

Climate Change and Insect Populations: A Decade of Ecological Responses, Adaptation and Emerging Challenges

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ABSTRACT

Climate change alters insect populations through interacting effects on development, reproduction, seasonal timing and habitat suitability. This narrative review evaluates research published during 2015–2024, distinguishing population decline from redistribution and changes in community composition. Evidence from monitoring, experiments and ecological models indicates substantial vulnerability, but responses differ among climatic regions, life histories and land uses. Earlier emergence can favour insects with several annual generations, whereas heat extremes, restricted dispersal and reproductive damage can undermine persistence. Behavioural flexibility and evolutionary change provide partial buffering, without establishing that adaptation will match future warming. Agricultural intensification further modifies climatic exposure and access to refuges. The principal emerging challenges concern disrupted ecological interactions, crop protection, vector redistribution and inadequate monitoring of poorly studied taxa. Effective responses require emissions mitigation, connected and thermally diverse habitats, and demographic observations that separate climatic effects from concurrent environmental pressures. Conserving insect diversity therefore depends on understanding which populations can persist, where ecological functions are changing, and which interventions reduce exposure before losses become irreversible.

Keywords- Insect Biodiversity; Climate Change; Phenology; Thermal Tolerance; Adaptation; Ecological Monitoring.

I. INTRODUCTION

Insects connect plant production with pollination, decomposition and food webs. Their responses to climatic change consequently extend beyond individual species to ecosystem functioning. Nevertheless, the expression “insect decline” combines several different measurements: abundance counts individuals, biomass measures their collective mass, richness counts species, and occupancy records where species occur. These quantities can change independently. A community dominated by a few large, common species may retain substantial biomass while losing ecological diversity [1].

Research during 2015–2024 increasingly examined how climatic exposure interacts with land management and biological traits. A central question is whether populations can maintain recruitment and access

suitable habitat as temperatures and precipitation patterns change. The evidence does not support an identical trajectory for all insects. Some populations expand, others contract, and apparently stable assemblages can undergo considerable replacement. This review evaluates these differences and their implications for conservation and environmental management.

II. REVIEW APPROACH AND INTERPRETATION

This focused narrative review considers peer-reviewed studies published from 2015 through 2024. Studies were selected for their relevance to climatic mechanisms, documented ecological responses, adaptation or management, with emphasis on primary research spanning field observations, experiments and projections. Publication dates define the reviewed decade;

several underlying observation series extend substantially further into the past. The selection is interpretive rather than exhaustive and does not constitute a systematic review or a new meta-analysis.

Reported estimates retain their original ecological meaning and geographical scope. Spatial comparisons are not treated as temporal decline rates, and modelled climatic suitability is not equated with realized population size. The numerical figures reorganize published estimates without pooling incompatible outcomes or generating artificial observations. Mechanistic interpretation is distinguished from demonstrated causation, particularly where climate and land-use pressures coincide.

III. ECOLOGICAL RESPONSES DURING THE REVIEWED DECADE

3.1 Population change and climatic attribution

Hallmann et al. [2] estimated a 76% seasonal reduction in flying-insect biomass across sampled German protected areas between 1989 and 2016. Their measured weather and habitat variables did not explain the overall decline. The result established the severity of a regional biomass change; it did not establish that climate alone caused it. Protected status also cannot isolate insects from environmental pressures operating beyond reserve boundaries.

Climatic associations become clearer when studies examine biologically relevant exposure. Soroye et al. [3], analysing 66 bumblebee species in Europe and North America, linked increasingly frequent temperatures beyond historically experienced conditions with local losses, colonization dynamics and richness changes. The associations persisted after accounting for land-use change. This supports a climatic contribution, although observational adjustment cannot remove every unmeasured influence. Analyses of northern Californian butterflies likewise identify serious declines at high elevations where immediate habitat conversion is less prominent, demonstrating that climatic vulnerability is not confined to intensively cultivated landscapes [4].

The relevant exposure is therefore more specific than a rising annual average. Seasonal rainfall, prolonged drought and brief thermal extremes may affect different life stages. A favourable spring can coexist with damaging summer conditions. Inference improves when population records are matched to these biological windows rather than to a single annual temperature statistic [4].

3.2 Redistribution and community replacement

Poleward or uphill movement can reduce exposure, but redistribution is rarely a simple displacement of an intact range. Kerr et al. [5]

documented losses at southern bumblebee range margins without equivalent expansion at northern margins, alongside elevational shifts among southern species. Suitable climate beyond a range boundary does not ensure that populations can reach it, establish nests or obtain food. Restricted colonization can therefore convert geographical movement into net range contraction.

Evidence published in 2024 further complicates reliance on richness alone. Monràs-Janer et al. [6] examined British birds, butterflies and plants and found that richness gains could accompany increasing similarity among communities and greater representation of warm-adapted species. Because the analysis included several taxonomic groups, it should not be generalized to every insect assemblage. Its butterfly component nevertheless illustrates a crucial conservation problem: local species counts may increase while regional distinctiveness declines. Baseline land use and historical environmental change also influence the apparent direction of recent trends.

3.3 Phenology and ecological interactions

Warming can accelerate development and advance emergence, but the demographic consequences depend on life history. In 130 British butterfly and moth species, Macgregor et al. [7] found that earlier emergence favoured population growth among species capable of multiple reproductive cycles each year. Responses among species with one annual cycle were neutral or negative, depending on habitat specialization. A longer apparent growing season thus represents an opportunity only when developmental schedules and resource availability permit its use.

Timing also matters because insects interact with organisms responding to different environmental cues. An emerging pollinator requires flowers; a developing herbivore requires suitable host tissue. Kharouba et al. [8] found substantial changes in the relative timing of interacting species across a broader ecological synthesis, but no uniform direction of change. Earlier activity should therefore not automatically be described as harmful mismatch. Demonstrating mismatch requires evidence that temporal overlap has become insufficient and that this change affects survival, reproduction or another relevant ecological outcome.

3.4 Climate and agricultural land use

Outhwaite et al. [9] found that intensive agriculture combined with greater historical warming was associated with nearly 50% lower insect abundance and 27% lower richness relative to less-disturbed, less-warmed reference habitats. Nearby natural vegetation moderated losses in low-intensity agriculture, with marked differences between landscapes containing 25% and 75% natural habitat (Figure 1). These are modelled spatial contrasts, not global annual decline rates. Their implication is that climatic exposure and landscape context must be assessed together.

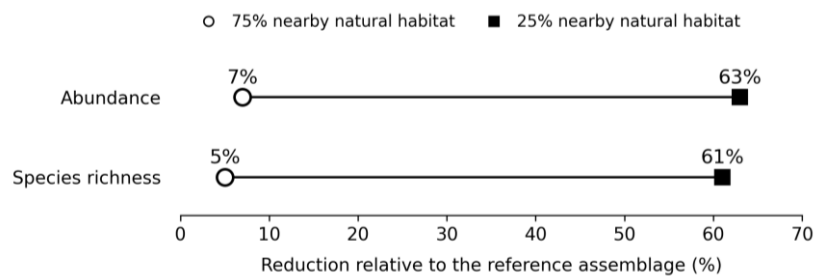


Figure 1. Habitat context and insect losses in low-intensity agriculture under substantial historical warming. Paired symbols show published reductions relative to the study reference, at 25% and 75% nearby natural-habitat cover [9]. The reference represents primary vegetation without historical warming and with 100% nearby natural habitat. Lines connect rounded estimates; they are not confidence intervals or temporal trajectories.

IV. ADAPTATION AND ITS LIMITS

4.1 Behavioural and developmental flexibility

Behavioural avoidance, phenotypic plasticity and evolutionary adaptation operate through different processes (Figure 2). Moving into shade can alter immediate exposure. Developmental plasticity can alter emergence timing or seasonal reproduction within an existing genotype. Evolution requires heritable population change across generations. These mechanisms may interact, but evidence for one does not demonstrate the others.

Observed flexibility in phenology and generation number helps explain why some Lepidoptera expand under warming [7]. It also identifies a limit: populations with inflexible seasonal schedules may not obtain the same benefit. Behavioural buffering similarly depends on accessible microhabitats. A shaded location is useful only if insects can reach it while meeting their needs for food, hosts and reproduction. Evaluating adaptation therefore requires demographic outcomes, rather than treating an altered trait as sufficient evidence of successful persistence.

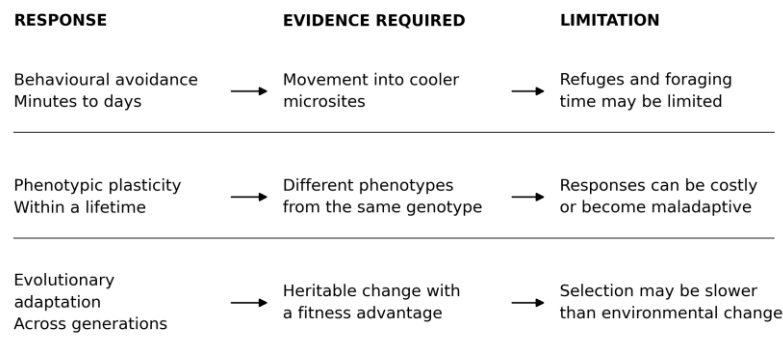


Figure 2. Framework for distinguishing immediate responses from evolutionary adaptation. The diagram identifies the evidence needed to interpret behavioural avoidance, developmental plasticity and inherited change, together with constraints on each pathway. It is an original conceptual synthesis informed by phenological and experimental research [7,10]; arrows indicate interpretation, not measured effect sizes.

4.2 Evolutionary capacity and trade-offs

Urban warming offers an informative, although imperfect, analogue for adaptation to regional climatic change. Diamond et al. [10] used common-garden experiments with acorn ants to investigate divergence in thermal tolerance between urban and rural populations. Evidence of evolved differences demonstrates that rapid thermal adaptation is possible in some insects. Urban environments also differ in many other respects, however, and findings from one species cannot establish a universal rate of climatic adaptation.

Evolutionary persistence depends on available genetic variation, population size, generation time and the relationship between selected traits and reproductive

success. A gain in heat tolerance may entail a loss of performance under other conditions. Moreover, a population must remain sufficiently viable during selection for beneficial variants to spread. Short generation times create opportunities for adaptation, but do not guarantee evolutionary rescue. Conservation planning should consequently treat demonstrated adaptive capacity as a population-specific attribute, rather than assuming that all insects will evolve out of climatic risk.

4.3 Reproductive damage below lethal limits

Survival alone provides an incomplete measure of thermal safety. Experimental heatwaves reduced male reproductive performance in red flour beetles, with effects

extending beyond the directly exposed generation [11]. Such results identify a mechanism through which apparently surviving adults may contribute fewer offspring. Their magnitude remains dependent on species, exposure conditions and experimental design; laboratory responses cannot be transferred unchanged to wild communities.

This distinction has practical consequences for vulnerability assessment. Measurements of lethal temperature thresholds should be accompanied by fertility, development and recruitment data. Repeated events may also leave insufficient time for recovery. A population that survives each isolated heatwave can still decline if reproductive output remains depressed between events. Evaluating the interval between stressful episodes may therefore be as important as identifying the hottest temperature experienced.

V. EMERGING ECOLOGICAL AND SOCIETAL CHALLENGES

5.1 Pollination and food-web stability

Climate-related changes in insect communities can alter the timing and reliability of ecological functions. Declining bumblebee occupancy, for example, raises questions about where pollination remains available and which plant species lose effective visitors [3]. Yet neither total insect biomass nor simple species richness directly measures pollination. Uhler et al. [1] showed that these biodiversity indicators respond differently across land uses and temperature gradients. Functional monitoring should therefore measure relevant interactions, such as visitation and successful pollen transfer, alongside community composition.

Ecological replacement also deserves attention. A newly arriving generalist may increase local richness without replacing the function of a disappearing specialist. Similarly, unchanged annual abundance can conceal a seasonal shortage of prey. The management objective should be sustained ecological functioning

across space and time, supported by species-resolved observations, rather than preservation of a single aggregate indicator.

5.2 Crop pests and vector redistribution

Conservation losses can coincide with increased pressure from particular pests. Deutsch et al. [12] projected that insect-related losses of wheat, rice and maize would increase by approximately 10–25% per degree of global warming, through temperature-dependent changes in insect metabolism and population growth. This denotes a relative increase in existing pest losses, not a 10–25 percentage-point reduction in total crop yield. Outcomes depend on crop geography, insect thermal responses and management; the estimate is a model projection rather than an observed global trend.

For vector insects, warming can redistribute seasonal suitability without increasing risk everywhere. Ryan et al. [13] modelled temperature-dependent transmission suitability for two *Aedes* mosquitoes and projected different geographical responses because their thermal niches differ. Climatic suitability is only one component of realized transmission, which also depends on vector presence and other biological and social conditions. Surveillance must therefore follow changing seasonal and geographical patterns without assuming a simple linear relationship between warming and disease incidence.

5.3 Nonlinear future risk

Scenario comparisons demonstrate the ecological importance of relatively small differences in global warming. Warren et al. [14] projected that 6%, 18% and approximately 49% of assessed insect species would lose more than half their climatically determined geographical range under warming of 1.5°C, 2°C and approximately 3.2°C, respectively (Figure 3). These are conditional range-suitability projections, not predicted extinction percentages. They nevertheless indicate that climatic exposure can increase sharply across warming levels. The 3.2°C scenario reflects the study's 2018 framing and should not be presented as an updated assessment of policy commitments.

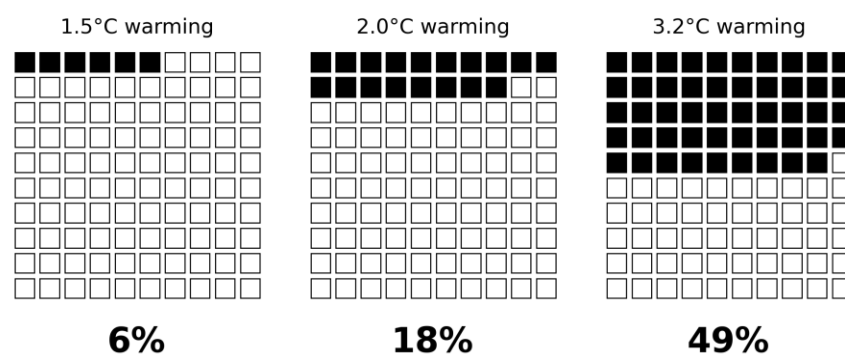


Figure 3. Projected proportion of assessed insect species losing more than 50% of their climatically determined range at alternative warming levels relative to preindustrial conditions [14]. Each filled square represents one percentage point, not an individual sampled species. The 49% estimate is approximate. These scenario summaries are not extinction rates; uncertainty intervals are not reproduced.

VI. RESEARCH PRIORITIES AND CONSERVATION RESPONSES

6.1 Measuring the processes that determine persistence

The reviewed evidence identifies a need for linked observations of exposure, life history and demographic change. Monitoring should record abundance, occupancy and species identity repeatedly through the active season, while documenting sampling effort and local temperature and moisture. Trap catches also depend on activity and detectability, so warmer-weather captures can increase without equivalent population growth [1]. Repeated observations and appropriate detection models can help separate these processes.

Future attribution studies should combine long-term population records with experiments addressing plausible mechanisms. Analyses should test delayed climatic effects, distinguish colonization from local disappearance, and evaluate interactions with habitat condition. Where possible, intervention studies should compare restored and unrestored sites before and after management. These designs would make conservation claims more testable than correlations between a single climatic variable and a broad biodiversity index.

Geographical and taxonomic coverage remains a limitation of this review. British Lepidoptera, European landscapes and North American bees cannot represent the full diversity of tropical, soil-dwelling or aquatic insects. Spatially extensive studies improve coverage, but cannot replace observations of change through time. Future syntheses should report where evidence is absent and test whether conclusions survive changes in study selection, baseline period and outcome metric.

6.2 Reducing exposure and supporting recovery

Management should preserve a range of microclimates and connect breeding and feeding habitats across environmental gradients. Evidence from British biodiversity change supports protecting natural and semi-natural habitats while attending to species composition rather than richness alone [6]. Restoration should be evaluated against the requirements of target populations: vegetation cover without suitable hosts or reproductive habitat may provide limited benefit.

Local interventions and emissions mitigation operate at complementary scales. Habitat management can improve opportunities for persistence and recolonization, while limiting warming reduces the scale of future climatic displacement indicated by range models [14]. Conservation and crop protection should also be assessed together. Decisions that suppress pests should account for effects on pollinators and natural enemies, with monitoring used to revise practices when ecological costs emerge. The appropriate response is adaptive management grounded in measured outcomes, rather than a uniform prescription across insect groups and landscapes.

VII. CONCLUSION

Research published during 2015–2024 establishes climate change as an important contributor to insect redistribution, altered seasonal dynamics and population vulnerability. Its effects depend on biological traits, exposure history and landscape condition. Earlier emergence and evolved tolerance can provide benefits, but these do not offset all reproductive, dispersal or habitat constraints. The strongest interpretation of the decade's evidence is therefore conditional: persistence is possible where suitable environments, demographic capacity and adaptive responses coincide. Conservation should reduce climatic exposure, retain ecological heterogeneity and measure whether populations successfully reproduce and recover. This approach accommodates both local increases and serious losses without obscuring the ecological consequences of community change.

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