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Behavioral Thermoregulation Connects Microhabitat Choice with Whole-Organism Performance and Population Persistence in Insects

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ABSTRACT

Sexuality, which plays an essential and significant role in human life, is provided through healthy sexual organs. Therefore, any disease in the genital area, including vaginitis, can interfere with these tendencies and thus affect the quality of life of the individual. The researchers, therefore, conducted a study aimed at comparing sexual satisfaction in pregnant women with vaginal candidiasis. This is a cross-sectional study to evaluate the effect of Candida vaginitis infection on sexual satisfaction that should be considered in healthy individuals and comparative work. Therefore, in this study, 160 pregnant mothers referred to the gynecology clinic, Shahid Beheshti Hospital, Tehran were selected by convenience sampling method and divided into two groups of healthy pregnant women and vaginal candidiasis women (each group 80 people). Data were collected using the Larson Sexual Satisfaction Questionnaire. After data collection, data were analyzed in SPSS software and analyzed by independent t-test. The results showed that sexual satisfaction in healthy pregnant women was slightly higher than pregnant women with vaginal candidiasis, and there was a significant difference between the two groups regarding sexual satisfaction ($p < 0.05$). These results suggest that there is a relationship between sexual satisfaction and Candida infection. Regarding the difference of sexual satisfaction in the group of pregnant women with vaginal candidiasis and healthy pregnant women, it can be concluded that the rate of sexual satisfaction with the vaginal candidate will be effected and makes problems and disorders.

Keywords: Behavioral thermoregulation, Microclimate, Microhabitat selection, Thermal performance, Insect demography, Thermal ecology.

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Introduction

Behavioral thermoregulation can alter the temperatures insects experience through changes in position, posture, orientation, activity time and microhabitat use, but its mechanisms and efficacy vary among taxa and environmental settings [1]. This variability makes “thermoregulation” an insufficient endpoint by itself. A useful eco-physiological account must ask what thermal alternatives exist, whether an insect can detect and reach them, how much body temperature changes after selection, and whether that change improves functions that matter beyond immediate heat avoidance.

That sequence begins with scale. Standard meteorological temperature can differ substantially from the fine-scale thermal environments available to small ectotherms, so macroclimate alone can misrepresent insect exposure [2].

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Yet the existence of a cooler patch does not demonstrate that it is accessible, selected or beneficial. Extreme heat likewise elicits several distinct responses, including behavioral avoidance and physiological adjustments, whose limits and costs should not be conflated with evolutionary adaptation [3].

The most important inferential break occurs between reduced exposure and maintained fitness components. In a plant-feeding treehopper, heat-escape behavior largely prevented lethal exposure while failing to preserve reproduction, showing directly that survival buffering need not be reproductive buffering [4]. Behavioral-rescue theory similarly treats persistence as conditional on usable environmental heterogeneity, appropriate behavioral responses and demographic consequences rather than on behavior alone [5]. Building on those premises, this article proposes a framework that separates thermal opportunity, behavioral access, realized body temperature, whole-organism performance and demographic consequence. The framework is intended as an analytically testable architecture, not as an empirically validated forecasting model.

Theoretical methods

This is a conceptual synthesis. The evidence base was organized by biological level and inferential role rather than pooled statistically. Thermal-response parameters were kept taxon specific because comparative mosquito evidence shows that thermal performance and vulnerability vary among species; modeled climatic suitability therefore cannot be treated as a universal demographic threshold [6]. The framework consequently uses classes of processes and boundary conditions rather than common numerical cut-offs.

Mechanistic reasoning was structured around organism-relevant environmental exposure, physical heat exchange, biological response and explicit validation, consistent with biophysical-ecology approaches to climate-response forecasting [7]. Microclimate was treated as an intermediate environmental layer between regional climate and the conditions actually encountered by an insect, while remaining distinct from behavioral use of that layer [8]. Physiological plasticity was also separated from behavior: a meta-analysis across insect species found critical thermal limits to be plastic but generally only weakly so, which does not justify treating those limits as freely adjustable buffers [9].

The proposed framework therefore asks, in order: what thermal states are available; which are behaviorally accessible and selected; how selection changes realized thermal exposure; how physiology, activity and resource acquisition respond; and whether survival and reproduction change in ways capable of affecting population dynamics. Each transition is treated as conditional and open to failure.

Thermal heterogeneity at microhabitat scale

Thermal heterogeneity is biologically relevant only after physical conditions are translated into organismal exposure. For plant-associated insects, body size changes thermal coupling to plant surfaces, so individuals occupying the same nominal microhabitat may not experience identical body temperatures [10]. Morphology is therefore an exposure translator rather than a minor covariate. The same logic cautions against equating air temperature, substrate temperature and insect body temperature.

Fine-scale differences can propagate beyond acute exposure. In Pieris napi, high-resolution temperatures recorded across 110 natural sites produced substantial differences in modeled developmental rates, emergence timing and synchrony [11]. Those results make microclimate relevant to phenology, but not automatically to population growth: photoperiod, diapause and nonlinear stage-specific thermal responses can constrain how local thermal differences are expressed over a season.

Microhabitat use can also redistribute thermal risk among life stages. In Mediterranean ecotones, Pieris napi and P. rapae differed in oviposition microhabitat, exposing larvae to contrasting leaf temperatures and predicted heat mortality [12]. Shading could reduce thermal danger while coinciding with lower host-plant availability, demonstrating why “cooler” cannot be treated as synonymous with “better.” A second boundary arises from water balance. In high-latitude click beetles, water-loss physiology covaried with upper thermal tolerance, whereas acute humidity treatment did not directly alter CTmax [13]. Heat and hydric physiology can therefore interact without supporting a universal directional effect of humidity on tolerance.

At larger scales, associations remain heterogeneous. Across 32 Orthoptera species along Alpine gradients, microclimate and macroclimate interacted with species traits and ecological preferences in shaping abundance and climatic niches [14]. Because these were community-level observational associations, they do not establish individual behavioral thermoregulation as the mechanism. Collectively, the evidence supports a distinction

between thermal heterogeneity that is physically present and thermal heterogeneity that becomes biologically usable after morphology, life stage, habitat structure, water balance and behavior are considered.

Behavioral temperature selection

Behavioral temperature selection is not simply movement toward cooler conditions. It is better treated as a relation among available operative temperatures, the insect's state-dependent thermal preferences or avoidance thresholds, and the costs of occupying alternative locations. In urban ants, four of five species avoided baits at temperatures far from their preferred range, yet ants at warmer sites still experienced warmer conditions; fixed diel activity therefore provided only partial compensation for site-level warming [15]. Preference-concordant occupancy can reduce exposure without achieving environmental invariance.

Comparative butterfly evidence further argues against treating behavior and physiology as interchangeable buffers. Among 54 tropical butterfly species, stronger behavioral thermal buffering was associated with lower CTmax, with variation among families and morphological traits [16]. This association is consistent with alternative combinations of behavioral buffering and physiological tolerance, but it does not establish an evolved trade-off or its causal direction.

Selection can also generate costs that reverse its apparent thermal benefit. In the aphid Sitobion avenae, leaving heated host-plant positions reduced heat exposure but decreased survival and reproduction when relocation compromised continued access to the host [17]. This motivates a proposed access-cost gate: a thermally preferable microhabitat contributes to net buffering only when reaching or remaining in it does not impose larger losses through food access, relocation failure or other ecological constraints.

Finally, voluntary heat avoidance must remain distinct from critical physiological limits. Across 54 odonate species and 846 individuals, voluntary avoidance temperature, CTmax and CTmin showed different relationships with morphology, sex, taxonomy and environment [18]. The proposed framework therefore treats behavioral selection threshold and physiological tolerance as separate axes.

Identical reductions in apparent thermal exposure can consequently have different biological meanings depending on how the selected state was reached and what was sacrificed to occupy it; the decision matrix below separates those interpretations before downstream performance is inferred.

Table 1. Behavioral temperature-selection states that change the interpretation of apparent thermal buffering

Evidential standing	Biological context · Evidence basis · Biological setting · Evidence	Interpretation for thermal buffering · Boundary or uncertainty · Limits and uncertainty	Research or test
Preference-concordant occupancy			
Evidence-supported pattern	Mobile foragers within heterogeneous habitat Occupancy shifts toward temperatures near independently measured preference	Indicates temperature-sensitive habitat use Fixed activity schedules or correlated habitat cues can produce similar patterns	Pair field occupancy with independent preference measurements
Partial behavioral compensation			
Evidence-supported pattern	Ant workers across warmer and cooler sites Avoidance of nonpreferred temperatures while realized thermal exposure still increases	Behavior modifies exposure but does not neutralize warming Effectiveness depends on the range and accessibility of alternatives	Quantify residual warming after selection, not selection alone
Behavior–tolerance decoupling			
Evidence-supported distinction	Tropical butterflies and odonates Behavioral buffering or avoidance differs from critical thermal limits	Behavioral and physiological buffers require separate estimates Comparative associations can reflect phylogeny, morphology or ecology	Measure preference or avoidance and tolerance within the same taxa
Access-cost reversal			
Evidence-supported pattern	Host-associated insects Thermal escape reduces exposure but disrupts resource access or relocation	Cooler occupancy can reduce net performance Cost depends on habitat connectivity and resource distribution	Measure resource and demographic consequences after movement
Usable thermal option			
Proposed synthesis	Cross-system analytical state	Defines the behavioral condition required before downstream buffering is inferred	Measure availability, access, body-

	Accessible temperature alternative changes exposure without disproportionate ecological cost	Must be tested separately by species, life stage and environment	temperature change and cost jointly

Physiological performance

A selected microhabitat matters only if the resulting body temperature changes physiological functions relevant to performance. Insect heat responses span molecular, cellular and organismal levels, but the presence of a stress response cannot itself be interpreted as improved performance or adaptation [19]. Protective pathways, metabolic changes or damage signals therefore belong to a mechanistic layer that requires an organismal endpoint before a benefit is inferred.

Critical thermal limits are useful boundary measures, but they do not describe the full performance landscape. Their generally weak plasticity across insects [9] cautions against assuming that acclimation can readily compensate for altered exposure. Conversely, a critical limit says little about locomotion, feeding or reproduction at sublethal temperatures. The odonate evidence is instructive because voluntary avoidance temperature and CTmax or CTmin varied with different predictors [18]. The proposed framework consequently separates tolerance limits, preferred or avoided temperatures and sublethal performance functions. Physiological performance acts as a gate between changed exposure and ecologically meaningful activity, not as a synonym for thermal survival.

Activity and resource acquisition

Activity is the first downstream domain in which thermoregulatory benefit can be converted into ecological opportunity. In Bombus terrestris, flight performance varied across experimental temperatures from 12 to 30°C, demonstrating that sublethal thermal conditions can constrain locomotor capacity relevant to foraging before lethal thresholds are reached [20]. Because tethered flight is a laboratory performance measure, it should be interpreted as foraging potential rather than realized resource intake.

Resource acquisition also depends on the thermal response of the resource environment. Experimental heatwaves disrupted bumblebee foraging through direct effects on bees and through reduced nectar production, showing that heat can act simultaneously on consumer performance and resource supply [21]. Controlled experiments with bumblebees likewise found that elevated temperature altered foraging and flight speed without requiring mortality as the endpoint [22]. These findings make activity a distinct intermediate level between tolerance and demography. Microhabitat can moderate this intermediate effect. Across six insect species from three orders, local microhabitat conditions reduced some heat-stress effects on activity [23]. Such moderation should not be interpreted as complete protection: preserved movement may still be insufficient for feeding, mating or other performance demands, and the magnitude is taxon and setting dependent. The proposed framework therefore distinguishes an activity-access benefit from a resource-acquisition benefit. The first occurs when thermoregulatory choice preserves the capacity to act; the second requires that food, hosts, mates or other resources remain available where and when that activity is possible.

A single activity measure therefore cannot establish whether behavioral thermoregulation preserves ecological opportunity; the context–mechanism–outcome register below separates locomotor capacity, direct thermal impairment, resource-mediated limitation and microhabitat relief.

Table 2. Context–mechanism–outcome register for converting thermal activity into resource acquisition

Activity or resource state	Article-specific dimension	Scientific content
Sublethal locomotor limitation	**Biological context · Evidence basis · Biological setting · Evidence**	Bumblebee workers Flight performance changes across nonlethal temperatures
	Mechanistic interpretation · Boundary or failure mode	Temperature constrains movement before survival is threatened Laboratory flight may not equal field foraging
	Consequence for the proposed	Activity performance must precede resource inference
	Test implication · Status · Evidential standing	Couple free-flight or field behavior to microclimate Evidence-supported
Direct heat constraint on foraging	**Biological context · Evidence basis · Biological setting · Evidence**	Bumblebee foragers Foraging changes under elevated temperature
	Mechanistic interpretation · Boundary or failure mode	Thermal conditions act directly on insect performance Colony state and exposure history may modify response

	Consequence for the proposed	A thermally suitable microhabitat can preserve activity opportunity
	Test implication · Status · Evidential standing	Measure body temperature and foraging simultaneously Evidence-supported
Resource-mediated heat constraint	**Biological context · Evidence basis · Biological setting · Evidence**	Plant–pollinator systems Heat reduces nectar while foraging also changes
	Mechanistic interpretation · Boundary or failure mode	Resource supply can fail even if insect locomotion is retained Plant species and phenology alter the pathway
	Consequence for the proposed	Behavioral cooling is insufficient when the resource layer deteriorates
	Test implication · Status · Evidential standing	Measure resource quantity or quality with insect behavior Evidence-supported
Microhabitat relief of activity stress	**Biological context · Evidence basis · Biological setting · Evidence**	Multiple insect orders Local habitat conditions moderate heat-related activity loss
	Mechanistic interpretation · Boundary or failure mode	Fine-scale habitat modifies the performance consequence of heat Moderation may be incomplete and species specific
	Consequence for the proposed	Usable heterogeneity can preserve an activity window
	Test implication · Status · Evidential standing	Test across structured habitats and taxa Evidence-supported
Activity–resource mismatch	**Biological context · Evidence basis · Biological setting · Evidence**	Cross-system analytical state Activity remains possible but required resources are absent, inaccessible or thermally degraded
	Mechanistic interpretation · Boundary or failure mode	Performance capacity fails to translate into acquisition Resource distribution and timing can dominate
	Consequence for the proposed	Breaks the chain from thermoregulation to fitness components
	Test implication · Status · Evidential standing	Jointly measure activity, encounter rate and acquisition Proposed synthesis

Reproduction and survival

Thermal buffering becomes demographically relevant only when it protects fitness components that determine replacement, and reproduction can fail at temperatures that remain survivable. Across animal studies, temperature alters mating behavior and mating success in heterogeneous ways, so reproductive response cannot be inferred from survival tolerance alone [24]. Within insects, the boundary is sharpened by sex and reproductive context. In Callosobruchus maculatus, the mating system altered the temperature sensitivity of male and female fertility, demonstrating that even within one species a single reproductive thermal limit can obscure sex-specific responses [25].

Exposure timing adds another dimension. In Nicrophorus vespilloides, reproductive consequences of experimental heatwaves depended on when heat occurred relative to reproduction [26]. Stress duration matters as well: in Drosophila suzukii, thermal limits for survival and reproduction shifted with exposure duration and differed between endpoints [27]. A brief avoidance response that prevents immediate death therefore cannot be assumed to preserve later fertility when cumulative thermal dose or reproductive state differs.

Pollinator evidence reinforces taxonomic heterogeneity. Simulated heatwaves altered male reproductive traits in three Bombus species, but responses differed among species and endpoints [28]. At broader comparative scales, temperatures causing male sterility corresponded more closely with warm distribution limits than lethal temperatures across Drosophila species [29]. Independent work likewise found male fertility limits informative for warming vulnerability beyond survival thresholds [30]. These studies make reproduction a plausible demographic bottleneck, but they do not establish male fertility as the universal constraint on insect persistence.

A further implication is that thermal state should be evaluated against the reproductive function actually required at that moment. Courtship, gamete production, mating, oviposition and post-mating fertility can occupy different temporal windows, so a refuge that is adequate during one phase may be inadequate during another. This matters especially for insects with short adult reproductive windows or sex-specific exposure patterns. The framework therefore treats reproductive safety as state dependent rather than as a single species-level constant. It also avoids assuming that a thermally protected individual necessarily contributes offspring: mate availability, resource access and prior heat exposure can remain limiting even after current body temperature improves.

The proposed framework therefore places survival and reproduction in a two-dimensional state space rather than a single fitness axis. Behavioral cooling may move an insect from a lethal to a survivable state without moving it into a reproductively viable state; alternatively, it may preserve both. The decisive quantity is not "successful thermoregulation" in isolation, but whether the post-behavior thermal state lies within the performance space required by the relevant sex, life stage and reproductive phase.

Because survival-safe and reproduction-safe conditions need not coincide, the figure below resolves the distinct post-thermoregulation states and the boundaries that prevent a survival benefit from being read automatically as demographic buffering.

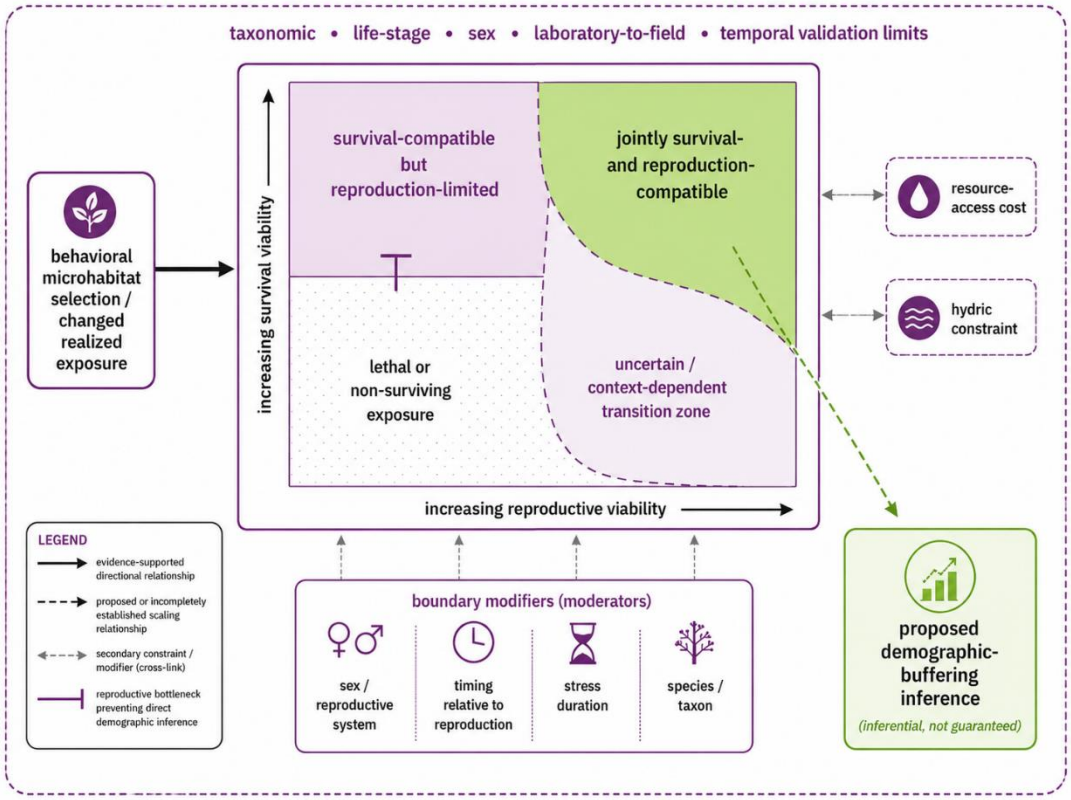


Figure 1. Survival-safe thermal states can remain reproduction-limited after behavioral cooling

Scaling to demography

The transition from individual performance to demography requires changes in survival or reproduction that alter recruitment, replacement or population growth; behavior alone is insufficient. Direct aphid evidence illustrates why: heat escape reduced exposure but also reduced survival and reproduction when relocation disrupted host access [17]. The demographic sign of thermoregulatory movement can therefore depend on ecological opportunity costs.

Temperature can also alter mating, competition and mate choice, creating reproductive pathways between thermal performance and population consequences [31]. Those pathways should not be interpreted automatically as adaptive evolutionary responses. Comparative Drosophila evidence provides a stronger but still bounded bridge: reproductive thermal limits can align with climatic vulnerability more closely than lethal limits [29, 30]. This supports treating reproductive performance as a candidate scaling bottleneck, not as a universal determinant of insect range or abundance.

This scaling logic also distinguishes demographic compensation from demographic buffering. A transient reduction in adult performance may have little population consequence if later survival or fecundity compensates, whereas a small thermal effect on a tightly limiting reproductive stage could propagate strongly. The framework therefore does not assign equal demographic weight to all performance traits. Instead, the relevant link is whichever temperature-sensitive trait constrains replacement under the focal population's life history and environmental context. Identifying that link requires longitudinal evidence rather than extrapolation from a single acute endpoint.

The proposed demographic scaling rule is therefore conjunctive: an exposure change must persist long enough to alter a fitness component, that fitness component must matter for population replacement under the focal life history, and ecological compensation elsewhere in the life cycle must not erase the effect. Evidence coverage is uneven across these links, which is more clearly represented as a coverage-and-gap map than as a linear causal claim.

To prevent well-supported individual effects from being mistaken for population evidence, the map below identifies how far each evidential pathway currently reaches and what remains necessary before demographic buffering can be inferred.

Table 3. Coverage and unresolved links in scaling behavioral thermal effects to insect demography

Scaling link	Insect context represented · Missing evidence before a · Missing evidence before a demographic	Evidence currently reaches · Permitted inference	Evidential standing
Microhabitat escape → survival/reproduction	Host-associated aphids; plant-feeding insects Replication across habitats, stages and movement costs	Direct fitness-component change after thermal movement Movement can change both exposure and fitness components	Evidence-supported link
Thermal state → reproductive viability	Beetles, bumblebees, Drosophila Field exposure histories and sex-specific contribution to replacement	Fertility, mating or reproductive output under heat Reproduction can be more restrictive than survival	Evidence-supported link
Reproductive limit → climatic vulnerability	Drosophila Demonstration that fertility is the limiting demographic process in focal populations	Comparative association with distribution or warming vulnerability Reproductive limits can add information beyond lethal limits	Evidence-supported association
Activity preservation → demographic benefit	Bumblebees and multi-order activity studies Evidence connecting preserved activity to net reproduction and recruitment	Activity or foraging remains possible under favourable microhabitat Performance opportunity may be retained	Evidence gap
Joint survival + reproduction → population buffering	Cross-system synthesis Longitudinal population validation under measured microclimate use	Conceptual conjunction of preserved fitness components Defines the minimum direction of evidence needed for population inference	Proposed synthesis

Conditions producing population buffering

Population buffering should be inferred only when local thermal heterogeneity remains usable through the sequence already defined. Longitudinal butterfly-community evidence shows that habitat and microclimatic heterogeneity can be associated with delayed tracking of macroclimatic warming [32]. This is an upper-level ecological pattern, not direct proof that individual behavioral thermoregulation caused the delay; dispersal, habitat occupancy and species turnover remain alternative explanations.

The proposed buffering condition therefore requires more than refuge availability. First, insects must have access to a microhabitat that materially changes realized exposure. Second, the movement must not impose costs that outweigh the thermal gain, as the aphid example demonstrates [17]. Third, the altered exposure must preserve relevant performance rather than merely activity; local microhabitats can moderate heat-related activity impairment without demonstrating reproduction or population protection [23]. Fourth, thermal improvement must not leave another physiological axis limiting. Hydric physiology can alter thermal vulnerability [13], and reproductive limits can remain more restrictive than survival limits [27].

Temporal continuity is another requirement. A refuge that is available only intermittently may still reduce peak exposure, but its demographic value depends on whether critical activities can be shifted into those intervals without creating new costs. Likewise, spatial heterogeneity can cease to function as a buffer when movement distances exceed the insect's capacity, when predators or competitors alter refuge use, or when the refuge lacks required hosts or mates. These possibilities are framework-level boundary conditions rather than established universal failure modes.

These conditions are expected to vary across taxa and landscapes. Evidence from microhabitat-dependent butterfly mortality, trait-dependent Orthoptera climate associations and delayed butterfly-community tracking shows that

local thermal effects are species-, trait- and context-dependent [12, 14, 32]. Consequently, population buffering is best treated as a proposed conditional outcome of usable heterogeneity, effective behavioral access, net-positive organismal performance and preservation of demographic bottlenecks—not as an intrinsic property of heterogeneous habitat.

Results and Discussion

The proposed framework resolves a recurring scale problem in insect thermal ecology. Microclimatic heterogeneity creates thermal possibilities, but biological buffering emerges only if those possibilities survive a sequence of filters. Physical coupling determines the body temperature produced by a location; behavior determines whether that location is used; physiology determines whether the resulting temperature supports function; activity and resources determine whether function becomes ecological opportunity; and reproduction and survival determine whether individual effects can plausibly reach demography. None of these transitions is guaranteed.

This structure helps explain apparently contradictory outcomes without forcing them into a single measure of thermoregulatory "quality." Treehoppers can escape lethal heat yet remain reproduction limited [4]. Ants can select temperatures near preference while still warming with their environment [15]. Aphids can avoid heat at the cost of host access [17]. Bumblebee activity can be altered directly by temperature or indirectly by temperature-sensitive nectar supply [21]. These are not failures of one universal mechanism; they occupy different positions in the proposed sequence.

An important consequence is that the same observed body-temperature reduction can carry different inferential weight across studies. If body temperature is measured without operative-temperature availability, behavioral selectivity cannot be quantified. If behavior is measured without performance, physiological benefit remains uncertain. If performance is measured without reproduction or survival, demographic relevance remains unresolved. This nested evidential logic offers a practical way to compare studies that otherwise use incompatible endpoints without forcing them into a common effect scale.

That approach also prevents a misleading search for one "best" thermal trait. Preferred temperature, voluntary avoidance, CTmax, locomotor performance, fertility and demographic rate answer different questions. Their disagreement may be biologically informative rather than methodological noise, because each marks a different point at which thermal exposure can cease to be compatible with persistence.

The framework also clarifies where mechanistic language should stop. A correlation between buffering behavior and physiological tolerance does not establish an evolved trade-off [16]. Community associations with microclimate do not identify individual behavioral mechanisms [14]. Molecular or physiological heat responses do not demonstrate improved organismal performance [19]. Conversely, acute survival thresholds cannot substitute for reproductive or duration-dependent limits [27]. The article therefore treats observation, mechanism, performance and demographic inference as separate evidential levels.

Validation should measure those levels together. At minimum, tests should quantify microclimate availability at organism-relevant resolution, actual microhabitat use or body temperature, a functionally relevant performance endpoint, survival and reproduction, and a demographic response over a timescale appropriate to the focal life history. Mechanistic forecasts likewise require empirical validation rather than complexity alone [7]. For many insects, complete population data will be impractical; staged validation can still test individual transitions without claiming that the complete framework has been prospectively validated.

Generality is deliberately bounded. Body size changes thermal coupling to surfaces [10]; water balance can alter thermal vulnerability [13]; behavioral buffering and tolerance vary among taxa [16]; voluntary avoidance and critical limits have different predictors [18]; and reproductive thermal responses depend on sex and mating context [25]. These constraints make a single universal thermal-buffering index unlikely to be defensible. The more useful target is a taxon- and context-specific diagnosis of where the chain from microhabitat choice to demographic consequence is intact, where it fails, and which transition requires measurement.

The framework therefore generates a testable expectation rather than a population forecast: behavioral thermoregulation is most likely to contribute to population buffering when thermal refuges are accessible, selection meaningfully changes body temperature, ecological costs remain limited, sublethal performance is preserved, and the most restrictive survival or reproductive endpoint is protected. Failure of any one condition can weaken or reverse the apparent benefit. Future field studies that measure these transitions simultaneously

would determine whether the proposed architecture captures demographic outcomes better than approaches based on macroclimate, critical thermal limits or behavioral preference alone.

Conclusion

Behavioral thermoregulation links microhabitat choice to population persistence only conditionally. Fine-scale thermal heterogeneity can change exposure, but successful movement is not equivalent to physiological protection, preserved resource acquisition, reproductive viability or demographic buffering. The proposed framework makes these transitions explicit and treats survival, reproduction, ecological cost and nonthermal constraints as potential bottlenecks. Its value lies in identifying the measurements required to test each link while preserving taxonomic, life-stage, environmental and laboratory-to-field boundaries. Population persistence should therefore remain the endpoint to be demonstrated, not an assumed consequence of thermoregulatory behavior.

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