Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Insect Science

Review

Can rapid evolution allow insects to keep pace with global warming? Reviewing contributions from quantitative genetics, experimental evolution, and environmental gradients

José M Alruiz and Luis E Castañeda

Global warming is exposing insect populations to environmental conditions that may change faster than they can adapt. Therefore, understanding whether rapid evolution can enable insects to persist in the face of ongoing warming has become a central challenge in evolutionary ecology. Here, we examined recent advances in assessing the potential for and constraints on rapid thermal adaptation. We focus on quantitative genetics, experimental evolution, and environmental gradients as complementary approaches. Quantitative genetic approaches have revealed that thermal traits have sufficient genetic variation to respond to natural selection; however, these responses may be constrained by their underlying genetic architecture. Experimental evolution has demonstrated that rapid adaptive responses are possible; however, laboratory conditions may oversimplify the environmental complexity experienced by natural populations. Environmental gradients can impose differential selection on populations, leading to phenotypic differentiation that can be evaluated through common-garden experiments. Recent evidence further suggests that thermal adaptation under climate warming cannot be fully understood from a single-stressor perspective because interacting selective pressures can reshape both the direction and magnitude of evolutionary responses. To improve predictions of insect persistence under future warming scenarios, it is essential to integrate evolutionary, ecological, and genomic approaches.

Address
Núcleo Interdisciplinario de Biología y Genética (NiBG), Instituto de Ciencias Biomédicas (ICBM), Facultad de Medicina, Universidad de Chile, Santiago, Chile & Research Ring in Pest Insects and Climate Change (PIC2), Santiago, Chile

Corresponding author: Castañeda, Luis E (luis.castaneda@uchile.cl)

Current Opinion in Insect Science 2026, **77**:101577

This review comes from a themed issue on **Global change biology**

Edited by **Sarah Diamond, Ryan Martin, Mike Moore** and **Carmen da Silva**

Available online 12 June 2026

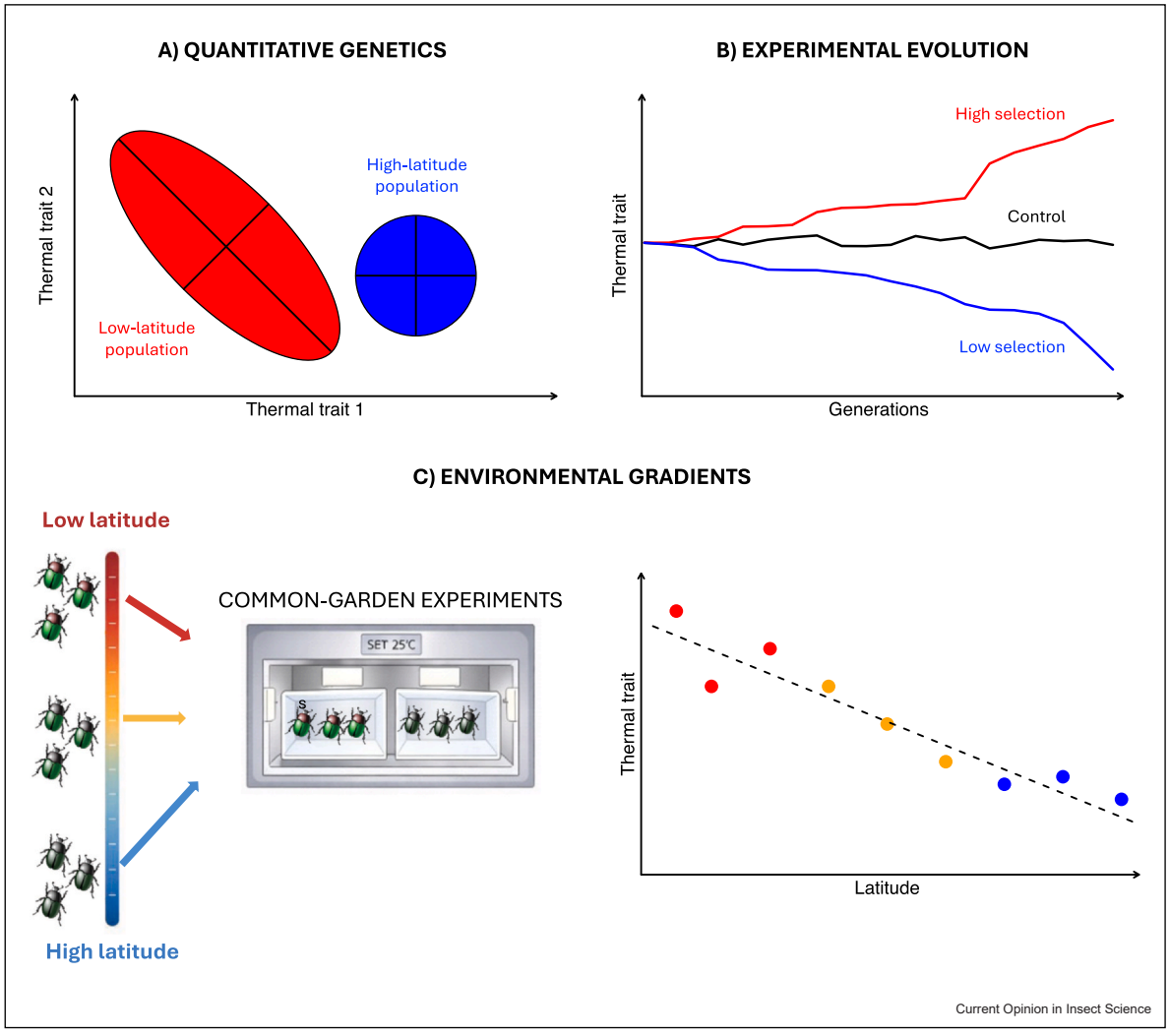
https://doi.org/10.1016/j.cois.2026.101557

Introduction

Global change is advancing at an unprecedented pace, reshaping the thermal, chemical, and ecological landscapes inhabited by insects and imposing strong selective pressures on their populations [1,2]. Although insects are often considered prime candidates for rapid evolutionary responses due to their short generation times and large population sizes, these adaptive responses may be insufficient to keep pace with the speed and multidimensionality of contemporary climate change [3,4], especially among tropical insects [5]. Understanding how quickly insect populations can evolve under conditions of global change is critical for fundamental and applied reasons alike. From an ecological perspective, an evolutionary failure to keep up with environmental changes can lead to local extinctions and disrupted species interactions [4,6]. From an applied perspective, rapid evolutionary responses can influence the spread and adaptation of invasive species, the stability of biological control, and the emergence of insecticide resistance in pest insects [7,8]. Therefore, predicting whether and how insects can adapt evolutionarily is essential for forecasting biodiversity dynamics and designing sustainable management strategies.

Rising mean temperatures, an increased frequency and intensity of extreme heat events, and the proliferation of urban heat islands act as strong selective pressures across

Figure 1



Schematic representation of how rapid evolution in response to global change can be tested in natural populations. **(a)** Quantitative genetics provides estimates of genetic variances and covariances, which offer insights into the potential and constraints of thermal trait evolution. Here, thermal traits 1 and 2 are negatively correlated in the low-latitude population, suggesting an evolutionary trade-off between the two traits. In contrast, these same traits are uncorrelated in the high-latitude populations, indicating that they traits can evolve independently. **(b)** Experimental evolution: artificial selection experiments can evaluate the speed and magnitude of the evolution in thermal traits. These experiments typically select for the highest (high selection) or lowest (low selection) phenotypic values each generation, resulting in evolutionary responses in the thermal traits. **(c)** Environmental gradients: populations distributed along geographic gradients (e.g. latitude or altitude) may undergo strong spatial selection, resulting in phenotypic differentiation among populations. Here, populations distributed along a latitudinal gradient that were reared in common-garden conditions exhibit phenotypic differentiation, with the thermal trait being negatively associated with latitude. This can be explained by genetic differentiation among populations driven by local adaptation.

natural, agricultural, and urban ecosystems [9]. Evidence from thermal biology thus provides a powerful mechanistic framework for evaluating how rapidly insects can evolve under conditions of global warming. Thermal performance curves, critical thermal limits, and time-temperature relationships define the boundaries that shape key features of insect populations, such as survival, reproduction, and population growth [10,11]. Understanding whether these traits can evolve as quickly as environmental change is fundamental to predicting the future of insects in a warming world. Here, we examine recent evidence from three complementary empirical approaches that are widely used to assess the evolutionary responses of insect populations to global warming (Figure 1): (i) quantitative genetic analyses, (ii) experimental selection, and (iii) a combination of environmental gradients and common-garden experiments. While recent reviews have synthesized the contributions of these approaches in evaluating the likelihood of persistence under global change through rapid evolution [6,12,13], here we

highlight emerging patterns, unresolved challenges, and promising directions for integrating evolutionary processes into predictions of insect thermal adaptation to a rapidly warming world.

Quantitative genetics and evolutionary potential

Predicting the adaptive responses to climate change requires estimating heritable genetic variation of traits that allow populations to adapt to changing thermal conditions [13]. Several studies have revealed a polygenic basis and significant heritability for thermal tolerance [14–16]. Additionally, substantial genetic variation for stress-resistance traits, such as desiccation resistance and its underlying traits (e.g. hydrocarbon cuticular composition), has been also reported in several insect species [17,18]. However, predictions about the adaptive capacity to global warming may be limited because estimates of heritability depend on the methodology used to measure thermal tolerance [13]. Furthermore, most of these studies have been conducted under benign conditions, and it is recognized that cryptic genetic variation may be revealed under stressful conditions, thereby increasing the phenotypic variation on which natural selection can act [19, but see 16].

Although single-trait quantitative genetic studies provide information about the evolutionary potential, it is important to note that phenotypic evolution is shaped by the genetic relationships among traits. These relationships are encapsulated in the genetic (co)variance matrix, commonly referred to as the G matrix [20]. The G matrix captures genetic correlations among traits (Figure 1a) and provides critical insights into the potential and constraints of evolutionary responses to selection. For instance, aligning genetic covariances among resistance-stress traits in *Drosophila melanogaster* with the direction of selection can boost the evolutionary potential to thermal selection [21]. Conversely, low heritabilities and genetic correlations among parameters of the thermal performance curves (TPCs) suggest evolutionary constraints on thermal adaptation in the harlequin beetle (*Harmonia axyridis*) [22]. In this context, TPCs offer a comprehensive phenotypic framework for understanding the relationship between fitness and temperature and can provide meaningful information regarding the evolutionary capacity of thermal traits [23]. This can be achieved by testing trade-offs between maximum performance and breadth of performance (specialist-generalist trade-off hypothesis) or positive associations between the maximum performance and optimal temperature (hotter is better hypothesis) [24]. Demographic simulations have suggested that genetic constraints of TPCs drive the extinction risk of ectotherm populations [25]. However, these findings should be interpreted with caution due to limitations of simulations.

Quantitative genetic studies provide valuable information about evolutionary potential and constraints in response to global warming. However, these studies require complex breeding designs and large sample sizes to accurately estimate genetic parameters. Recently, genetic association panels have allowed us to identify genetic variants associated with phenotypic traits, and estimate heritability and genetic correlations between stress-resistance traits at a reduced cost in terms of experimentation and logistics. For instance, genetic reference panels (e.g. the *Drosophila* Genetic Reference Panel (DGRP) and the *Drosophila* Synthetic Population Resource (DSPR)) have revealed substantial genetic variation in stress-resistance traits [26–28]. However, the genetic variation of TPC parameters in these association panels has not yet been explored, leaving key questions about the genetic architecture and polygenic nature of thermal performance unanswered. It is important to note that the genetic basis of stress-resistance traits in *D. melanogaster* may differ from that in other insect species. Nevertheless, these panels are a valuable approach for generating robust data to predict insect evolutionary responses to global change.

Experimental evolution and adaptive dynamics

Experimental evolution is the study of evolutionary processes within populations across multiple generations under defined and reproducible conditions (Figure 1b). It encompasses a broad range of experimental designs, including artificial selection (i.e. individuals are selected based on their phenotypic value), laboratory culling (i.e. populations are exposed to stress, and the survivors become the founders of the next generation), and laboratory natural selection (i.e. populations are maintained under contrasting environments under laboratory conditions), among others [29,30]. In general, studies of experimental evolution have provided clear evidence that insect populations can evolve rapidly under different thermal conditions [31]. For example, several studies have demonstrated that heat tolerance, thermal performance curves, fecundity, and reproduction can change quickly within a few dozen generations in response to selection, suggesting that insect populations have the genetic variation to evolve rapidly [32–34]. However, recent quantitative syntheses indicate that these responses are often weaker and more variable than expected. For example, a recent meta-analysis revealed that TPCs can evolve in response to temperature selection, at the cost of reduced fitness at lower temperatures [24]. Similarly, fitness-related traits such as fecundity, development rate, and body size often exhibit weak or inconsistent evolutionary responses across studies [35], which is consistent with theoretical expectations that these traits tend to have lower heritability [36]. The discrepancy between focal studies and meta-analyses (i.e. rapid versus weak evolutionary responses) may

be explained by the limited representation of a broad range of taxa, which limits our ability to identify general patterns in the evolutionary responses to global warming.

Although laboratory natural selection experiments have been useful for understanding the effects of a particular abiotic or biotic factor, they are typically conducted in simplified, constant, and homogeneous environments. In contrast, natural populations encounter combinations of environmental factors that can lead to complex evolutionary dynamics due to the nonadditive effects between stressors [37]. Evidence from multi-stressor studies shows that evolutionary responses can vary substantially depending on the environmental context. For example, warming can either amplify or suppress the evolution of insecticide resistance, depending on the environmental context and metabolic architecture [38], by increasing the energetic and detoxification costs associated with resistance [39]. Additionally, the molecular mechanisms underlying resistance can be temperature-dependent, thereby influencing detoxification pathways and gene regulation [40,41]. In summary, multi-stressor experiments provide more realistic estimates of the constraints and opportunities for rapid evolution in response to global warming.

An additional limitation of laboratory selection experiments is their reduced ability to capture the ecological complexity of natural environments, which can strongly modulate adaptive responses in the wild [42]. Mesocosm and semi-natural experiments partially bridge this gap by increasing environmental realism while retaining experimental control, allowing populations to be exposed to multiple environmental factors. Recently, a series of studies combining field enclosures and common garden experiments have demonstrated that *D. melanogaster* can rapidly track environmental changes, showing evolutionary responses at the genome-wide level as well as stress resistance traits, pigmentation, and insecticide resistance [43–45]. However, it is more difficult to include and control complex demographic dynamics in these experimental settings. For instance, dispersal can facilitate evolutionary rescue by enabling populations to track suitable microclimates and introduce beneficial alleles from other populations [6,46]. However, immigration can also erode local adaptation through gene flow from maladapted populations [47].

Environmental gradients and local adaptation

Latitudinal, altitudinal, and urbanization gradients expose insect populations to persistent differences in thermal regimes, generating predictable selection pressures on thermal tolerance, performance, and life-history traits (Figure 1c) [48]. In recent years, evidence suggests rapid local adaptation to climatic conditions, even over relatively short geographic distances, as observed in rural-urban gradients [49,50]. Additionally, empirical studies across tropical systems have demonstrated that insect populations inhabiting contrasting thermal environments often exhibit distinct tolerance thresholds and performance patterns [5,51]. Furthermore, a recent fitness-based approach revealed that thermal adaptation reflects local performance optimization rather than simple shifts in thermal limits, suggesting that spatial temperature variation shapes evolutionary fitness landscapes [52].

Though temperature is one of the most important environmental variables that changes along a latitudinal gradient, photoperiod, solar radiation, and humidity (among other variables) also covary with latitude [49]. Thus, populations distributed along latitudinal gradients may experience multiple stressors that can affect evolutionary responses and our predictions regarding global warming [53]. Additionally, geographic variation in thermal tolerance often aligns more closely with local climate than with broad latitudinal patterns [54]. Therefore, incorporating multiple environmental variables, the influence of microclimatic heterogeneity, and the local thermal history should provide a clearer picture of how adaptive responses are shaped across environmental gradients. At a broader scale, studies across climatic gradients have demonstrated that populations from warmer or more variable environments often exhibit greater heat tolerance, higher thermal optima, and broader performance breadth across temperatures [52,55,56]. Conversely, thermal traits rapidly converge after populations are reared under common-garden conditions, suggesting that phenotypic plasticity also plays an important role in the adaptive responses [57]. Furthermore, species can exhibit seasonal plasticity, enhancing their resilience to future climate conditions [58]. Overall, experimental evolution studies have demonstrated that evolutionary responses to warming environments are population-specific, which suggests that environmental heterogeneity, phenotypic plasticity, and the initial population differences occur despite exposure to similar thermal selection regimes [59].

Despite the presence of cumulative evidence of local thermal adaptation, demographic processes can limit evolutionary responses to climate change. For instance, high dispersal rates and gene flow can erode local adaptation by introducing maladapted genotypes, especially in mobile insects such as crop pests and disease vectors [60]. Immigration can delay adaptation following environmental change, but it cannot necessarily prevent it [61]. In addition, dispersal traits themselves may evolve under strong selection in changing environments [62]. Consequently, the likelihood of evolutionary rescue in insect populations depends on the interaction between local adaptation, dispersal, and landscape structure [63]. While rapid adaptive evolution can enable populations to persist and expand into new environments, demographic and genetic factors often constrain these responses, limiting the extent to which populations can adapt to ongoing global warming [19].

Table 1

Comparative synthesis of the main empirical approaches used to investigate rapid evolutionary responses to global warming in insects.

	Quantitative genetic analyses	Experimental selection	Environmental gradient
Main question	Is there genetic variation for adaptation?	Can populations evolve under imposed selection?	Have populations diverged along natural gradients?
Main strength	Predicts adaptive potential	Directly tests evolutionary responses	Captures natural ecological variation
Main caveat	Genetic variation may not translate into realized evolution	Simplified laboratory environments	Environmental history and gene flow may confound inference
Evolutionary inference	Adaptive potential [14,16]	Direct evolutionary response [69,71]	Local adaptation/clinal divergence [78,79]
Temporal scale	Present-day variation [66]	Multi-generational selection [69,72]	Historical/long-term[45,80]
Ecological realism	Low-intermediate [16,67]	Intermediate [72–74]	High [81–83]
Control for environmental noise	High [14,15]	High [75]	Intermediate [83,84]
Empirical support	Evidence for adaptive potential, but realized evolution remains uncertain [14,16,68]	Frequent responses to selection, but magnitude and correlated responses vary [33,70,71,76,77]	Evidence for clinal divergence and local adaptation, but patterns are context dependent [55,78–82,85–87]

The table summarizes evidence from empirical studies primarily published within the last five years. It compares quantitative genetic analyses, experimental selection, and environmental gradient approaches based on evolutionary inference, temporal scale, ecological realism, experimental control for environmental noise, and overall empirical support. Together, these studies emphasize the complementary strengths and limitations of each approach in understanding and predicting insect adaptation to ongoing global warming.

Conclusions

Are insects evolving quickly enough to keep up with global warming? The answer is complicated because current evidence shows that evolutionary responses are shaped by the interaction between genetic architecture, environmental complexity, and demographic dynamics (see Table 1). While quantitative genetic and experimental evolution studies reveal substantial genetic variation for key thermal traits, thermal evolution may be constrained by soft (e.g. selection not aligned to genetic correlations, life-history trade-offs) or hard limits (e.g. molecular or physiological constraints) [13]. Furthermore, experimental evolution demonstrates that rapid responses are possible but often depend on the trait. More consistent responses are observed in upper thermal limits and acute stress resistance, while other traits, such as life-history traits, show more variable and context-dependent evolutionary responses. However, multi-stressor environments reveal non-adaptive selection dynamics that reshape metabolic trade-offs and alter both the direction and magnitude of evolutionary change. Geographic patterns also suggest that adaptation occurs at fine spatial scales but is strongly influenced by plasticity and gene flow, which can facilitate or hinder evolutionary rescue. In this context, long-term monitoring efforts and multigenerational field datasets are increasingly important for detecting adaptive changes in the face of ongoing global warming [64]. Furthermore, combining the experimental approaches reviewed here with genomic analyses (e.g. genetic variation and GWAS, experimental evolution and evolve and resequence (E&R), latitudinal gradients and genome-environment associations) can provide important insights into the genetic basis of rapid adaptation across generations under laboratory and semi-natural conditions [31,65]. Ultimately, understanding insect adaptation in a changing world requires shifting from single-stressor perspectives to a more integrative framework in which evolution is viewed as a dynamic outcome of interacting selective pressures acting across biological and spatial scales.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors have no competing interests to declare.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL to improve language, flow, and spelling of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Acknowledgements

JMA and LEC are supported by the Agencia Nacional de Investigación y Desarrollo (ANID-Chile) through the grant ANILLO ATE230025. We would like to thank Ryan Martin for inviting us to write this review and two anonymous reviewers for their valuable comments on the manuscript.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Outhwaite CL, McCann P, Newbold T: **Agriculture and climate change are reshaping insect biodiversity worldwide**. *Nature* 2022, **605**:97-102, https://doi.org/10.1038/s41586-022-04644-x

2. •• Noble DW, Mayfield MM, Hoffmann AA, Chen ZH, Lade SJ, Bai X, Way DA, Medlyn BE, Atkin OK, Nocotra AB, Cook JM, Singh BK, Bentley AR, Wright IJ, Kearney MR: **A systems modelling approach to predict biological responses to extreme heat**.

Trends Ecol Evol 2026, **41**:451-464, https://doi.org/10.1016/j.tree.2026.01.009.
This study demonstrates that a systems biology approach can improve our understanding of how different biological levels, from individuals to communities, will respond to global warming.

3. Gotthard K, Berger D, Rohner P: **Life-history evolution of insects in response to climate variation: seasonal timing versus thermal physiology**. *Annu Rev Entomol* 2025, **71**:129-148, https://doi.org/10.1146/annurev-ento-121423-013506

4. Harvey JA, Tougero K, GolsvR, Heinenv R, Abarca M, Abram PK, *et al*.: **Scientists' warning on climate change and insects**. *Ecol Monogr* 2023, **93**:e1553, https://doi.org/10.1002/ecm.1553

5. •• Holzmann KL, Schmitzer T, Abels A, *et al*.: **Limited thermal tolerance in tropical insects and its genomic signature**. *Nature* 2026, **651**:672-678, https://doi.org/10.1038/s41586-026-10155-w.
This study examines the lower and upper thermal tolerances of over 2300 insect species across elevation gradients in Africa and South America. The results demonstrate that tropical species are at high extinction risk.

6. Martin RA, da Silva CR, Moore MP, Diamond SE: **When will a changing climate outpace adaptive evolution?** *Wiley Interdiscip Rev Clim Change* 2023, **14**:e852, https://doi.org/10.1002/wcc.852

7. Gunn JC, Christensen BM, Bueno EM, Cohen ZP, Kissonergis AS, Chen YH: **Agricultural insect pests as models for studying stress-induced evolutionary processes**. *Insect Mol Biol* 2005, **33**:432-443, https://doi.org/10.1111/imb.12915

8. Nauen R, Bass C, Feyereisen R, Vontas J: **The role of cytochrome P450s in insect toxicology and resistance**. *Annu Rev Entomol* 2022, **67**:105-124, https://doi.org/10.1146/annurev-ento-070621-061328

9. IPCC: **Summary for Policymakers**. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by Lee H, Romero J. IPCC; 2023:1-34, https://doi.org/10.59327/IPCC/AR6-9789291691647.001

10. Bozinovic F, Cavieres G, Martel SI, Alruiz JM, Molina AN, Roschzttardtz H, *et al*.: **Thermal effects vary predictably across levels of organization: empirical results and theoretical basis**. *Proc R Soc B Biol Sci* 2020, **287**:20202508, https://doi.org/10.1098/rspb.2020.2508

11. Ørsted M, Jørgensen LB, Overgaard J: **Finding the right thermal limit: a framework to reconcile ecological, physiological and methodological aspects of CTmax in ectotherms**. *J Exp Biol* 2022, **225**:jeb244514, https://doi.org/10.1242/jeb.244514

12. Urban MC, Swaegers J, Stoks R, Snook RR, Otto SP, Noble DW, *et al*.: **When and how can we predict adaptive responses to climate change?** *Evol Lett* 2023, **8**:172-187, https://doi.org/10.1093/evlett/qrad038

13. Hoffmann AA, Sgrò CM, van Heerwaarden B: **Testing evolutionary adaptation potential under climate change in invertebrates (mostly *Drosophila*): findings, limitations and directions**. *J Exp Biol* 2023, **226**:jeb245749, https://doi.org/10.1242/jeb.245749

14. Ware-Gilmore F, Novelo M, Sgrò CM, Hall MD, McGraw EA: **Assessing the role of family level variation and heat shock gene expression in the thermal stress response of the mosquito *Aedes aegypti***. *Philos Trans R Soc B Biol Sci* 2023, **378**:20220011, https://doi.org/10.1098/rstb.2022.0011

15. Lecheta MC, Awde DN, O'Leary TS, Unfried LN, Jacobs NA, Whitlock MH, *et al*.: **Integrating GWAS and transcriptomics to identify the molecular underpinnings of thermal stress responses in *Drosophila melanogaster***. *Front Genet* 2020, **11**:658, https://doi.org/10.3389/fgene.2020.00658

16. • Soto J, Pinilla F, Olguín P, Castañeda LE: **Genetic architecture of the thermal tolerance landscape in *Drosophila melanogaster***. *Mol Ecol* 2025, **34**:e17697, https://doi.org/10.1111/mec.17697.
This work demonstrates that the thermal tolerance landscape is polygenic and that genetic variants associated with heat tolerance are not shared across stressful temperatures. It also found that the thermal tolerance landscape displays plastic responses.

17. Serrano-Carnero D, García Y, Millet-Gil E, Moya-Laraño J, Montserrat M: **Heritability estimates in 22 traits of the biological control agent *Amblyseius swirskii* point to allele losses from mass rearing**. *Entomol Gen* 2025, **35**:1201-1209, https://doi.org/10.1127/entomologia/3316

18. Walsh J, Pontieri L, d'Ettorre P, Linksvayer TA: **Ant cuticular hydrocarbons are heritable and associated with variation in colony productivity**. *Proc R Soc B* 2020, **287**:20201029, https://doi.org/10.1098/rspb.2020.1029

19. Riley CL, Oostra V, Plaistow SJ: **Does the definition of a novel environment affect the ability to detect cryptic genetic variation?** *J Evol Biol* 2023, **36**:1618-1629, https://doi.org/10.1111/jeb.14238

20. Blomberg SP, Muniz M, Bui MN, Janke C: **Multivariate trait evolution: models for the evolution of the quantitative genetic G-matrix on phylogenies**. *Evol Lett* 2025, **9**:706-718, https://doi.org/10.1093/evlett/qraf037

21. Hangartner S, Lasne C, Sgrò CM, Connallon T, Monro K: **Genetic covariances promote climatic adaptation in Australian *Drosophila***. *Evolution* 2020, **74**:326-337, https://doi.org/10.1111/evo.13831

22. Logan ML, Minnaar IA, Keegan KM, Clusella-Trullas S: **The evolutionary potential of an insect invader under climate change**. *Evolution* 2020, **74**:132-144, https://doi.org/10.1111/evo.13862

23. Malusare SP, Zilio G, Fronhofer EA: **Evolution of thermal performance curves: A meta-analysis of selection experiments**. *J Evol Biol* 2023, **36**:15-28, https://doi.org/10.1111/jeb.14087

24. Buckley LB, Kingsolver JG: **Evolution of thermal sensitivity in changing and variable climates**. *Annu Rev Ecol Evol Syst* 2021, **52**:563-586, https://doi.org/10.1146/annurev-ecolsys-011521-102856

25. Garcia-Costoya G, Williams CE, Faske TM, Moorman JD, Logan ML: **Evolutionary constraints mediate extinction risk under climate change**. *Ecol Lett* 2023, **26**:529-539, https://doi.org/10.1111/ele.14173

26. Williams-Simon PA, Oster C, Moaton JA, Ghidey R, Ng'oma E, Middleton KM, King EG: **Naturally segregating genetic variants contribute to thermal tolerance in a *Drosophila melanogaster* model system**. *Genetics* 2024, **227**:iyae040, https://doi.org/10.1093/genetics/iyae040

27. Robin C, Battlay P, Fournier-Level A: **What can genetic association panels tell us about evolutionary processes in insects?** *Curr Opin Insect Sci* 2019, **31**:99-105, https://doi.org/10.1016/j.cois.2018.12.004

28. Zwoinska MK, Rodrigues LR, Slate J, Snook RR: **Phenotypic responses to and genetic architecture of sterility following exposure to sub-lethal temperature during development**. *Front Genet* 2020, **11**:573, https://doi.org/10.3389/fgene.2020.00573

29. •• Griffiths JS, Sasaki M, Neylan IP, Kelly MW: **The potential for experimental evolution to uncover trade-offs associated with anthropogenic and climate change adaptation**. *Glob Change Biol* 2024, **30**:e17584, https://doi.org/10.1111/gcb.17584.
This opinion establishes that adaptation to climate change is limited by evolutionary costs, resulting in adaptive trade-offs. The authors suggest that combining experimental evolution and sequencing could provide a new approach to understanding these trade-offs.

30. In *Experimental Evolution: Concepts, Methods, and Applications of Selection Experiments*. Edited by Garland T, Rose MR. University of California Press; 2009.

31. • Santos MA, Carromeu-Santos A, Quina AS, Antunes MA, Kristensen TN, Santos M, *et al*.: **Experimental evolution in a warming world: the omics era**. *Mol Biol Evol* 2024, **41**:msae148, https://doi.org/10.1093/molbev/msae148.
This review emphasizes the importance of combining experimental evolution with high-throughput sequencing approaches to understand the polygenic nature of thermal adaptations.

32. Mesas A, Jaramillo A, Castañeda LE: **Experimental evolution on heat tolerance and thermal performance curves under contrasting thermal selection in *Drosophila subobscura***. *J Evol Biol* 2021, **34**:767-778, https://doi.org/10.1111/jeb.13777

33. Mesas A, Castañeda LE: **Evolutionary responses of energy metabolism, development, and reproduction to artificial selection for increasing heat tolerance in *Drosophila subobscura***. *Evolution* 2023, **77**:509-518, https://doi.org/10.1093/evolut/qpac033

34. • Sales K, Gage MJG, Vasudeva R: **Experimental evolution reveals that males evolving within warmer thermal regimes improve reproductive performance under heatwave conditions in a model insect**. *J Evol Biol* 2024, **37**:1329-1344, https://doi.org/10.1093/jeb/voae116.
This study demonstrates that adaptation to climate change can be trait-specific, depending on the interaction between evolutionary and thermal acclimatory processes.

35. Grainger TN, Levine JM: **Rapid evolution of life-history traits in response to warming, predation and competition: a meta-analysis**. *Ecol Lett* 2022, **25**:541-554, https://doi.org/10.1111/ele.13934

36. Merilä J, Sheldon BC: **Genetic architecture of fitness and nonfitness traits: empirical patterns and development of ideas**. *Heredity* 1999, **83**:103-109, https://doi.org/10.1046/j.1365-2540.1999.00585.x

37. Kelly MW: **Experimental evolution reveals complex responses to environmental change**. *Proc Natl Acad Sci USA* 2022, **119**:e2214263119, https://doi.org/10.1073/pnas.2214263119

38. Pélissié B, Chen YH, Cohen ZP, Crossley MS, Hawthorne DJ, Izzo V, Schoville SD: **Genome resequencing reveals rapid, repeated evolution in the Colorado potato beetle**. *Mol Biol Evol* 2022, **39**:msac016, https://doi.org/10.1093/molbev/msac016

39. Gul H, Gadratagi BG, Güncan A, Tyagi S, Ullah F, Desneux N, *et al*.: **Fitness costs of resistance to insecticides in insects**. *Front Physiol* 2023, **14**:1238111, https://doi.org/10.3389/fphys.2023.1238111

40. Yang X, Wei X, Yang J, Du T, Yin C, Fu B, *et al*.: **Epitranscriptomic regulation of insecticide resistance**. *Sci Adv* 2021, **7**:eabe590, https://doi.org/10.1126/sciadv.abe5903

41. Gunn JC, Christensen BM, Bueno EM, Cohen ZP, Kissonergis AS, Chen YH: **Agricultural insect pests as models for studying stress-induced evolutionary processes**. *Insect Mol Biol* 2024, **33**:432-443, https://doi.org/10.1111/imb.12915

42. Phillips MA, Burke MK: **Can laboratory evolution experiments teach us about natural populations?** *Mol Ecol* 2021, **30**:877-879, https://doi.org/10.1111/mec.15790

43. Rudman SM, Greenblum SI, Rajpurohit S, Betancourt NJ, Hanna J, Tilk S, *et al*.: **Direct observation of adaptive tracking on ecological time scales in *Drosophila***. *Science* 2022, **375**:eabj7484, https://doi.org/10.1126/science.abj7484

44. • Prileson EG, Campagnari B, Clare CI, Gabidulin AR, Shahmohamadloo RS, Rudman SM: **Overwintering drives rapid adaptation in *Drosophila* with potential costs to insecticide resistance**. *Evolution* 2026, **80**:56-66, https://doi.org/10.1093/evolut/qpaf205.
This study shows that the rapid evolution to winter conditions results in a trade-off between overwintering success and insecticide resistance. This suggests important consequences for pest management strategies.

45. Berardi S, Beltz JK, Rudman SM, Grainger TN, Levine JM, Oken H, *et al*.: **Seasonal evolution of *Drosophila melanogaster* abdominal pigmentation is associated with a multifarious selective landscape**. *Evolution* 2026, **80**:1111-1121, https://doi.org/10.1093/evolut/qpag038

46. Grummer JA, Booker TR, Matthey-Doret R, Nietlisbach P, Thomaz AT, Whitlock MC: **The immediate costs and long-term benefits of assisted gene flow in large populations**. *Conserv Biol* 2022, **36**:e13911, https://doi.org/10.1111/cobi.13911

47. Durkee LF, Olazcuaga L, Melbourne BA, Hufbauer RA: **Immigration delays but does not prevent adaptation following environmental change: experimental evidence**. *J Evol Biol* 2024, **37**:665-676, https://doi.org/10.1093/jeb/voae031

48. Verheyen J., Tüzün N., Stoks R. : **Using natural laboratories to study evolution to global warming: contrasting altitudinal, latitudinal, and urbanization gradients**. *Curr Opin Insect Sci* 2029, 35:10-19, https://doi.org/10.1016/j.cois.2019.06.001.

49. Diamond SE, Martin RA: **Physiological adaptation to cities as a proxy to forecast global-scale responses to climate change**. *J Exp Biol* 2021, **224**:jeb229336, https://doi.org/10.1242/jeb.229336

50. Diamond SE, Prileson EG, Martin RA: **Adaptation to urban environments**. *Curr Opin Insect Sci* 2022, **51**:100893, https://doi.org/10.1016/j.cois.2022.100893

51. Dongmo MA, Hanna R, Smith TB, Fiaboe KKM, Fomena A, Bonebrake TC: **Local adaptation in thermal tolerance for a tropical butterfly across ecotone and rainforest habitats**. *Biol Open* 2021, **10**:bio058619, https://doi.org/10.1242/bio.058619

52. Alruiz JM, Peralta-Maraver I, Cavieres G, Bozinovic F, Rezende EL: **Fitness surfaces and local thermal adaptation in *Drosophila* along a latitudinal gradient**. *Ecol Lett* 2024, **27**:e14405, https://doi.org/10.1111/ele.14405

53. Litchman E, Thomas MK: **Are we underestimating the ecological and evolutionary effects of warming? Interactions with other environmental drivers may increase species vulnerability to high temperatures**. *Oikos* 2023, **2**:e09155, https://doi.org/10.1111/oik.09155

54. Pincebourde S, Woods HA: **There is plenty of room at the bottom: microclimates drive insect vulnerability to climate change**. *Curr Opin Insect Sci* 2020, **41**:63-70.

55. Alruiz JM, Peralta-Maraver I, Bozinovic F, Santos M, Rezende EL: **Thermal tolerance in *Drosophila*: repercussions for distribution, community coexistence and responses to climate change**. *J Anim Ecol* 2022, **91**:655-667, https://doi.org/10.1016/j.cois.2020.07.001

56. Orlinick BL, Smith A, Medley KA, Westby KM: **Genetically based variation in heat tolerance covaries with climate in a globally important disease vector**. *Front Ecol Evol* 2024, **11**:1248673, https://doi.org/10.3389/fevo.2023.1248673

57. • Lenard A, Diamond SE: **Evidence of plasticity, but not evolutionary divergence, in the thermal limits of a highly successful urban butterfly**. *J Insect Physiol* 2024, **155**:104648, https://doi.org/10.1016/j.jinsphys.2024.104648.
The authors demonstrate that variation in thermal limits is driven by plasticity rather than evolutionary divergence. This highlights the limits of genetic adaptation in urban thermal environments.

58. Elmer MC, Monro K, Thompson H, Stuckey A, Kellermann V: **Phenotypic plasticity underlies seasonal and latitudinal variation in thermal tolerance in a native bee**. *Ecology* 2025, **106**:e70183, https://doi.org/10.1002/ecy.70183

59. Santos MA, Antunes MA, Grandela A, Quina AS, Santos M, Matos M, Simões P: **Slow and population specific evolutionary response to a warming environment**. *Sci Rep* 2023, **13**:9700, https://doi.org/10.1038/s41598-023-36273-3

60. Lewis R, Pointer MD, Friend L, Gage MJ, Spurgin LG: **Tests of evolutionary and genetic rescue using flour beetles, *Tribolium castaneum*, experimentally evolved to thermal conditions**. *Ecol Evol* 2024, **14**:e11313, https://doi.org/10.1002/ece3.11313

61. Durkee LF, Olazcuaga L, Melbourne BA, Hufbauer RA: **Immigration delays but does not prevent adaptation following environmental change: experimental evidence**. *J Evol Biol* 2024, **37**:665-676, https://doi.org/10.1093/jeb/voae031

62. Pointer MD, Spurgin LG, Gage MJ, McMullan M, Richardson DS: **Genetic architecture of dispersal behaviour in the post-harvest pest and model organism *Tribolium castaneum***. *Heredity* 2023, **131**:253-262, https://doi.org/10.1038/s41437-023-00641-6

63. Hufbauer RA, Szűcs M, Kasyon E, Youngberg C, Koontz MJ, Richards C, *et al*.: **Three types of rescue can avert extinction in a changing environment**. *Proc Natl Acad Sci USA* 2015, **112**:10557-10562, https://doi.org/10.1073/pnas.1504732112

64. •• Stroud JT, Ratcliff WC: **Long-term studies provide unique insights into evolution**. *Nature* 2025, **639**:589-601, https://doi.org/10.1038/s41586-025-08597-9.
This review emphasizes the importance of long-term experimental evolution in generating new hypotheses and research questions in evolutionary biology.

65. Demayo JA, Ragland GJ: **(Limited) Predictability of thermal adaptation in invertebrates**. *J Exp Biol* 2025, **228**:JEB249450, https://doi.org/10.1242/jeb.249450

66. Couper LI, Dodge TO, Hemker JA, Kim BY, Exposito-Alonso M, Brem RB, *et al*.: **Evolutionary adaptation under climate change: *Aedes* sp. demonstrates potential to adapt to warming**. *Proc Natl Acad Sci USA* 2025, **122**:e2418199122, https://doi.org/10.1073/pnas.2418199122

67. Yang K, Yuan MY, Liu Y, Guo CL, Liu TX, Zhang YJ, *et al*.: **First evidence for thermal tolerance benefits of the bacterial symbiont *Cardinium* in an invasive whitefly, *Bemisia tabaci***. *Pest Manag Sci* 2021, **77**:5021-5031, https://doi.org/10.1002/ps.6543

68. Stazione L, Sambucetti PD, Norry FM: **Mating success at elevated temperature is associated to thermal adaptation in a set of recombinant inbred lines of *Drosophila melanogaster***. *J Insect Physiol* 2023, **144**:104468, https://doi.org/10.1016/j.jinsphys.2022.104468

69. Santos MA, Antunes MA, Grandela A, Carromeu-Santos A, Quina AS, Santos M, *et al*.: **Heat-induced female biased sex ratio during development is not mitigated after prolonged thermal selection**. *BMC Ecol Evol* 2023, **23**:64, https://doi.org/10.1186/s12862-023-02172-4

70. • Burc E, Girard-Tercieux C, Metz M, Cazauz E, Baur J, Koppik M, *et al*.: **Life-history adaptation under climate warming magnifies the agricultural footprint of a cosmopolitan insect pest**. *Nat Commun* 2025, **16**:827, https://doi.org/10.1038/s41467-025-56177-2.
This study demonstrates the importance of exploring thermal adaptation in pest species, which is highly relevant in terms of food security strategies.

71. Dayal Aggarwal D, Mishra P, Patel Y, Singh M, Sharma V, Korol AB, *et al*.: **Experimental evolution-induced transcriptome and phenotype responses of *Drosophila melanogaster* to novel thermal environments**. *J Exp Biol* 2025, **228**:jeb251365, https://doi.org/10.1242/jeb.251365

72. Preston DB, Johnson SG: **Effects of acclimation, population, and sex on behavioral thermoregulation, CT_{Max}, symptoms of heat stress, and gene expression of *Melanoplus differentialis*, a generalist grasshopper – does temporal thermal heterogeneity prepare populations for a warming world?** *J Insect Behav* 2022, **35**:136-154, https://doi.org/10.1007/s10905-022-09805-4

73. Sales K, Gage MJG, Vasudeva R: **Experimental heatwaves reduce the effectiveness of ejaculates at occupying female reproductive tracts in a model insect**. *R Soc Open Sci* 2024, **11**:231949, https://doi.org/10.1098/rsos.231949

74. Malinski KH, Willett CS, Kingsolver JG: **Prior heat waves improve survival of field but not domesticated populations of tobacco hornworm exposed to repeated bacterial infections**. *Funct Ecol* 2025, **39**:711-722, https://doi.org/10.1111/1365-2435.70001

75. Barghi N, Tobler R, Nolte V, Jakšić AM, Mallard F, Otte KA, *et al*.: **Genetic redundancy fuels polygenic adaptation in *Drosophila***. *PLoS Biol* 2019, **17**:e3000128, https://doi.org/10.1371/journal.pbio.3000128

76. Castañeda LE: **Cross-tolerance evolution is driven by selection on heat tolerance in *Drosophila subobscura***. *PeerJ* 2025, **13**:e19743, https://doi.org/10.7717/peerj.19743

77. Zhu L, Yuan MZ, Armitage DW, Ma CS: **Responses of a widespread pest insect to extreme high temperatures are stage-dependent and divergent among seasonal cohorts**. *Funct Ecol* 2025, **39**:165-180, https://doi.org/10.1111/1365-2435.14711

78. Alfaro-Tapia A, Alvarez-Baca JK, Tougeron K, Lavandero B, Le Lann C, Van Baaren J: **Overwintering strategies and life-history traits of different populations of *Aphidius platensis* along a latitudinal gradient in Chile**. *Entomol Gen* 2021, **42**:127-145, https://doi.org/10.1127/entomologia/2021/1186

79. Kojima W, Lin CP: **Non-linear latitudinal cline of egg size and its consequence for larval survival in the rhinoceros beetle**. *Biol J Linn Soc* 2022, **136**:375-383, https://doi.org/10.1093/biolinnean/blac020

80. Meza-Joya FL, Morgan-Richards M, Trewick SA: **Phenotypic variation is greater in the absence of gene flow in three alpine grasshoppers**. *R Soc Open Sci* 2026, **13**:250791, https://doi.org/10.1098/rsos.250791

81. Vives-Ingla M, Sala-Garcia J, Stefanescu C, Casadó-Tortosa A, Garcia M, Peñuelas J, *et al*.: **Interspecific differences in microhabitat use expose insects to contrasting thermal mortality**. *Ecol Monogr* 2023, **93**:e1561, https://doi.org/10.1002/ecm.1561

82. Moreira X, Abdala-Roberts L, Lago-Núñez B, Cao A, De Pauw K, De Ro A, *et al*.: **Effects of experimental warming at the microhabitat scale on oak leaf traits and insect herbivory across a contrasting environmental gradient**. *Oikos* 2024, **2024**:e10353, https://doi.org/10.1111/oik.10353

83. Barreiro JB, Ratoni B, Baena-Díaz F, González-Tokman D, Dáttilo W: **Thermal tolerance of honeybees (*Apis mellifera* L.) changes across an elevation gradient in the Mexican transition zone**. *Sociobiology* 2024, **71**:e10155, https://doi.org/10.13102/sociobiology.v71i1.10155

84. Westby KM, Tayon L, Orlinick B, Smith S, Medley KA: **Interpopulation variation in egg mortality in response to hot and dry conditions in North American populations of the invasive tiger mosquito, *Aedes albopictus***. *Ecol Evol* 2026, **16**:e73557, https://doi.org/10.1002/ece3.73557

85. Dewenter BS, Shah AA, Hughes J, Poff NL, Thompson R, Kefford BJ: **The thermal breadth of temperate and tropical freshwater insects supports the climate variability hypothesis**. *Ecol Evol* 2024, **14**:e10937, https://doi.org/10.1002/ece3.10937

86. Bota-Sierra CA, García-Robledo C, Escobar F, Novelo-Gutiérrez R, Londoño GA: **Environment, taxonomy and morphology constrain insect thermal physiology along tropical mountains**. *Funct Ecol* 2022, **36**:1924-1935, https://doi.org/10.1111/1365-2435.14083

87. Moos M, Overgaard J, Hůla P, Byrge CG, Šmilauer P, Nedvěd O, *et al*.: **Metabolomic signatures associated with cold adaptation and seasonal acclimation of *Drosophila*: profiling of 43 species**. *J Exp Biol* 2025, **228**:JEB250076, https://doi.org/10.1242/jeb.250076