PLANT SCIENCE TODAY
Vol 12(sp1): 1-9
https://doi.org/10.14719/pst.8943

eISSN 2348-1900

REVIEW ARTICLE

Climate resilience in natural enemies: Key players of ecological control

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Received: 17 April 2025; Accepted: 09 August 2025; Available online: Version 1.0: 07 October 2025

Cite this article: Arya M, Baskaran V, Sumathi E, Srinivasan T, Savitha BK, Murugan M, Sathyaseelan V. Climate resilience in natural enemies: Key players of ecological control. Plant Science Today. 2025; 12(sp1): 1-9. https://doi.org/10.14719/pst.8943

Abstract

Natural enemies, such as predators and parasitoids, are essential for good agricultural ecosystems by regulating pest populations and maintaining ecological balance, which helps in reducing reliance on chemical pesticides and promotes sustainable farming practices. Climate change affects these organisms, disturbing insect distribution patterns, causing changes in their life cycles and potentially misaligning natural enemies with hosts or prey due to shifts in environmental conditions. Such disruptions reduce their effectiveness in pest control, undermining agroecosystem balance. However, generalist natural enemies (e.g., lacewings, spiders, ladybugs) can adapt more flexibly to climate shifts due to their broader diet and habitat range, offering resilience against such changes. The review explores strategies to enhance the climate resilience of natural enemies, including habitat management and conservation practices they depend on. Proactive measures to safeguard these organisms are vital for maintaining their role in pest regulation despite climate change. Strengthening the adaptability of natural enemies can ensure continued natural, sustainable pest control, supporting food security, sustainable agricultural practices and biodiversity protection. The paper also elaborates on how climate-smart pest management (CSPM) can improve pest control as the climate changes. By helping these organisms adapt through CSPM, these beneficial insects may continue to play a key role in natural pest management, which supports food security, sustainable farming and biodiversity and the environment.

Keywords: climate change; climate resilience; climate-smart pest management; insect pests; natural enemies

Introduction

Agriculture is influenced by climatic parameters like increased temperature, changing precipitation patterns and rising atmospheric CO_2 levels, etc., which are together termed global climate change (GCC) (1). It is an important issue that the modern-day world currently experiences (1). Animal kingdom surfaces major disturbances due to these climatic shifts such as changes in their diversity and abundance, especially of arthropods, their geographical distribution, activity and abundance of natural enemies, newer insect biotypes and herbivore-plant interactions, etc. (2). However, during the last 100 years, climate change effects have increased multiple times (3). There can be altered interspecific interaction, altered synchrony between plants and pests, increased range of geographic distribution, increased number of generations, increased survival during overwintering, increased risk of invasion by migratory pests, increased incidence of insect-transmitted plant diseases and reduced effectiveness of biological control like predators and parasitoids due to climatic variations as well as efficacy of insecticides (4). These environmental changes have also led to increased disease and pest outbreaks, worsening of soil conditions, water shortages, drought and desertification, etc. (5). Due to shifting climatic conditions, insect populations (roughly two-thirds of all animal species) are exposed to unusual stresses (6). They are susceptible to environmental alterations because of their sensitivity to temperature, short generation times, high reproductive capacity, etc. (7). Changes in ambient temperature influence prey ingestion rates of ectothermic predators (8). Likewise, the pest population is also supposed to change along with climate change (9).

The selection of climate-resilient organisms, development of techniques and strategies in an effective manner oriented to agriculture for improving performance and production is the only way to overcome the problems perceived because of GCC (10). Knowledge of climate resilience is essential to build mitigation strategies to safeguard the agricultural sector's susceptibility to climate change. The integration of resilient practices and the adaptation of those practices into agriculture will enhance the system's capability to resist and recover from a wide range of climate change interferences and is known as climate-resilient agriculture (11). Therefore, maintaining ecosystem stability and guaranteeing efficient biological control in the face of the stresses of GCC requires improving climatic resilience in natural enemies through their selection, conservation and incorporation into adaptive pest management techniques (10). This comprehensive review analyses current scientific knowledge on climate change effects on natural enemies in agricultural systems, focusing on temperature, precipitation and atmospheric CO_2 impacts on predators, parasitoids and beneficial arthropods. The urgent need to understand climate-driven disruptions in biological control effectiveness necessitates developing climate-smart pest management strategies that support sustainable agriculture and food security.

Natural enemies: cornerstones of ecosystem functioning

Among their many ecological functions, natural enemies significantly contribute to essential ecosystem services such as pest control, pollination and organic matter decomposition in agricultural systems. These services include biological pest control, cross-pollination and decomposition (12). In the United States, beneficial arthropods such as bees, parasitoids and predators generate ecosystem services valued at $ 8 billion, contributing to agricultural productivity and reducing pesticide inputs. These natural enemies are essential components of pest regulation systems, targeting a wide range of insect pests and minimizing crop damage through biological suppression. Predatory beetles, spiders, hoverflies and parasitoid wasps are among the most effective agents, exerting top-down control that supports yield stability and environmental sustainability (13). The effectiveness of these arthropod natural enemies is strongly influenced by landscape features and resource availability, especially during periods when pests are scarce or climatic conditions are suboptimal. Natural enemies of crop pests, including parasitic wasps and predatory insects, are often harboured by native vegetation, acting as mutualists with plant defense mechanisms (14, 15). The conservation of these natural enemies is critical for multiple reasons, including reducing pesticide use, protecting the environment, adopting suitable crop varieties for higher yields, promoting biodiversity, preventing secondary pest outbreaks, improving soil health, supporting sustainable farming and building resilience against climate change (16).

Habitat management, a form of conservation biological control that provides natural enemies with essential resources such as alternative prey, hosts, shelter and food sources during adverse climatic conditions. The goal is not just to attract natural enemies but to enable them to persist and exert long-term pest suppression across cropping cycles (17). Tritrophic interactions reveal the complex interconnections between host plants, herbivores and their natural enemies, significantly influencing the prey-seeking behaviours of predators and parasitoids. Natural enemies do not interact with herbivores in isolation; instead, their ability to locate, attack and regulate pest populations is frequently mediated by plant-derived cues or by herbivore modifications of the host plant. For example, plant structural complexity, chemical defences, or nutrient composition may alter the foraging success and efficiency of parasitoids and predators, sometimes enhancing or impeding their biological control potential (15). Natural enemies rely on various chemical stimuli from pests to gather critical information, including pest population numbers, species identification, predation or parasitism status and hiding behaviour (18). Changing climatic conditions, particularly temperature increase, can substantially impact pest populations, potentially leading to biological and physiological changes that amplify pest reproduction and increase the number of generations per season. Climate change can influence migration patterns, forcing natural enemies to shift their geographical ranges in search of suitable environmental conditions. This movement may not always align with that of their target pests, leading to localized pest outbreaks in regions where natural enemy pressure has declined. In some cases, extreme weather events such as droughts or unseasonal rains may also directly reduce natural enemy populations, particularly those with limited dispersal abilities or narrow environmental tolerance (19). Ultimately, biological control facilitated by these natural enemies, remains the primary ecosystem service delivered to agriculture worldwide. Thus, understanding the ecological relationships among natural enemies is essential for optimizing their collective impact. It is not just the presence of multiple species, but how they interact, coexist and partition resources that determines the stability and success of natural pest control (20).

Climate change impacts on natural enemies

Climate change significantly impacts pest populations through complex direct and indirect mechanisms. The temperature rise induces profound changes in insect metabolism, mobility, metamorphosis and host availability, which ultimately influence pest population dynamics (9). Notably, insects' metabolic rates can double with a mere 10 °C increase in temperature (21). These changes affect both plants and insects through interconnected pathways: direct effects modify climate-sensitive characteristics of insects and plants, while indirect effects alter interactions at higher trophic levels involving natural enemies such as predators, parasitoids and pathogens (22).

The consequences of climate change propagate through ecological systems, with modifications at any trophic level directly impacting related individuals due to their intricate interconnections (22). Climate change will substantially influence the distribution, abundance and temporal occurrence of pests, consequently affecting the biological control mechanisms by their natural enemies. *Dolichogenidea tasmanica*, a braconid wasp that parasitizes *E. postvittana* eggs or larvae. Under warmer conditions, its spatial dispersal may shift, potentially creating a phenological mismatch with its host (23). Herbivores are managed through two primary mechanisms: top-down control by natural enemies and bottom-up control based on the quality and availability of host plants essential for their survival and reproduction (22). In diverse ecosystems like agriculture and forestry, herbivorous insects play a crucial role by linking host plants and natural enemies in tri-trophic interactions. For instance, there is a report that elevated ozone disrupts herbivore-induced volatile signals from lima beans attacked by the two-spotted spider mite (*Tetranychus urticae*), which in turn impairs the attraction and efficiency of predatory mites such as *Phytoseiulus persimilis*, reducing natural enemy suppression of this key pest (24). Climate change is expected to alter the phenology, spatial distribution and functional responses of predators and parasitoids, potentially disrupting their synchronization with host prey and compromising their effectiveness as biological control agents. For example, warming was found to influence the interaction between the corn leaf aphid (*Rhopalosiphum maidis*) and its natural enemies, where elevated temperatures reduced the protective behaviour of winter ants, thereby enhancing the effectiveness of predatory beetles like *Harmonia axyridis* in suppressing aphid populations (25). Climate change is not limited to rising temperatures-it also includes more frequent and intense cold extremes. These lower temperature events can be just as harmful to insects, especially parasitoids, which rely on delicate physiological and ecological balances for survival. Although some parasitoids have evolved remarkable adaptations such as freeze tolerance, supercooling and diapause to endure cold, unpredictable or severe drops in temperature can still lead to lethal or sublethal effects, disrupt host-parasitoid synchrony and increase the risk of local extinction. Thus, climate change poses a dual threat, not only through heat stress but also through cold stress, making both ends of the thermal spectrum critical for insect survival (26). Sublethal consequences of exposure to extreme temperatures on natural enemies are given in Table 1 and alterations in natural enemies according to climate change is given in Fig. 1. Under most situations, lower temperature is less abrupt and it can result in adaptation or migration; the real issue is of higher temperature and we need to know how the predatory behaviour of insects is altered with rising temperature. Predators and parasites ratio under high temperature is important for the management strategy as mentioned below.

Influence of climate change on biocontrol efficiency

Understanding the life stages of pests and their natural enemies is crucial for effective biological control, with life table analysis serving as a key ecological method to study predator-prey and host-parasitoid relationships. Climate change significantly disrupts this delicate ecological balance by altering the timing between pests and their natural enemies, as the growth of arthropods is fundamentally temperature-dependent. Higher temperatures can shorten growth periods, making pests more vulnerable and accelerating their development, which consequently impacts the effectiveness of biological control strategies (27). The phenomenon of phenological synchronization becomes critical in this context, where the timing of life cycles can determine the success of pest management. Different species respond variably to temperature changes, creating potential mismatches that compromise biological control effectiveness. A compelling example is the parasitoid *Tamarixia radiata*, which targets *Diaphorina citri*: at 35 ° C, it grows faster but experiences lower survival and parasitism rates, while at 20 °C, its development is too slow to effectively parasitize the pest. The optimal temperature of 27.5 °C represents a critical point where the parasitoid's development aligns perfectly with the pest's vulnerable stages (28).

Temperature variations also impact beneficial microorganisms like *Wolbachia* and *Buchnera*, which are essential for parasitoid health, further complicating biological control mechanisms. The house fly presents an intriguing contrast, adapting more rapidly to increasing temperatures due to its greater genetic diversity and shorter developmental cycle. Unlike its hymenopteran parasitoids, whose reproductive success dramatically decreases under high temperatures, the house fly maintains its fecundity, potentially leading to more frequent pest outbreaks with global warming. Among the studied parasitoids, *Muscidifurax raptor* demonstrated the most significant heat tolerance (29). Successful biological control in warming environments depends on multiple interconnected factors, including species' dispersal capacity, humidity levels and broader ecological variations. The intricate relationships between pests, natural enemies and environmental conditions underscore the complexity of maintaining effective biological control strategies in the face of climate change (30).

How insects survive in changing climate

Insects have evolved sophisticated mechanisms to survive sudden temperature changes, with heat shock proteins (HSPs), particularly HSP70, serving as critical protective agents. These molecular bodyguards shield and repair proteins during heat stress, demonstrating remarkable adaptive capabilities. For instance, flesh flies exposed to 40 °C for 2 hr could subsequently survive an ordinarily lethal temperature of 45 °C, with heat resistance persisting for 72 hr despite the protective proteins' active period lasting only 24 hr (31). The heat stress response involves a complex network of protective mechanisms, including heat shock proteins, biogenic amines and neuroendocrine factors that safeguard the nervous system and vital organs. Higher temperatures accelerate metabolism, often favouring smaller body sizes to minimize energy expenditure. Thermal perception in insects, exemplified by *Drosophila melanogaster*, involves specialized thermoreceptor neurons located in the brain's

Table 1. Sublethal consequences of exposure to extreme temperatures on natural enemies

Category	Effect	Distribution	Example	Reference
Size	Decreased size	Premature feeding cessation at low temperatures reduces adult size.	*Sarcophaga bullata*:smaller adults after cold exposure. *Trichogramma carverae*:reduced size after exposure to 10°C or lower.	
Longevity	Reduced lifespan	Cold exposure during immature stages reduces adult longevity.	Adult *Scelionidae* showed reduced lifespan after cold exposure.	
	Lower reproductive output	Females surviving cold exposure show reduced fecundity, proportional to temperature and duration.	*Telenomus podisi* and *A. galleriae*:up to 80 % reduction.	
Fecundity	No effect during proper diapause	When immatures enter diapause, cold exposure has little effect on fecundity.	*Trichogramma brassicae*:no fecundity decreases after 5 months outdoors in Switzerland.	(26)
	Impaired foraging and host location	Parasitoids emerging from chilled pupae show reduced response to host-related cues.	*Microplitis demolitor*:no response to volatile semiochemicals after cold exposure.	
Parasitoid endosymbionts	Reduced endosymbiont density or loss	Low temperatures can reduce or eliminate endosymbionts, affecting reproduction or host interaction.	*Wolbachia* and *Buchnera* strains decline or are lost during prolonged diapause or high-temperature exposure.	
	Reproductive shift	Temperature shifts can restore bisexual reproduction by eliminating *Wolbachia*.	*Trichogramma spp.* shifts from parthenogenesis to bisexual reproduction after heat exposure.	

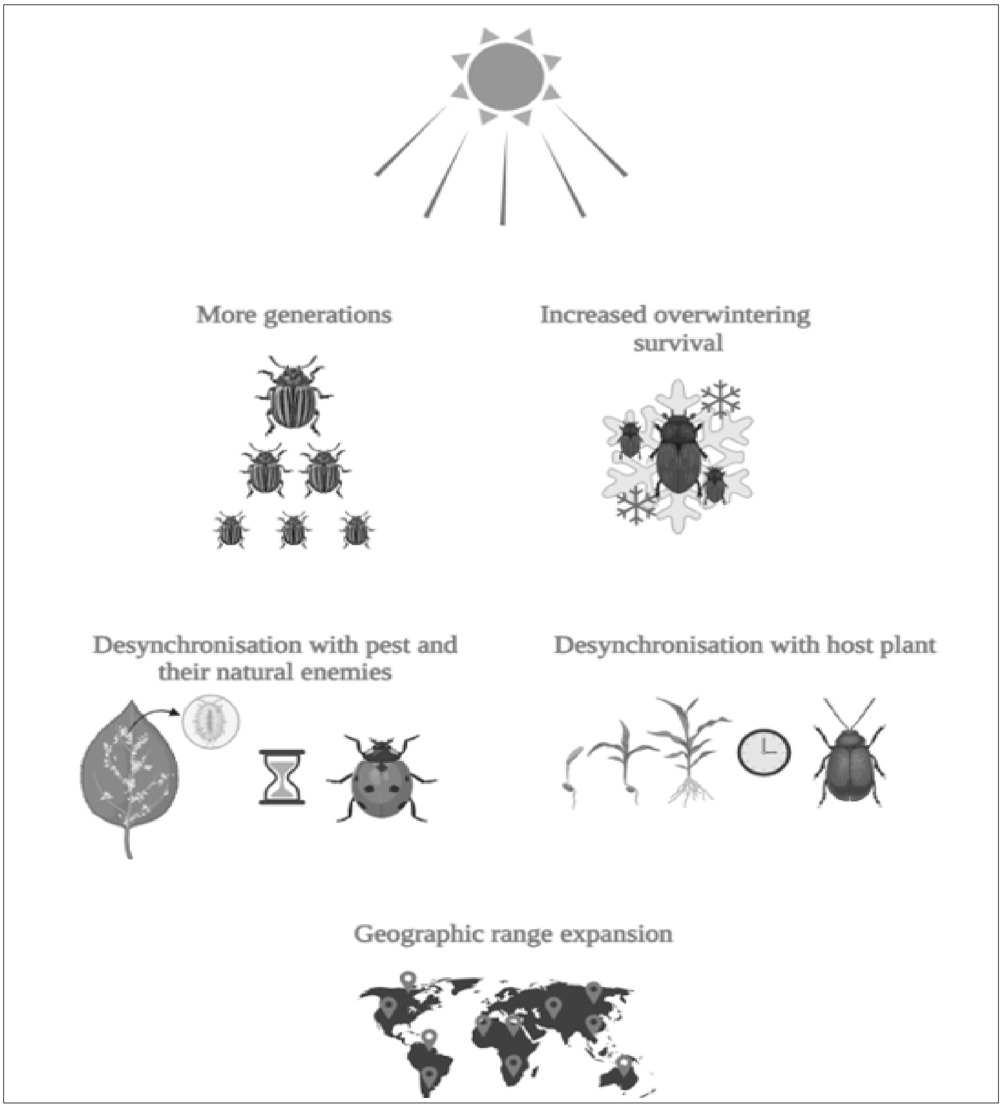

Fig. 1. Alterations in natural enemies according to climate change- increased temperature will lead to an increased number of generations and increased overwintering survival of the pests, desynchronisation with pests and their natural enemies, desynchronisation with host plant, and geographic range expansion.

anterior cells and arista, which detect temperature variations through changes in ion flow across neuronal membranes. Temperature shifts trigger the release of neurotransmitters, neuromodulators and neurohormones, facilitating neural communication and physiological adaptations. At elevated temperatures, hemolymph levels of juvenile hormone and 20-hydroxy-ecdysone increase, regulating critical processes like diapause. Insects employ multiple thermo-regulatory strategies, including cuticular modifications, evaporative cooling, muscle activity and behavioural adaptations. In extreme heat conditions, insects may induce a reversible heat coma-a sophisticated energy conservation mechanism controlled by neurons in the metathoracic ganglion-to manage gas exchange and protect vital physiological functions (32).

Survival strategies of natural enemies

Increasing temperature, increasing concentration of greenhouse gases and changes in precipitation patterns are the key climate change effects (33). These changes in the environment will affect and make changes in every species' ecosystem functioning, interaction networks, physiology and ecology and community composition (34). The feeding capacity of predators and parasitoids will also change according to the changes happening in the climate (35). And these changes will produce strong impacts on the tritrophic interaction as well as the biocontrol of pests (36). The studies conducted earlier revealed that increased CO_2 concentration in the atmosphere affects the third trophic level (natural enemies) (37). External and internal mechanisms with respect to climate change will make the natural enemies suffer. Internal mechanisms include how abiotic factors directly affect an organism concerning climate change (38). External mechanisms are indirect effects like changed distribution, physiology or phenology of host plants and their pests (39). To predict how climate change will impact different communities, it's vital to study both the indirect effects across various trophic levels and the direct effects on each level. This approach helps us understand the underlying processes and interactions in the ecosystem (23). During the last few years, experiments have assessed the direct effect on natural enemies of every single abiotic factor related to climate change. For instance, parasitoid dispersal rate, fecundity, survival rate, parasitism and developmental rates are greatly influenced by temperature (40). According to thermal performance curves, the activity of parasitoids will increase when the temperature rises to an optimum level. After that, the performance of the parasitoids will decrease due to the rise in temperature more than the needed temperature (39). The optimum temperature needed for parasitoids to survive and perform their maximum is reported to be less than their host temperature and increasing the temperature due to climate change will affect parasitoid efficiency (41). Likewise, alterations in the precipitation and CO_2 levels were also reported to be detrimental to natural enemies. It's crucial to remember that elevated CO_2 can directly influence parasitoids and predators, even though changes in lower-level components often impact higher-level components (42). Crucially, increased CO_2 can alter the natural enemies, such as parasitoids and predators, to sense their surroundings, making it more challenging for them to pick up on crucial indications like smells. This occurs because their olfactory receptors become less sensitive. Over time, the brain cells that receive these signals may become less sensitive, which might impact their reactions to their surroundings (43). Alterations in precipitation were also studied and it was shown that they affect the behaviour and physiology of natural enemies (44). Insects and arachnids possess a waxy cuticle that prevents water loss from their body during drought (45). Drought makes the predators and parasitoids hide in the soil, build shelters, or migrate to avoid desiccation and thus it leads to their reduced foraging activity (46).

Studies on single climatic factors that affect natural enemies of herbivores are more than how the combined and interactive effects of different parameters affect natural enemies (47). The impact of climate change on pest control is crucial to maintain genetic diversity, as this enables predator species to better adapt to changing environmental conditions, allowing them to continue managing pest populations efficiently, which in turn helps to keep ecosystems balanced and stable (48). Spider populations from higher latitudes found it difficult to control grasshopper populations as temperatures rose effectively (49). However, spiders collected from areas with high temperatures showed a significant reduction in this effect, indicating that these populations had successfully adapted to the heat. These findings suggest that natural predator species can adapt to changing environmental conditions along with the pests they control as long as they have enough time to evolve a diverse gene pool within their populations and proper gene flow between populations (50). The discovery shows that the effectiveness of having multiple natural enemies improves under higher temperatures. Having a variety of natural enemies at normal temperatures does not significantly enhance pest control. At 3 ˚C higher temperatures, the combination has a more substantial and more beneficial impact. Higher predation rates, *i.e.*, predators consume more pests and improved collaboration between various natural enemy species, were two examples of this shift, which occurred more frequently at higher temperatures (51). Different populations within a species can vary in their heat tolerance based on location. Populations in colder regions, typically at higher latitudes or elevations, are generally more vulnerable to temperature increases compared to populations in warmer areas, often found closer to the equator. This difference occurs because cold-adapted populations are physiologically suited to cooler conditions, making them more affected by warming. Conversely, populations from warmer areas have adaptations that help them cope with high temperatures, so they show less sensitivity when temperatures rise (52). The ability of a species to react to changes in its environment depends on several different ways it can adapt. While these adaptive responses are primarily controlled by the species' genes, it is helpful to break them down into different systems that are responsible for how the species immediately reacts to changes in temperature, food availability, or other environmental factors. These systems help the species survive and function as conditions around them change (53).

How to help helpful insects thrive

Climate-Smart Pest Management (CSPM) is an innovative approach that leverages natural enemies such as parasitoids, diseases and predators to control pest populations in the context of changing climate conditions. This strategy encourages agricultural practices that include growing diverse crops and creating natural habitats to support these biological control agents, ultimately reducing pest problems and enhancing ecosystem resilience. CSPM focuses on comprehensive pest and climate monitoring, risk prediction and proactive management, enabling farmers to make informed decisions and take preventive actions before pests can cause significant damage (54). The core principle of CSPM is to create a supportive environment that enhances the role of natural enemies, making pest control more adaptable to climate change. This approach recognises that pest control strategies can be both short-term and long-term, aligning with broader climate change adaptation techniques that aim to reduce risks using current risk management strategies (55).

Anticipating and identifying future pest outbreaks

As the climate changes, more pests are moving to cooler areas and higher altitudes. For instance, the southern green stink bug has spread through Europe and Japan since the 1960s because of warmer winters. The black coffee twig borer, which usually damages coffee plants below 1400 m, has been found at 1800 m, causing crop losses in higher areas like Uganda, where many farms are family-run and have lower yields. CSPM highlights the need for the use of models to understand the pests better and create effective control methods. To improve preparedness, Climate-smart pest management (CSPM) encourages using predictive models and early warning systems. These tools combine weather, crop and pest data to help farmers know about pest outbreaks in advance, before they become serious. CSPM also supports making pest risk maps that show which areas are more likely to face problems. This helps in planning quick and effective actions. By promoting better monitoring and faster responses, CSPM helps reduce crop loss, avoid too much pesticide use and make farms more resilient (54).

Role of weeds in maintaining natural enemies

Weed plants harbour many insects and are a must for their survival. Weeds have a direct correlation with climate change. Increasing temperature also moves weeds to higher elevations and has been reported in many countries, particularly North America (56-58). Weeds offer alternative prey, nectar and habitat to predators and parasitoids, even when crop pests are not present, helping maintain natural enemies year-round (59). Weeds provide alternative prey, nectar, pollen and microhabitats that sustain predatory and parasitoid species year-round, even when crop pests are scarce. These resources help maintain populations of natural enemies such as lady beetles (Coccinellidae), predatory flies (Syrphidae) and spiders, especially under stress from temperature and drought. Under warming scenarios, diverse weed cover can moderate microclimates (e.g. shading, humidity retention) that support natural enemies' survival and activity. Such structural complexity helps preserve predator-prey synchrony and resilience, indirectly enhancing pest suppression even as pests accelerate their life cycles (60).

A study conducted at a grapevine FACE facility (~ 480 ppm vs. ~ 400 ppm CO_2) found that under elevated CO_2 for Riesling vines, specifically *L. botrana* eggs were larger and better parasitized by *T. cacoeciae* than under ambient CO_2 conditions. This resulted in higher parasitoid emergence rates, indicating that elevated CO_2 did not decrease biological control and may even improve suppression in certain cultivar systems (61). The role of weeds in maintaining natural enemies is given in Fig. 2.

Strengthening farms and landscapes for pest resilience

Farms with more biodiversity can handle extreme weather like droughts and storms more effectively (62). CSPM supports crop diversification to improve farm biodiversity. Adopting climate-smart pest management (CSPM) or broader climate-smart approaches like agroforestry in countries characterized by small land holdings and high population pressure is feasible (63). This helps grow the population of natural enemies. Switching from planting a single crop (mono-cropping) to growing different crops in strips (strip-cropping) provides safe spaces for these natural enemies to live and control pests (64). Farms with a variety of plants performed better than those with little or no plant diversity. They had less crop damage, more natural pest enemies and fewer herbivores (62). Factors enhancing natural enemy efficiency in a changing climate is given in Table 2.

Conclusion and Future Prospects

To sustain effective pest control under changing climate conditions, it is crucial to conserve resilient natural enemies such as *Trichogramma cacoeciae*, lady beetles (Coccinellidae), predatory flies (Syrphidae), spiders and *Muscidifurax raptor*. *T. cacoeciae* has shown adaptability not only to rising temperatures but also to elevated CO_2 levels, maintaining high parasitism rates under such conditions. *M. raptor* demonstrates the highest heat tolerance among the studied parasitoids, remaining effective as temperatures increase. Supported by diverse habitats like weed-covered areas, these natural enemies continue to suppress pests even during climatic stress. Prioritizing their conservation can boost ecological stability, reduce reliance on chemical control and support sustainable agriculture in a changing climate. Habitat conservation, restoration and sustainable land management are key strategies to strengthen the resilience of natural enemies. Protecting biodiversity-rich areas and promoting diverse agricultural landscapes helps enhance the survival and effectiveness of predators and parasitoids. Investment in research-including ecological modelling, remote sensing and field studies-can improve predictions of climate impacts and guide better pest management strategies. Collaboration among scientists, farmers and policymakers is essential to develop innovative, climate-resilient solutions. Enhancing the resilience of natural enemies can reduce reliance on chemical pesticides, support sustainable agriculture and safeguard ecosystem services, ensuring long-term food security and ecological stability.

Acknowledgements

The authors would like to express their deepest gratitude to Tamil Nadu Agricultural University, Coimbatore, India, for supporting them throughout the process. Special thanks are extended to the Chairman, advisory members and Head of the Department for their valuable feedback and constructive suggestions on the manuscript.

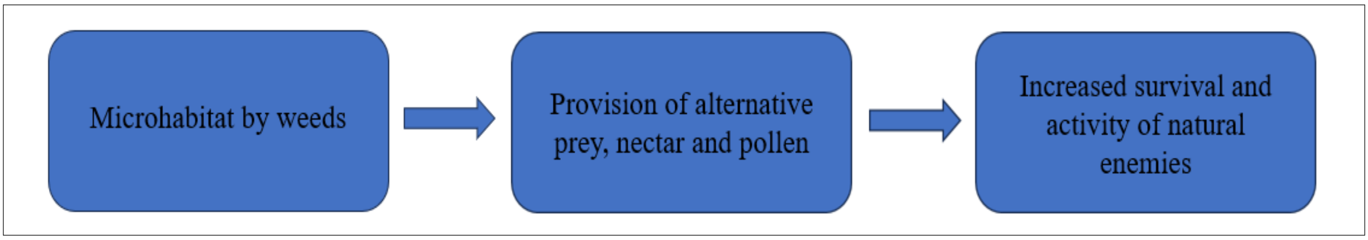

Fig. 2. Role of weeds in maintaining natural enemies.

Table 2. Factors enhancing natural enemy efficiency in a changing climate

Factor	Mechanism of support	Natural enemies benefited	Positive outcome	Reference
Genetic diversity	Enables adaptation to rising temperatures and other stressors	Spiders, *Muscidifurax raptor*, others	Improved heat tolerance, continued pest suppression	(29)
Weed cover and plant diversity	Provides nectar, pollen, alternative prey, and refugia during climatic stress	Lady beetles, Syrphid flies, Spiders	Sustained populations year-round; enhanced pest suppression	(60)
Habitat management	Creates microclimates and continuous resources; reduces climate exposure	Generalist predators, parasitoids	Increased abundance, foraging, and persistence of natural enemies	(17)
Crop diversification	Supports natural enemy diversity and stabilizes food webs	Generalist predators, parasitoids	Maintains enemy-prey balance even under climate variability	(63)
CSPM adoption	Promotes early warning, risk prediction, and enemy conservation	All types of beneficial insects	Climate-informed pest control decisions enhance biocontrol success	(54)
Heat shock protein (HSP) expression	Increases thermal resilience in natural enemies	Insects like flesh flies, others	Survival under heat stress and improved recovery	(31)
Thermal adaptation by local populations	Local acclimatization to regional climate conditions	Spiders, House flies	Maintained efficiency despite regional warming	(50)

Authors' contributions

AM prepared the manuscript. VB reviewed and approved the final version of the manuscript. ES contributed to editing, summarizing and revising specific sections of the manuscript. TS assisted in summarizing results and refining the manuscript language. BKS participated in editing and restructuring the manuscript content. MM and VS contributed to revising the manuscript and improving clarity. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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