance due to abiotic stress (Dhaliwal *et al.*, 2015). The combination of heightened pest damage and low plant fitness creates a very alarming pattern in agricultural output.

Climatic differences across geographic boundaries will significantly transform global patterns of production. Yields of wheat, rice, and maize will be most affected in tropical and subtropical areas, where temperatures have already reached the thermal optima of these crops. In contrast, the north may gain a temporary advantage through longer growing seasons (Farooq *et al.*, 2023). The far-reaching consequences of this geographic restructuring on food security in the developing countries that continue to depend on agriculture and are less adaptive are immense. The spread of pest areas into formerly temperate regions has been accompanied by weakened host plant resistance, posing some of the most problematic management challenges. Concurrent effects of increasing pest pressure and heat stress on grain growth will result in reduced quality parameters of the grain, such as grain protein content, nutritional value, and contamination by pests (Hatfield *et al.*, 2011). An increase in temperature increases the rate of grain-filling and limits nutrient translocation. At the same time, pest

infestations also reduce seed viability and nutritional content. The resulting decrease in crop quality extends beyond yield measures, directly threatening human nutrition and lowering farmers' market value.

Farmer livelihoods are at stake, especially in developing nations, where adaptive capacity and financial resources are limited due to economic losses associated with increased pesticide use, reduced yields, and crop failures. Smallholder farmers who operate on narrow profit margins face difficult decisions between increasing pesticide use to control rising pest numbers and accepting lower production due to a lack of control over many infestations. The economic burden (cumulative economic), which includes increased cost of inputs, reduced productivity, and post-harvest quality loss, causes a cascading crisis of rural livelihoods that derail development in agricultural-based economies. The lack of significant investments in adaptive management infrastructure, improved germplasm, and the institutionalisation of support will result in agricultural disruption due to climate change, leading to mass rural-to-urban migration and increasing food insecurity in areas that contribute the least to climate change. The need to create climate-resilient production systems cannot be overemphasised, as the opportunities to develop adaptation measures are shrinking every year as the world continues to warm.

ADAPTIVE PEST MANAGEMENT STRATEGIES UNDER CLIMATE CHANGE

Due to climate-driven changes in pest biology and distribution, a fundamental redistribution of pest management is needed to sustain crops and farms. The traditional systems, grown in a stable climate and foreseeable interactions with pests, are becoming useless. Adaptive IPM substitutes calendar- or historically parameterised degree-day models with real-time climatic, phenological, and population data to modify thresholds, timing, and interventions dynamically (Skendžić *et al.*, 2021c). With climate surveillance, risk mapping in GIS, and species-specific models incorporated, biological control, targeted chemical applications, and cultural practices can be deployed at the right time to maintain effectiveness as the environment rapidly transforms. Climate-smart pest management (CSPM) is an extension of IPM to the entire agroecosystem, minimising losses and maximising ecosystem services, input efficiency, and resilience by combining research, extension, and policy actions (Heeb *et al.*, 2019). Distributed monitoring and crowdsourced information are used by early detection and rapid response systems (e.g., EDDMapS) to detect range expansions early, enabling containment before establishment (Ziska *et al.*, 2018). Optimised irrigation and fertilisation, resistant varieties, habitat regulation, and organic practices in bottom-up ecological practices reinforce plant vigour and control natural enemies (Han *et al.*, 2022).

Sustainable plant protection focuses on the selective use of tools, including botanicals, entomopathogens, semi-chemicals, and precision application technologies, to reduce non-target effects while controlling pests (Lankinen *et al.*, 2024). Altogether, adaptive monitoring and flexible decision-making are the most resilient strategies when combined with biological control, which outperforms rigid, single-mechanism strategies in a climate-variability

environment. This ranking is based on the combined evaluation of the IPM strategy's effectiveness in various climate conditions and management situations. Ranked strategies 1-3 exhibit significantly greater resistance to climate variability due to the maintenance of multiple overlapping pest control pathways, adaptability to a changing environment, and the sustainability of ecosystem services. Strategies numbered 5-7, which are potentially effective in stable climatic conditions, have significantly lower resilience to climate change because of their inflexibility in implementation, reliance on a single control mechanism, or excessive reliance on external inputs. The most viable control measures involve integrating biological control with adaptive monitoring and decision-making schemes, so that management responses can vary dynamically with pests' and climate's fluctuating dynamics, rather than using fixed protocols applicable to historical climate scenarios that no longer dominate.

MONITORING, PREDICTION TOOLS, AND DECISION SUPPORT SYSTEMS

To facilitate a successful response to the changing dynamics of insect pests driven by climate change, real-time monitoring, predictive modelling, and decision-support systems are integrated. Management strategies designed for stable climatic conditions are becoming ineffective, requiring significant restructuring of surveillance and forecasting systems. The next-generation plans are based on phenological and population-dynamics models that combine climate and pest life-history data with crop phenology to forecast generation timing, population dynamics, and the probability of outbreaks (Tonnang *et al.*, 2017). When combined with species-distribution and bioclimatic models, they identify current and future high-risk areas, enabling proactive, spatially focused management (Lankinen *et al.*, 2024).

More sophisticated computational methods, such as machine learning, neural networks, agent-based models, and fuzzy logic, are more effective than traditional statistical models for nonlinear responses, thresholds, and emergent pest-climate interactions (Ali *et al.*, 2023). Long-term monitoring datasets enhance their reliability by showing delayed, nonlinear, and threshold-related population responses to climate, which are critical to calibration and forecasting of robust models (Yamamura *et al.*, 2006). Analysis of 50 years of light-trap records on 3 rice paddy pest species indicated a nonlinear response to temperature, a multi-year lag, and threshold behaviour, in which population trends change abruptly at a temperature inflexion point. It is not possible to detect these processes on the short-term scale, and thus needs multi-decadal datasets. In this regard, future climate change projections need to consider these complex dynamics when estimating changes in pests' responses. By breaking down long-term population patterns into baseline and environmentally motivated components, the investigators will be able to measure the effects of individual factors and forecast shifts in equilibrium population densities and future climatic conditions (Fig. 3). Precision agriculture technologies (especially drone-based remote sensing with multispectral and hyperspectral sensors) can further improve the real-time observation of pest hotspots and provide an opportunity to take site-specific actions (Subramanian *et al.*, 2021). By integrating weather data and phenology models into decision-support systems, these tools can

provide localised, optimally timed pest control with fewer inputs, less environmental impact, and greater management efficacy.

INTEGRATED CLIMATE-RESPONSIVE PEST MANAGEMENT

Genome editing, genetic biocontrol, biological control, and nanotechnology collectively represent a paradigm shift in climate-resilient pest management. Advanced genome editing tools, particularly CRISPR/Cas9, have enabled the rapid development of transgene-free, insect-resistant crop varieties with enhanced tolerance to heat, drought, and biotic stress, thereby reducing dependence on chemical pesticides (Haque *et al.*, 2018; Chen *et al.*, 2024). Genetic biocontrol approaches such as the sterile insect technique (SIT) and the incompatible insect technique (IIT) offer effective population-suppression strategies for invasive and climate-adapted pests, especially in regions experiencing rapid pest range expansion (Vreysen *et al.*, 2021; Nikolouli *et al.*, 2020; Martín-Park *et al.*, 2022). Environmentally compatible biological control agents, including entomopathogenic fungi, bacteria, and viruses, further support sustainable pest regulation, although their success depends on strain-specific tolerance to temperature, humidity, and UV radiation under changing climatic conditions (Quesada-Moraga *et al.*, 2024). Emerging nanoparticle-based pesticides and nanofertilizers offer novel modes of action that may slow resistance development while improving nutrient use efficiency; however, unresolved concerns about persistence, bioaccumulation, and non-target impacts necessitate rigorous ecological risk assessment before large-scale deployment (Jafir *et al.*, 2023). Collectively, these innovations highlight the need for integrated, climate-responsive pest management systems that combine technological precision with ecological resilience.

Integrating remote sensing data with other precision agriculture tools, such as GPS-guided machinery, variable rate technology, and crop simulation models, can further enhance the precision and effectiveness of nitrogen management. This integration will enable a more holistic and site-specific approach to nitrogen fertiliser application. Climate Smart Agriculture (CSA) has emerged as a critical framework for addressing these challenges and transforming Indian agriculture into a more resilient, sustainable, and productive sector (Rengarajan *et al.*, 2024). User-friendly decision support systems are crucial for translating remote sensing data into actionable management recommendations for farmers, and future research should prioritise DSS platforms that are intuitive, interactive, and tailored to diverse agroecological and socioeconomic contexts. India can strengthen food security, improve farmers' livelihoods, and contribute to global climate mitigation efforts through such approaches. Pesticides are detrimental to the natural world and are therefore considered toxic to the environment (Murugesan *et al.*, 2022), with chemical pesticides posing serious threats to biodiversity through air and water pollution (Murugesan *et al.*, 2023). Consequently, increasing attention is being directed toward natural alternatives for safety and sustainability (Murugesan *et al.*, 2025). Traditional medicine and plant-derived secondary metabolites offer valuable resources for developing eco-friendly pest control agents (Kaleeswaran *et al.*, 2019; Rengarajan *et al.*, 2024; Murugesan *et al.*, 2024). Ultimately, addressing climate-driven

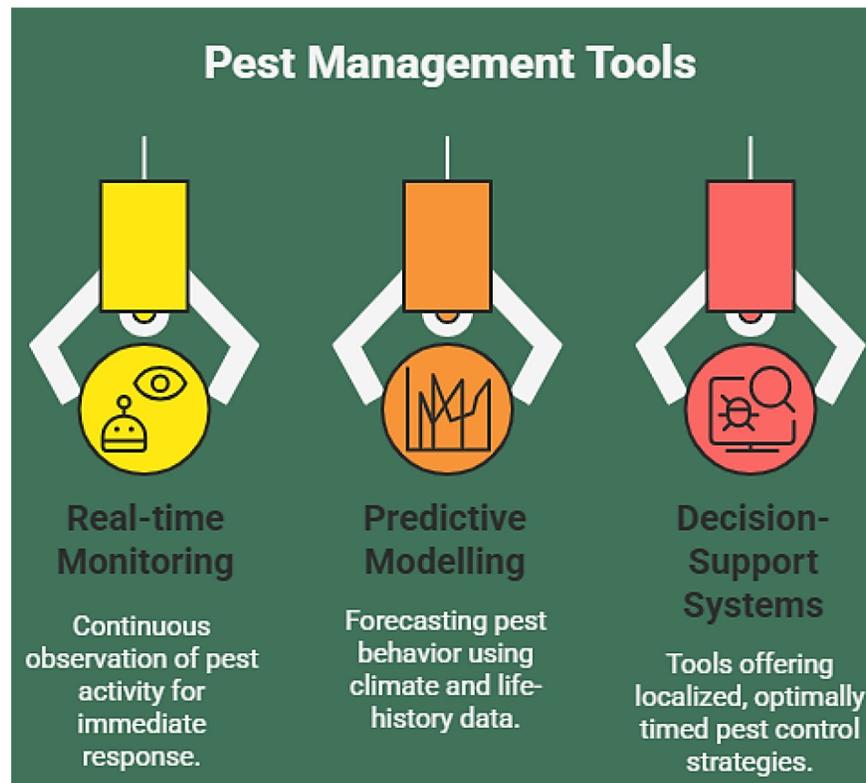


Fig. 3: Adapting pest management tools.

pest challenges requires a proactive, multidisciplinary strategy that integrates advanced technologies, ecological approaches, farmer engagement, and supportive policy frameworks to ensure resilient, sustainable food systems.

CONCLUSION

This review synthesizes current knowledge on climate-driven pest dynamics, range expansions, and tritrophic disruptions. Climate change makes it much harder to control insect pests in agriculture by altering their biological traits, habitats, and interactions with other organisms in agroecosystems. Higher temperatures and CO₂ levels accelerate pest growth and expand their ranges, making infestations more common and severe. These changes undermine traditional integrated pest management (IPM) by creating phenological mismatches among pests, crops, and natural enemies, reducing the effectiveness of biological control. The combined effects of increased pest pressure and climate stress lower crop yields and quality, hitting smallholder farmers and vulnerable regions hardest. We need flexible IPM frameworks that can adapt to climate change. These frameworks should include real-time monitoring, predictive modeling, precision technologies, and new genetic tools such as CRISPR and sterile insect techniques. Focusing on biological control and sustainable practices strengthens ecosystems. To protect global food security amid ongoing environmental change, we need a proactive, multidisciplinary strategy that combines cutting-edge technologies, ecological approaches, and supportive policies.

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