Eurasia Specialized Veterinary Publication

Entomological Research Letters

ISSN: 3108-639X

2025, Volume 5, Issue 1, Page No: 37-46
Copyright CC BY-NC-SA 4.0
Available online at: www.esvpub.com/

Insect Life-History Resilience Depends on Recovery, Compensation, and Reorganization Rather Than Resistance to Stress Alone

Hassan Ali[1]*, Mariam Farooq[1], Usman Shah[2]

[1]Department of Life-History Resilience and Recovery, Faculty of Life Sciences, University of Lahore, Lahore, Pakistan.
[2]Department of Compensation and Reorganization Under Stress, Faculty of Biosciences, National University of Sciences and Technology, Islamabad, Pakistan.

***E-mail** ✉ hassan.ali@gmail.com

ABSTRACT

Resilience in insect life histories is often inferred from the capacity to survive or maintain function during environmental stress. This resistance-centered interpretation is incomplete because organisms that survive the same disturbance can differ markedly in reproductive damage, recovery time, compensatory allocation, persistent costs, and subsequent responses. Here, a multidimensional resilience-state framework is developed to distinguish resistance from immediate recovery, delayed recovery, compensation, and functional reorganization. The framework treats resilience as a trajectory rather than a single tolerance endpoint and separates maintenance of an original state from restoration of function through biologically different routes. Evidence from thermal stress, desiccation, starvation, developmental plasticity, microhabitat buffering, and reproductive disruption shows that response dimensions can be partly decoupled across traits, life stages, sexes, species, and exposure histories. Particular attention is given to cases in which apparent recovery masks reproductive, physiological, developmental, or intergenerational costs. Compensation is defined conservatively as recovery of an output despite persistence of an altered underlying state, whereas reorganization refers to a changed configuration of traits, timing, behavior, or ecological relationships that sustains function without reconstructing the original state. The proposed architecture does not assume that compensation or reorganization is adaptive, cost-free, or sufficient for population persistence. It instead provides testable distinctions for comparing insect responses under repeated disturbance and for identifying when resistance alone misclassifies life-history resilience.

Keywords: Stress recovery, Compensatory growth, Reproductive resilience, Developmental plasticity, Repeated stress, Life-history trade-offs

Received: 22 March 2025
Revised: 18 April 2025
Accepted: 21 April 2025

How to Cite This Article: Ali H, Farooq M, Shah U. Insect Life-History Resilience Depends on Recovery, Compensation, and Reorganization Rather Than Resistance to Stress Alone. Entomol Res Lett. 2025;5(1):37-46. https://doi.org/10.51847/9wYtSAjV3s

Introduction

Environmental stress in insects is commonly quantified through endpoints measured during or immediately after exposure: survival, critical thermal limits, activity, development, or reproductive output. Such measurements are indispensable, but they can blur distinct biological questions. Extreme temperatures can affect insect physiology, species interactions, and ecological performance over different spatial and temporal scales, with responses varying strongly among taxa and contexts [1]. More specifically, assessments centered on mortality can overlook reproductive costs that remain biologically consequential after exposed individuals survive [2]. Resistance

© 2025 Entomological Research Letters

therefore captures only one component of a broader life-history response: what remains functional while stress is acting.

This limitation becomes clear when different traits are measured simultaneously or when the duration of disturbance is varied. Behavioral thermoregulation in a plant-feeding treehopper can buffer survival more effectively than reproduction, thermal limits for reproductive performance in *Drosophila suzukii* depend strongly on exposure duration, and comparative arthropod data show that temperatures associated with peak performance can differ among demographic traits [3–5]. A single "stress tolerance" value can consequently mix together the ability to avoid damage, endure damage, restore function, and maintain downstream fitness-related traits.

The central argument developed here is that insect life-history resilience should be represented as a proposed multidimensional trajectory rather than as resistance alone. The trajectory distinguishes five analytically separable states: resistance during disturbance, immediate recovery after disturbance, delayed recovery, compensation, and functional reorganization. These states need not occur sequentially, and more than one can characterize the same individual or population across different traits. A resistant insect may later show reproductive damage; a poorly resistant trait may recover rapidly; an output may be restored through compensatory allocation while costs accumulate elsewhere; or function may persist through a reorganized phenotype rather than restoration of the original state. The framework is therefore intended to classify response logic, not to assign a universal resilience score.

Materials and Methods

Resilience-state construction

The framework was constructed as a synthesis of insect studies that resolve at least one distinction necessary for separating resistance from post-stress trajectories. Particular weight was given to evidence in which multiple traits, multiple life stages, repeated exposures, or explicit recovery intervals were measured. Developmental heat exposure in *Harmonia axyridis*, for example, produced reversible effects in some adult performance dimensions while effects on immune function and fecundity remained detectable, demonstrating that "recovery" cannot be assigned to the organism without specifying the trait [6]. Experimental heatwaves in *Tribolium castaneum*, delayed fertility restoration in *Monochamus alternatus*, and repeated heat exposure in male *Drosophila melanogaster* likewise show that recovery depends on life stage, post-stress interval, and previous exposure history [7–9].

On this basis, the proposed resilience state is organized around six descriptors: the pre-disturbance functional condition, the response expressed during disturbance, the post-disturbance trajectory, the route by which function is restored or maintained, any persistent or displaced cost, and the history of prior exposure. These descriptors are conceptual coordinates rather than fitted variables. They are intended to prevent a return in one measured endpoint from being interpreted automatically as restoration of the entire life-history state.

Exposure history is included because prior stress can alter responses to subsequent challenge. In the rice leaf folder *Cnaphalocrocis medinalis*, prior heat exposure was associated with enhanced later thermal performance and molecular changes consistent with stress memory and acclimation [10]. Such evidence justifies treating exposure history as potentially consequential, but it does not justify collapsing acclimation, developmental plasticity, transgenerational effects, or evolutionary adaptation into a single process. The framework therefore preserves an explicit inference boundary between a changed phenotype after previous exposure and claims about evolved adaptation.

No new experimental dataset, effect estimate, resilience index, or statistical model is generated here. The analytical procedure instead asks, for each evidence pattern, whether function was maintained, restored, delayed, compensated for, or reorganized, and whether the underlying state was demonstrably equivalent to its pre-stress condition. Where equivalence cannot be established, the state is classified conservatively rather than assumed to have recovered.

Results and Discussion

Resistance is defined here as maintenance of a specified function while a disturbance is acting or before measurable disruption occurs. This definition deliberately requires the protected function to be named. Survival resistance, reproductive resistance, behavioral resistance, and physiological resistance are not interchangeable.

Experimental heatwaves in *T. castaneum* illustrate the problem: males can survive exposures that nevertheless impair sperm function, fertility, and offspring-related outcomes [11]. High survival therefore cannot be interpreted as maintenance of reproductive state.

Resistance can also arise by reducing realized exposure rather than by tolerating the same internal stress. Microhabitat structure modifies insect activity under heat and can provide behaviorally accessible conditions that buffer exposure [12]. This form of resilience is ecologically important but analytically different from intrinsic physiological tolerance. An insect that maintains function by occupying a cooler microsite has resisted the environmental event through exposure modification, not necessarily through greater tolerance of a given body temperature. Field generalization consequently requires information about realized microclimate, access to refuges, and the behavioral capacity to use them.

A third limitation is taxonomic and stressor specificity. Closely related *Ceratitis* fruit flies differ in desiccation physiology and in the plastic responses generated by acclimation, and broad geographic distribution does not translate into a simple universal superiority across measured resistance traits [13]. Resistance should therefore be represented as a trait-by-context state rather than an inherent property of a species. Strong resistance to one disturbance, life stage, or endpoint can coexist with weakness in another.

Immediate recovery

Immediate recovery concerns restoration detectable soon after the stressor is removed, but its interpretation depends on what has actually been restored. A return of reproductive output is especially ambiguous because the damaged biological component may be repaired, replaced, bypassed, or rendered irrelevant by a new reproductive event. In fruit flies exposed to damaging high temperatures, stored sperm can lose function, while remating can restore fertility by providing new sperm [14]. Functional output has returned, yet the damaged stored gametes have not necessarily been repaired. This distinction matters because identical reproductive outcomes can arise through different biological routes.

The proposed framework therefore separates output recovery from state restoration. Immediate output recovery is recorded when the focal function returns within the early post-stress observation window; state restoration requires evidence that the underlying component or process has also returned to the relevant baseline condition. Where only the endpoint is measured, restoration should remain unresolved rather than inferred.

Timing further complicates the category. Developmental heat stress in male *D. melanogaster* can interrupt spermatogenesis and produce early sterility, followed by later return of fertility as spermatogenesis resumes [15]. An observation made too soon after adult emergence could classify the state as persistent failure, whereas a later measurement could classify it as recovered. Immediate recovery is consequently meaningful only when the recovery window, developmental stage, and measured function are stated explicitly.

Delayed recovery

Delayed recovery is distinguished from immediate recovery because time itself can determine ecological consequence. A trait that returns after several days or weeks is not necessarily equivalent to one that remained functional throughout disturbance, particularly when mating opportunities, seasonal transitions, resource pulses, or a second disturbance occur during the deficit interval. Delayed recovery therefore describes the trajectory between initial damage and later functional return, rather than simply the final measurement.

Carry-over effects also show why delayed trajectories cannot be restricted to the originally exposed stage. Early-life starvation in the sawfly *Athalia rosae* altered subsequent life-history, consumption, and transcriptomic responses, with effects differing across traits and generations [16]. Such findings do not demonstrate that all intergenerational effects are adaptive or that every altered trait represents incomplete recovery. They establish instead that the biological consequences of a stress episode can extend beyond its temporal boundary and can be redistributed across later development or descendants.

Within the proposed framework, delayed recovery is assigned only when a defined focal function approaches or regains its reference state after an interval of impairment. Persistent carry-over without demonstrated return remains a legacy effect rather than recovery. This distinction prevents developmental delay, altered allocation, and transgenerational change from being relabeled automatically as resilience.

Compensation

Compensation is the most easily misclassified component of resilience because an apparently restored endpoint can coexist with a state that remains biologically altered. Here, compensation is defined as restoration or preservation of a focal output through increased investment, altered allocation, accelerated performance, or substitution elsewhere, while evidence indicates that the underlying organismal state is not simply unchanged or fully restored. This definition does not imply benefit, adaptation, or complete recovery.

Thermal acclimation provides one form of evidence conflict. In *Liriomyza trifolii*, acclimation that enhances thermotolerance can coincide with reproductive costs, showing that improvement along a resistance axis can be accompanied by deterioration in another life-history dimension [17]. The appropriate interpretation is therefore not "greater resilience" without qualification. The organism occupies a redistributed state in which one function is protected at the potential expense of another.

Compensatory growth provides a more direct example of restored performance carrying hidden cost. After transient starvation, larval *Lestes viridis* can accelerate growth, but rapid compensation is associated with oxidative damage and reduced performance, demonstrating that catching up in size does not necessarily reconstruct the physiological state of an unstressed larva [18]. Compensation is consequently distinct from full restoration: the visible endpoint can converge while energetic, oxidative, reproductive, or performance costs remain displaced to another dimension.

The proposed framework recognizes three compensation interpretations. Performance compensation restores the focal output while another measured function deteriorates. Allocation compensation maintains output through redistribution among competing life-history functions. Temporal compensation accelerates later performance after an earlier deficit. These categories are proposed analytical distinctions rather than established universal mechanisms. Their purpose is to force explicit comparison between what recovered and what paid for that recovery.

Because compensation can make one endpoint appear normal while another remains altered, a reconciliation table is more informative than a single resilience label. The table therefore distinguishes when apparent improvement should be interpreted as restoration, redistribution, or unresolved compensation rather than ranked on a common score.

Table 1. When restored performance does not mean restored state: reconciling evidence conflicts in insect compensation

Compensation pattern	Biological setting	Visible outcome	Life-history judgment	Unresolved cost	Recovery discriminator and state
Visible improvement with displaced cost					
Resistance gain with reproductive loss	Thermal acclimation in an adult leafminer	Higher thermal tolerance accompanied by reduced reproductive performance	Improvement in stress resistance coexists with loss in another function	Acclimation is not evidence of evolutionary adaptation; sex and temperature context matter	Measure resistance and reproduction simultaneously across recovery intervals Evidence-supported pattern; classification proposed
Catch-up growth with physiological cost	Starved damselfly larvae during post-starvation growth	Accelerated growth accompanied by oxidative and performance costs	Delayed size acquisition is offset by faster later growth without full state equivalence	Size convergence cannot establish energetic or physiological restoration	Compare growth, oxidative state, performance, and later fitness-related traits Evidence-supported pattern; classification proposed
Functional replacement					
Output restored through replacement rather than repair	Reproduction after heat-damaged stored sperm	Fertility returns after access to new sperm while prior gametes remain compromised	Functional restoration can occur without restoration of the damaged component	Requires separation of endpoint recovery from component-level repair	Track damaged component and reproductive output independently Evidence-supported interpretation
Hidden-cost and multi-trait convergence					

Apparent return with unmeasured displaced cost	Any stress context in which only one focal endpoint is reassessed	Focal trait returns but other life-history dimensions are not measured	Recovery cannot be distinguished from hidden redistribution	Absence of measured cost is not evidence of cost-free recovery	Reassess multiple traits, allocation states, and later performance Proposed classification
Multi-trait convergence toward baseline	Post-stress condition in which focal and supporting functions both recover	Several relevant traits return without detectable displaced cost in the measured window	Most consistent with restoration rather than compensation	Unmeasured or delayed costs may still remain	Extend follow-up across later life stages and repeated exposure Proposed decision rule

Compensation also creates feedback: costs generated while restoring one function can change the state from which the insect encounters its next disturbance. The figure below therefore represents compensation as a nested field of output restoration, altered internal state, and feedback to future stress response rather than as a one-way recovery step.

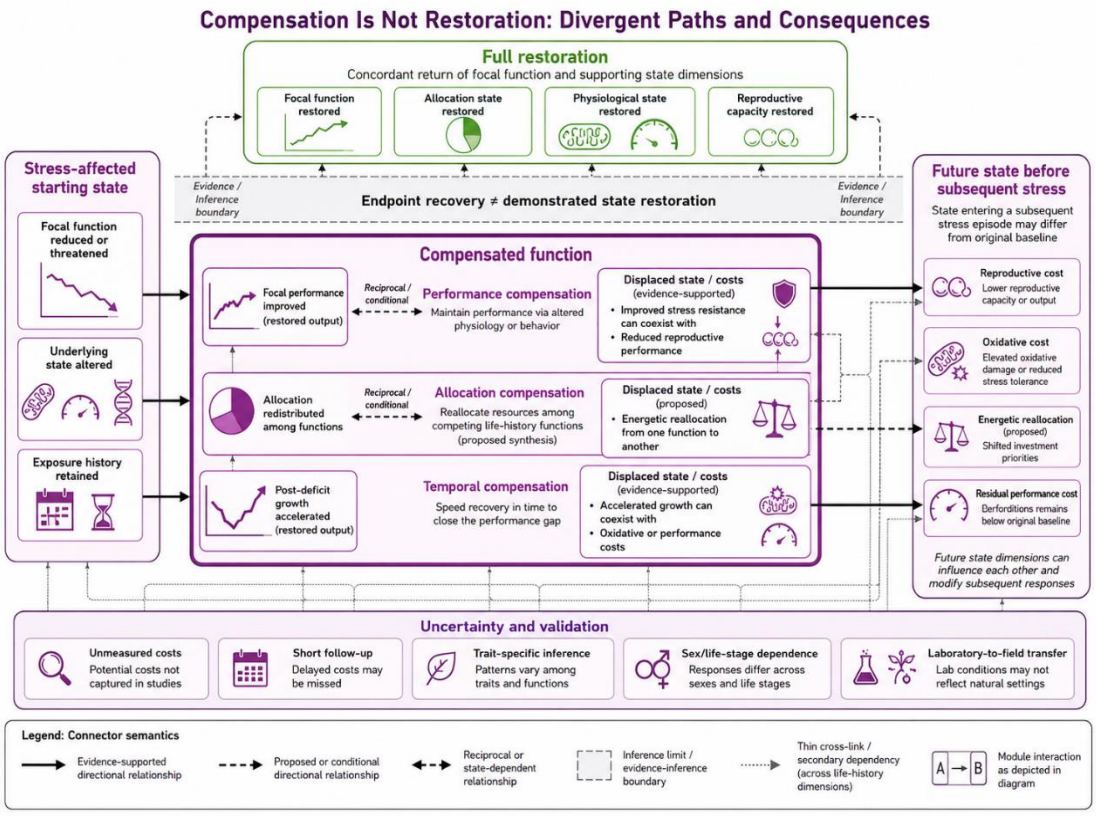


Figure 1. Compensated output can conceal an altered life-history state and redirect the next stress response

Functional reorganization

Recovery assumes that a prior functional state remains the relevant destination. Insects can instead respond to environmental change by occupying a different phenotype, schedule, allocation pattern, or ecological configuration. Thermal plasticity of wing pigmentation in *Bicyclus anynana*, for example, depends jointly on genotype and food availability, demonstrating that developmental responses cannot be represented as a uniform reaction to temperature alone [19]. Such plasticity is evidence for conditional phenotype construction, not by itself evidence that the resulting phenotype increases fitness under every environment.

Seasonal life histories provide a broader example. Closely related *Pieris* butterflies can exhibit divergent seasonal specialization and population dynamics, indicating that similar environmental constraints need not yield a single common life-history configuration [20]. The proposed framework therefore uses functional reorganization for cases in which performance is sustained or reconstructed through a changed organization of timing, phenotype,

behavior, or allocation rather than through simple return to the original configuration. Reorganization is descriptive unless its fitness consequences have been measured.

Ecological relationships can also alter the state that emerges after stress. Experimental interactions among heat, host-plant quality, and parasitism show that insect performance under thermal stress depends on trophic context rather than temperature in isolation [21]. Reorganization must therefore remain separable across biological levels: an altered individual phenotype, changed resource relationship, or modified host–parasitoid interaction should not be collapsed into a single organismal mechanism.

Costs of apparent recovery

A principal danger of endpoint-based resilience assessment is that a focal trait may appear normal while costs have shifted elsewhere. Such costs need not arise directly within the stressed insect. Extreme heat imposed on host plants can indirectly reduce fecundity and offspring survival in the solitary bee *Osmia lignaria*, demonstrating that apparently adequate adult activity or survival does not establish preservation of reproductive state when resource quality has changed [22]. This is an ecological pathway, not evidence of direct heat injury to the bee.

Timing and exposure history further determine whether apparent recovery is biologically equivalent across individuals. Reproductive consequences of heatwaves in *Nicrophorus vespilloides* vary with the timing of exposure, while chronic and acute thermal stress can interact non-additively [23, 24]. Thus, identical endpoint values after different disturbance histories may conceal different amounts, locations, or durations of biological cost.

The proposed framework distinguishes four forms of apparent recovery: trait-selective recovery, in which the measured endpoint returns while another trait remains impaired; replacement-mediated recovery, in which function returns through substitution rather than repair; cost-displaced recovery, in which restored performance is associated with physiological or reproductive cost elsewhere; and history-dependent recovery, in which present performance cannot be interpreted independently of previous exposure. These categories are analytical propositions, not universal mechanistic classes.

A stage-specific comparison is needed because the same apparent endpoint can have different biological meanings depending on when damage was imposed, where the cost is expressed, and whether the next life-history stage inherits that cost.

Table 2. Stage and pathway determine whether apparent recovery represents restoration or displaced life-history cost

Adult survival and damaged stored sperm		
Stage specific comparison dimension	**Adult survival with reproductive impairment**	**Recovery after damaged stored sperm**
Stage or biological context	Reproductive adults after thermal stress	Adult females following heat exposure
Restored endpoint and residual cost location	Viability or activity Gametes, mating success, fecundity, offspring performance	Fertility after remating Previously damaged gametes
Interpretive boundary	Survival cannot stand in for reproductive restoration	Functional return may reflect replacement rather than repair
Critical follow-up and state	Measure reproduction after survival has normalized Evidence-supported pattern	Track old versus newly acquired sperm contributions Evidence-supported interpretation
Post-starvation and resource-mediated recovery		
Stage specific comparison dimension	**Post-starvation catch-up**	**Resource-mediated apparent normality**
Stage or biological context	Developing larvae	Adults using heat-affected host resources
Restored endpoint and residual cost location	Body size or growth trajectory Oxidative state and performance	Adult presence or foraging Reproduction and offspring survival
Interpretive boundary	Morphological convergence need not equal physiological convergence	Individual appearance can conceal ecological transfer of stress

Critical follow-up and state	Follow multiple physiological and performance traits Evidence-supported pattern	Measure resource quality and descendant outcomes Evidence-supported pattern
Common endpoint after different histories		
Stage specific comparison dimension	**Similar endpoint after different exposure histories**	
Stage or biological context	Repeated or chronically stressed individuals	
Restored endpoint and residual cost location	Current focal performance Latent damage or altered response to the next disturbance	
Interpretive boundary	Present state is not interpretable without stress history	
Critical follow-up and state	Repeat challenge after standardized recovery intervals Proposed decision rule	

These discordances are summarized in **Figure 2** as a triage problem: the first question after an endpoint returns is not simply whether recovery occurred, but whether the restored value is concordant with reproductive, physiological, developmental, and ecological state.

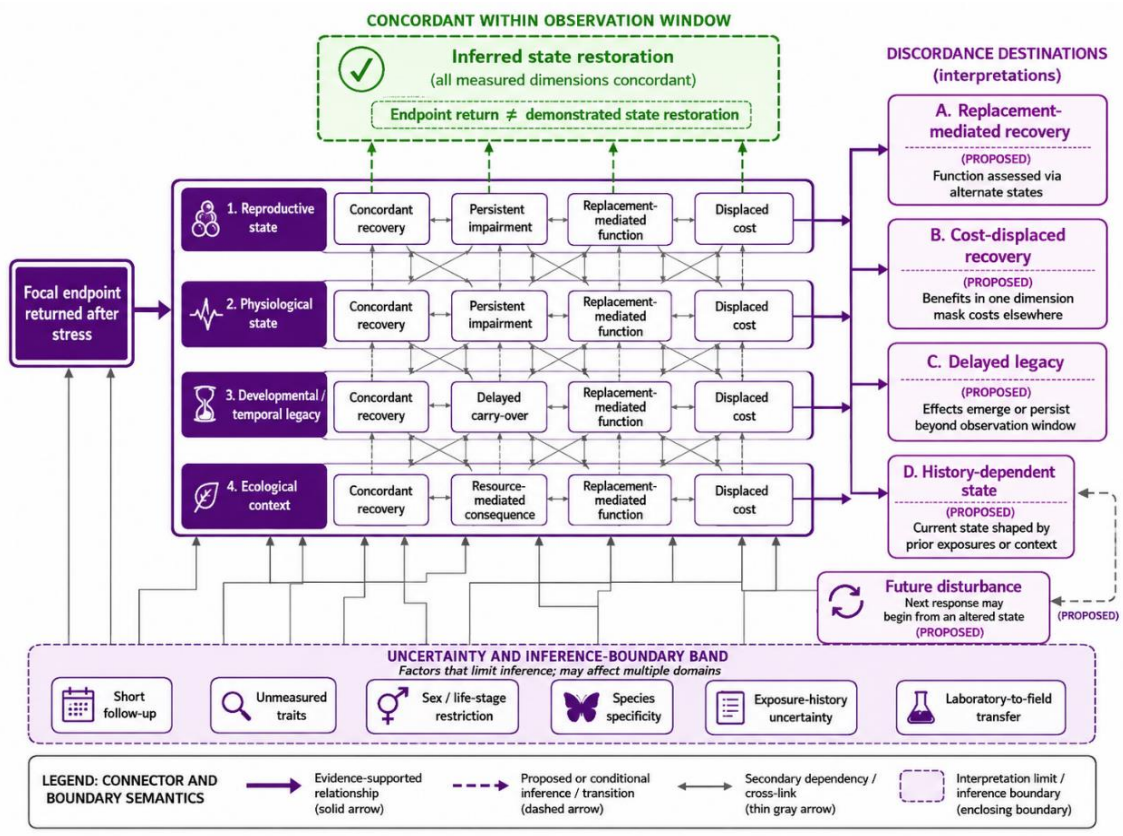


Figure 2. Concordant recovery, displaced cost, and unresolved state after an insect stress response

Multidimensional resilience architecture

The preceding distinctions imply that environmental exposure itself must be separated from the organismal state that is observed. Insects associated with plant surfaces experience body temperatures determined partly by body size and thermal coupling to their immediate substrate, so macroclimatic temperature alone does not specify realized thermal stress [25]. Exposure is therefore the first coordinate of the proposed architecture, not a proxy for the complete response.

A second coordinate is biological state. Extreme-temperature responses in *Grapholita molesta* differ among developmental stages and seasonal cohorts, indicating that a species-level tolerance value can hide within-species variation relevant to resilience [26]. Stage, sex, season, energetic condition, reproductive state, and prior disturbance should therefore be retained when the evidence indicates that they alter the trajectory.

A third coordinate is inference level. Thermal plasticity and evolutionary change can both affect ecological outcomes, but they are not interchangeable processes; work on competing aphid pests illustrates the need to distinguish transgenerational plasticity from thermal evolution when interpreting changing dominance [27]. The proposed multidimensional resilience architecture consequently links realized exposure, biological state, focal function, post-stress trajectory, displaced costs, and subsequent exposure while preserving a boundary between phenotypic response and evolutionary inference.

This architecture does not require every study to measure every dimension. Its practical purpose is diagnostic: it makes explicit which dimensions were observed and which remain unknown. A study measuring survival alone can establish survival resistance under its conditions; it cannot establish reproductive recovery, cost-free compensation, or population persistence.

Predictions under repeated stress

Repeated disturbance provides the clearest test of whether apparent recovery has restored the underlying state. Short experimental heatwaves can impair male reproduction in *T. castaneum* even when the exposure is sublethal [28]. Together with evidence for persistent or cumulative reproductive effects after repeated heat exposure, this supports treating the interval between events as biologically meaningful rather than assuming independent responses.

The framework therefore generates three proposed predictions. First, when the next disturbance occurs before slower traits have recovered, performance should depend on recovery interval as well as stress magnitude. Second, states produced through costly compensation should respond differently to a subsequent challenge from states produced through concordant restoration, even when the focal endpoint is initially similar. Third, stage transitions can either expose, redistribute, or obscure prior costs, making repeated-stress responses dependent on when in the life cycle the disturbance sequence occurs.

These propositions are not prospectively validated predictions. They are falsifiable expectations that require longitudinal experiments measuring more than one life-history trait before stress, during disturbance, during recovery, and after subsequent exposure. Designs should distinguish realized microclimate from nominal treatment where relevant and should test whether laboratory trajectories transfer to field or semi-field conditions.

The proposed framework shifts the central question from “Did the insect resist the stress?” to “What state remained, returned, compensated, reorganized, or persisted after the disturbance?” This distinction matters because global-change drivers can act indirectly and interact in non-additive ways, making single-driver, single-endpoint inference especially fragile [29]. Resistance remains essential, but it is only one axis of resilience.

Several boundaries prevent the framework from being treated as a universal mechanistic model. Much of the strongest trajectory evidence comes from controlled thermal experiments, whereas desiccation, starvation, host-mediated stress, seasonal change, and trophic interactions demonstrate that the same conceptual dimensions can arise through different processes. Evidence is also uneven across insect orders, sexes and developmental stages. Male reproductive sensitivity cannot automatically be transferred to females, and developmental carry-over cannot be assumed to operate identically in hemimetabolous and holometabolous insects.

The distinction between compensation and reorganization is especially important. Compensation retains a recognizable focal function while cost or effort is redistributed; reorganization changes the configuration through which function is expressed. In practice, the boundary may be difficult to resolve. A changed seasonal phenotype could represent developmental plasticity without proven benefit, while an altered allocation pattern could preserve current reproduction yet reduce later survival. Classification should therefore follow measured trajectories rather than presumed adaptive purpose.

Validation requires multi-trait longitudinal designs. Survival should be paired with reproductive or performance endpoints, recovery should be observed at more than one post-stress time, and repeated exposure should occur after experimentally defined recovery intervals. Where field transfer is intended, realized body temperature, refuge availability, resources, host condition, or interacting species should also be measured. The decisive test is whether states that look equivalent at one endpoint subsequently diverge when challenged again.

The framework is consequently best viewed as an evidence-bounded organizing system. It does not replace established measures of thermal limits, desiccation resistance, fertility, development, or behavior. Instead, it specifies what those measurements can and cannot establish about life-history resilience and identifies where additional observations are required before restoration, compensation, reorganization, or fitness consequence can be inferred.

Conclusion

Insect resilience cannot be represented adequately by resistance alone when survival, reproduction, development, physiological condition, and ecological performance follow different post-stress trajectories. A return of one endpoint may reflect genuine restoration, delayed repair, replacement, costly compensation, or functional reorganization. The proposed architecture separates these states while retaining exposure history, life stage, biological level, and uncertainty. Its value is therefore diagnostic rather than predictive: it clarifies which component of resilience has been observed and which remains unresolved. Longitudinal, multi-trait and repeated-stress tests are needed to determine when compensated or reorganized states provide durable function and when apparent recovery instead conceals costs that become visible later in the life history.

Acknowledgments: None

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

References

1. Harvey JA, Heinen R, Gols R, Thakur MP. Climate change-mediated temperature extremes and insects: From outbreaks to breakdowns. Glob Chang Biol. 2020;26(12):6685-701. doi:10.1111/gcb.15377
2. Morosinotto C, Gasparini C, Pilastro A, Rosenthal GG, Breedveld MC. Cryptic reproductive costs of heatwaves for animal populations. Glob Chang Biol. 2025;31(11). doi:10.1111/gcb.70558
3. Leith NT, Miller EA, Fowler-Finn KD. Thermoregulation enhances survival but not reproduction in a plant-feeding insect. Funct Ecol. 2024;38(6):1344-56. doi:10.1111/1365-2435.14546
4. Ørsted M, Willot Q, Olsen AK, Kongsgaard V, Overgaard J. Thermal limits of survival and reproduction depend on stress duration: A case study of Drosophila suzukii. Ecol Lett. 2024;27(3). doi:10.1111/ele.14421
5. Pawar S, Huxley PJ, Smallwood TRC, Nesbit ML, Chan AHH, Shocket MS, et al. Variation in temperature of peak trait performance constrains adaptation of arthropod populations to climatic warming. Nat Ecol Evol. 2024;8(3):500-10. doi:10.1038/s41559-023-02301-8
6. Awde DN, Řeřicha M, Knapp M. Increased pupal temperature has reversible effects on thermal performance and irreversible effects on immune system and fecundity in adult ladybirds. Commun Biol. 2023;6(1):838. doi:10.1038/s42003-023-05196-0
7. Sales K, Vasudeva R, Gage MJG. Fertility and mortality impacts of thermal stress from experimental heatwaves on different life stages and their recovery in a model insect. R Soc Open Sci. 2021;8(3):201717. doi:10.1098/rsos.201717
8. Li H, Li S, Yang H, Tan Y, Zhao P, Ye J, et al. The fertility recovering from heat stress and interactions of heat shock protein 20 with reproduction-related proteins in Monochamus alternatus. Insect Sci. 2025;32(6):2139-54. doi:10.1111/1744-7917.13470
9. Meena A, De Nardo AN, Maggu K, Sbilordo SH, Roy J, Snook RR, et al. Fertility loss and recovery dynamics after repeated heat stress across life stages in male Drosophila melanogaster: Patterns and processes. R Soc Open Sci. 2024;11(10):241082. doi:10.1098/rsos.241082
10. Quan PQ, Guo PL, He J, Liu XD. Heat-stress memory enhances the acclimation of a migratory insect pest to global warming. Mol Ecol. 2024;33(17). doi:10.1111/mec.17493
11. Sales K, Vasudeva R, Dickinson ME, Godwin JL, Lumley AJ, Michalczyk Ł, et al. Experimental heatwaves compromise sperm function and cause transgenerational damage in a model insect. Nat Commun. 2018;9(1):4771. doi:10.1038/s41467-018-07273-z
12. Terlau JF, Brose U, Eisenhauer N, Amyntas A, Boy T, Dyer A, et al. Microhabitat conditions remedy heat stress effects on insect activity. Glob Chang Biol. 2023;29(13):3747-58. doi:10.1111/gcb.16712

13. Bosua HJ, Weldon CW, Terblanche JS. Phenotypic plasticity in desiccation physiology of closely related, range restricted and broadly distributed fruit fly species. Funct Ecol. 2023;37(3):625-37. doi:10.1111/1365-2435.14250
14. Walsh BS, Parratt SR, Snook RR, Bretman A, Atkinson D, Price TAR. Female fruit flies cannot protect stored sperm from high temperature damage. J Therm Biol. 2022;105:103209. doi:10.1016/j.jtherbio.2022.103209
15. Canal Domenech B, Fricke C. Developmental heat stress interrupts spermatogenesis inducing early male sterility in Drosophila melanogaster. J Therm Biol. 2023;114:103589. doi:10.1016/j.jtherbio.2023.103589
16. Paul SC, Singh P, Dennis AB, Müller C. Intergenerational effects of early-life starvation on life history, consumption, and transcriptome of a holometabolous insect. Am Nat. 2022;199(6). doi:10.1086/719397
17. Wang YC, Chang YW, Yang F, Gong WR, Hu J, Du YZ. A potential trade-off between reproduction and enhancement of thermotolerance in Liriomyza trifolii populations driven by thermal acclimation. J Therm Biol. 2024;125:103988. doi:10.1016/j.jtherbio.2024.103988
18. Janssens L, Stoks R. Oxidative stress mediates rapid compensatory growth and its costs. Funct Ecol. 2020;34(10):2087-97. doi:10.1111/1365-2435.13616
19. van Bergen E, Atencio G, Saastamoinen M, Beldade P. Thermal plasticity in protective wing pigmentation is modulated by genotype and food availability in an insect model of seasonal polyphenism. Funct Ecol. 2024;38(8):1765-78. doi:10.1111/1365-2435.14602
20. von Schmalensee L, Caillault P, Gunnarsdóttir KH, Gotthard K, Lehmann P. Seasonal specialization drives divergent population dynamics in two closely related butterflies. Nat Commun. 2023;14:3663. doi:10.1038/s41467-023-39359-8
21. Parker AL, Kingsolver JG. The interactive effects of heat stress, parasitism and host plant quality in a host-parasitoid system. Funct Ecol. 2024;38(3):642-53. doi:10.1111/1365-2435.14498
22. Walters J, Barlass M, Fisher R, Isaacs R. Extreme heat exposure of host plants indirectly reduces solitary bee fecundity and survival. Proc Biol Sci. 2024;291(2025):20240714. doi:10.1098/rspb.2024.0714
23. Pilakouta N, Sellers L, Barratt R, Ligonniere A. The consequences of heatwaves for animal reproduction are timing-dependent. Funct Ecol. 2023;37(9):2425-33. doi:10.1111/1365-2435.14386
24. Pilakouta N, Allan D, Moore E, Russell AA. Chronic and acute thermal stressors have non-additive effects on fertility. Proc Biol Sci. 2024;291(2031):20241086. doi:10.1098/rspb.2024.1086
25. Pincebourde S, Dillon ME, Woods HA. Body size determines the thermal coupling between insects and plant surfaces. Funct Ecol. 2021;35(7):1424-36. doi:10.1111/1365-2435.13801
26. 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(1):165-80. doi:10.1111/1365-2435.14711
27. Zhu L, Hoffmann AA, Li SM, Ma CS. Extreme climate shifts pest dominance hierarchy through thermal evolution and transgenerational plasticity. Funct Ecol. 2021;35(7):1524-37. doi:10.1111/1365-2435.13774
28. Cole B, Vasudeva R, Dragoi K, Hibble J, King J, Maklakov AA, et al. Short experimental heatwaves have sublethal impacts on male reproduction in a model insect. J Exp Biol. 2025;228(15). doi:10.1242/jeb.250555
29. Yang LH, Postema EG, Hayes TE, Lippey MK, MacArthur-Waltz DJ. The complexity of global change and its effects on insects. Curr Opin Insect Sci. 2021;47:90-102. doi:10.1016/j.cois.2021.05.001