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Anthropogenic Ecological Traps Arise When Insect Attraction Is Guided by Cues That No Longer Predict Habitat Quality

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ABSTRACT

Anthropogenic change can alter the sensory information insects use to locate habitats, hosts, mates, refuges and seasonal environments. The ecological-trap problem arises not from attraction alone, but when a cue continues to guide selection after its relationship with habitat or resource quality has deteriorated. This ecological perspective separates cue response, behavioral selection, biological consequence and population inference. The distinction is necessary because many studies demonstrate strong responses to altered light, polarization, plants or substrates without simultaneously demonstrating that the selected option reduces survival, development or reproduction relative to available alternatives. Evidence from managed bumblebee colonies, invasive host plants, pesticide-contaminated hibernation substrates, restored aquatic habitats, artificial light and climate-shifted migration shows that cue–quality mismatches can occur through different mechanisms and at different life stages. Counterexamples show that anthropogenic habitat use can also be neutral or diagnostically incomplete. We therefore propose an evidence-bounded cue–quality mismatch classification in which ecological-trap inference strengthens only when attraction or selection and inferior biological consequences are independently demonstrated and appropriately linked. Population consequences require an additional scale-transfer step. This approach is intended to reduce false-positive trap diagnoses while retaining ecologically important disturbances that do not meet the stricter trap criterion.

Keywords: Ecological traps, Sensory ecology, Habitat selection, Artificial light at night, Preference–performance mismatch, Anthropogenic cues

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Introduction

Ecological traps are generated by a mismatch between the information used to select a habitat or resource and the consequences obtained after that selection. The distinction matters because poor habitat alone is not a trap: an organism must respond to cues in a way that directs use toward an option that is inferior to an available alternative. Restoration ecology has made this inferential problem explicit by showing that apparently improved or novel habitats can retain attractive characteristics while failing to deliver the outcomes those characteristics historically predicted [1]. For insects, whose decisions may depend on rapidly sampled optical, chemical, thermal and structural information, anthropogenic alteration can therefore create an information problem before it becomes a demographic one.

The term ecological trap is nevertheless easy to overextend. Urban habitats, illuminated environments and novel plants may contain large numbers of insects, whereas other disturbed sites may contain few. Neither abundance

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pattern establishes the preference–quality relationship required for trap diagnosis. A systematic review of urban ecological traps showed that conclusions differed according to whether studies assessed preference and fitness-related consequences directly or relied on indirect proxies [2]. The problem is therefore not only biological; it is also methodological.

Contemporary insect studies demonstrate why a stricter structure is needed. Commercial *Bombus impatiens* colonies can function as traps for wild queens that enter managed colonies and die; the invasive plant *Alliaria petiolata* can receive oviposition by *Anthocharis midea* despite unsuitable larval consequences; and climate-associated changes in seasonal conditions can produce a migration mismatch in rice leafroller moths [3–5]. These cases share the broad logic of misleading information, yet their mechanisms are not interchangeable. One concerns managed nesting resources, another host-plant choice and offspring development, and another seasonal movement under changing climatic conditions.

A counterexample is equally informative. Nonmigratory monarchs using urban gardens in northern California were classified as neither source nor ecological trap [6]. Human modification therefore does not define trap status. The central argument of this perspective is that insect ecological traps should be diagnosed by the evidential connection between cue, selection and quality rather than by the anthropogenic origin of a stimulus or by the observation of ecological harm alone.

Materials and Methods

This article uses a conceptual classification. No new dataset, pooled estimate or quantitative diagnostic score is produced. The classification was constructed by separating evidence into four questions: whether an anthropogenic or anthropogenically modified cue is detected; whether response to that cue alters selection or use; whether the selected option produces an inferior biological consequence; and whether any individual consequence can defensibly be transferred to population interpretation. The first three questions define the proposed cue–quality mismatch core; the fourth is treated as a separate scale-transfer problem.

The need to separate selection from quality is illustrated by bumblebee hibernation studies. *Bombus impatiens* queens can select pesticide-contaminated soils rather than consistently avoiding them [7]. Yet exposure during hibernation does not produce a single uniform performance pattern: responses vary with pesticide treatment and queen body size, and the preference experiment and performance experiment should not be fused into an unmeasured individual causal chain [8]. In the proposed classification, selection evidence and quality evidence therefore remain separate until a study links them directly.

A second distinction concerns incomplete versus stronger mismatch evidence. Restored post-mining waters may show poorer larval outcomes for Odonata without sufficient evidence that adults prefer those waters over alternatives, making “potential trap” a more defensible interpretation than confirmed trap [9]. By contrast, passion fruit can attract fruit-fly oviposition while host chemistry induces embryo arrest, connecting choice to a detrimental developmental outcome more directly [10]. These contrasts motivate a qualitative evidence hierarchy, not a numerical score.

The proposed classification consequently records taxon, life stage, setting and evidence class as boundaries on interpretation. A cue response observed in adult flight cannot automatically be transferred to larval performance; laboratory choice cannot automatically be generalized to landscapes; and a community decline cannot substitute for evidence that individuals preferred the conditions producing it.

Results and Discussion

A cue becomes vulnerable to anthropogenic mismatch precisely because it can be biologically informative under other conditions. Aquatic insects provide a clear example. Horizontally polarized light is associated with water surfaces, yet artificial polarizing materials can generate similar optical information. Field experiments show that susceptibility to such traps varies among closely related taxa and changes with spatial isolation from natural water [11]. The relevant point is not that every aquatic insect follows polarization identically, but that a strong historically useful cue can become misleading when its environmental distribution changes.

Spectral sensitivity further limits generalization. Experiments with ultraviolet polarized light found that responses differed among aquatic insect families rather than supporting a universal preference for the same polarization

conditions [12]. Thus, "evolutionarily reliable cue" should not be treated as a fixed species-independent category. Reliability is conditional on sensory system, taxon, developmental state and environmental context.

Artificial light at night adds a mechanistic caution. Three-dimensional flight analyses indicate that insects gathering around artificial lights may maintain a dorsal orientation response that generates orbiting, stalling or inversion rather than simply flying intentionally toward a beneficial resource [13]. Field attraction nevertheless remains strongly dependent on wavelength, intensity and taxonomic identity [14]. These findings separate sensory capture from habitat choice: a conspicuous anthropogenic signal can reorganize movement without demonstrating that an insect has evaluated and selected a habitat as high quality.

Anthropogenic cue modification

Anthropogenic change can modify cues by altering their spectrum, intensity, spatial position, persistence or timing. These dimensions are ecologically distinct because insects do not perceive "disturbance" as a single variable. Riverside lighting experiments with caddisflies show that colour temperature and placement affect attraction, demonstrating that the geometry and spectral composition of artificial light can change its salience [15].

Modification can also interfere with communication rather than habitat choice. In glow-worms, artificial illumination changes the context in which female sexual signals operate and can reduce mating opportunities; controlled experiments with males likewise show impaired approach to female-associated signals under artificial light [16, 17]. The two sexes therefore illustrate complementary, but not identical, routes by which the same anthropogenic driver can disrupt reproductive information.

Temporal organization is another boundary. Under semi-natural conditions, artificial light alters calling behaviour and temporal organization in *Gryllus bimaculatus* [18]. Across broader biological evidence, spectrum-specific effects are heterogeneous, and neither a universally benign colour nor a simple monotonic intensity rule is supported [19]. This heterogeneity cautions against treating lighting interventions as if every insect order shares the same sensory optimum.

The manuscript therefore uses "cue modification" in a restricted sense: a human-driven change in the availability or informational properties of a signal that insects use or respond to. Cue modification can precede an ecological trap, but it is not sufficient to diagnose one. The next requirement is evidence that attraction or selection is no longer matched by biological benefit.

Attraction without fitness benefit

The most important inferential boundary occurs between attraction and consequence. Strong attraction to an anthropogenic stimulus can identify sensory vulnerability, but an ecological trap requires evidence that the resulting choice is inferior to an alternative. Conversely, a harmful environmental exposure can reduce performance without showing that insects actively selected the harmful condition. Joining these two evidence types retrospectively creates a causal story that the underlying studies may never have tested.

Artificial-light experiments make this distinction visible. In aphids, part-night illumination can produce more detrimental colony responses than full-night illumination, showing that performance effects may be non-linear with exposure duration [20]. That experiment demonstrates a consequence of lighting regime, not attraction into a trap. Moth studies show a different evidential layer: street lighting alters abundance, activity and nocturnal pollen transport, establishing ecological disruption without jointly demonstrating preference and inferior individual outcome [21].

Accordingly, this perspective proposes five attraction–consequence states. Cue capture denotes an observed sensory or movement response without demonstrated selection. Selection with unresolved quality denotes preference or use without evidence that the chosen option is inferior. Quality loss without demonstrated preference denotes detrimental conditions lacking selection evidence. Preference–performance mismatch is reserved for cases where choice and lower biological value are both supported. Ecological disruption outside the trap pathway retains effects on activity, abundance or interactions that are important but do not satisfy the trap criterion.

These states answer different scientific questions and should not be ranked as a severity scale. The distinction is summarized below because the diagnostic consequence of each state is more efficiently compared across evidence types than repeated in prose.

Table 1. When insect attraction is insufficient for ecological-trap inference: a state-and-response ledger

Observed attraction-consequence state	Context and observable basis	Diagnostic gate established	Gate still unresolved, next measurement, and state
Cue engagement only			
Cue capture	Flight, orientation or sensory response to altered light or other signals Response occurs, but habitat/resource choice is not demonstrated	The signal affects behaviour	Attraction may reflect sensorimotor disruption rather than evaluated preference Add explicit alternatives and choice tests Proposed synthesis
Choice or quality partially established			
Selection with unresolved quality	Host, substrate, refuge or habitat use One option is selected more often or used preferentially	A candidate cue–quality mismatch exists	Preferred option may be equal or superior in biological value Measure consequences in selected and alternative options Proposed synthesis
Quality loss without demonstrated preference	Illuminated, contaminated or otherwise altered environments Survival, development, reproduction or condition differs	Anthropogenic exposure has biological consequences	Harm does not establish that insects chose the harmful exposure Pair performance endpoints with preference/use measurements Proposed synthesis
Linked preference-performance mismatch			
Preference–performance mismatch	Oviposition, refuge or habitat-selection systems Selection and inferior biological outcome are both demonstrated	Stronger support for ecological-trap interpretation	Effect may remain species-, stage- or context-specific Replicate the linked pathway under realistic alternatives Proposed synthesis
Ecological disruption outside the trap pathway			
Ecological disruption outside the trap pathway	Activity, abundance, community or interaction responses Ecological change occurs without a complete choice–quality chain	Conservation-relevant disturbance remains plausible	Population/community pattern cannot identify individual trap mechanism by itself Test the missing inferential link rather than relabelling the effect Proposed synthesis

Trap severity and persistence

Once a cue–quality mismatch is established, severity cannot be inferred from attraction magnitude alone. The same conspicuous cue may produce transient detours in one setting and repeated costly decisions in another. The proposed severity concept therefore concerns the temporal integration of four components: cue encounter, response recurrence, consequence accumulation and opportunity for corrective choice. None is assumed to operate identically across insect taxa.

Spatial context can alter the first two components. Polarized-light responses vary with the isolation of artificial sources from natural aquatic habitat [11]. A misleading cue surrounded by reliable alternatives may therefore produce a different behavioral history from the same cue embedded in a landscape where alternatives are scarce or difficult to detect. Spectrum and intensity further modify exposure, but broad synthesis of light pollution shows that biological responses are sufficiently heterogeneous to preclude a universal dose–severity function [19].

Persistence also requires caution when evidence moves from individual behaviour to population patterns. Long-term moth records show that groups characterized by stronger attraction to light have experienced stronger negative population trends, a pattern consistent with concern about chronic exposure but not sufficient to assign the trend uniquely to ecological trapping [22]. Paired field studies likewise report lower caterpillar abundance and altered development under street lighting, yet they do not demonstrate that adult moths selected those illuminated sites and thereby generated the larval pattern [23].

Community responses create an additional boundary. Direct street lighting and skyglow can alter moth abundance, richness, diversity and trait composition, with direct illumination exerting particularly strong local

effects in one recent field study [24]. These observations establish that artificial-light landscapes can filter insect communities, but community restructuring cannot retrospectively prove the individual cue–choice–quality pathway.

Figure 1 therefore treats severity and persistence as a temporal field rather than a linear chain. It distinguishes repeated cue exposure from accumulated consequence, keeps evidence-supported observations separate from proposed cross-stage integration, and places taxonomic, spatial and scale-transfer uncertainty around the central mismatch process.

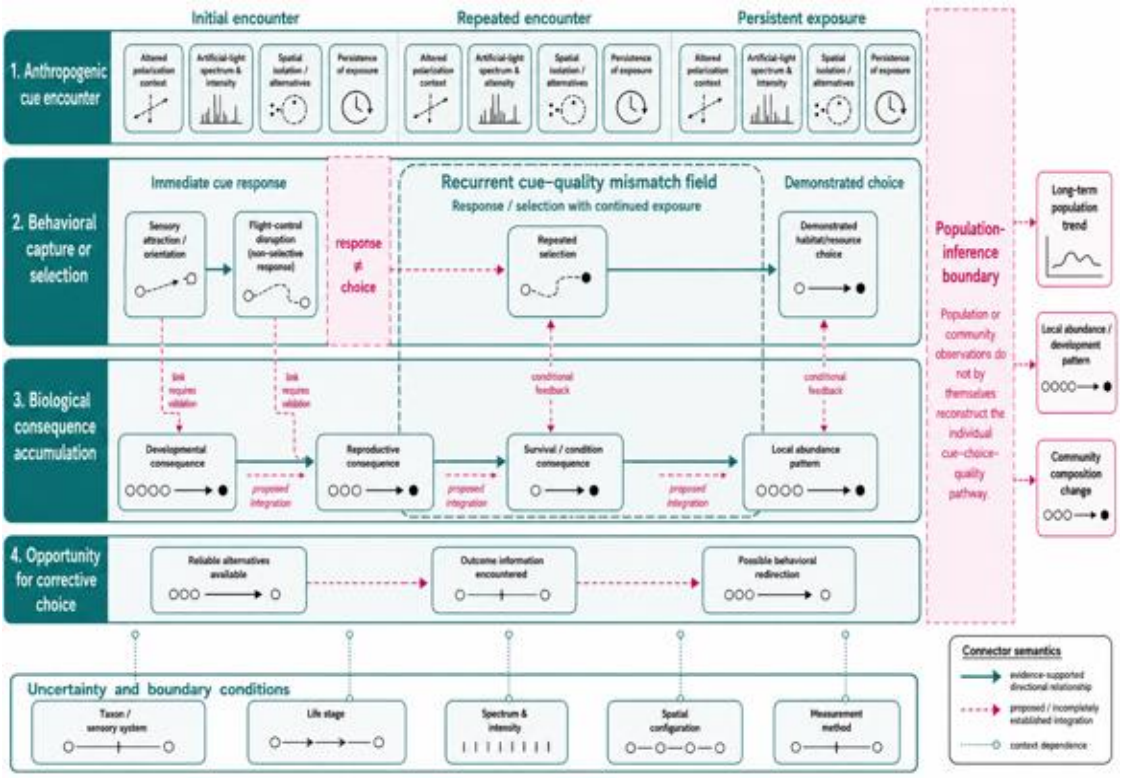


Figure 1. Repeated misleading cues become persistent traps only when exposure, choice and consequence remain coupled through time

Learning and avoidance

A misleading cue need not remain permanently misleading if insects can acquire information about its consequences and subsequently modify behaviour. Learning is therefore a plausible route out of some ecological traps, but it should not be treated as an automatic rescue mechanism. Theoretical analysis of evolutionary traps identifies several conditions that can prevent effective updating, including weak or delayed feedback, insufficient sampling of alternatives, persistent cue salience and cognitive limitations on associating a decision with its later outcome [25]. These constraints are particularly relevant when a decision is made only once or a few times during a life stage.

The insect evidence illustrates why behavioral persistence and learning capacity must remain separate concepts. Bumblebee queens may select pesticide-contaminated hibernation substrates rather than consistently avoiding them [7], yet subsequent performance effects depend on chemical identity and queen phenotype [8]. Failure to reject contaminated soil therefore cannot be interpreted simply as inability to learn: the biological value of available options may itself be heterogeneous.

Glow-worm responses provide a different boundary. Artificial illumination can impair reproductive communication [16], while male approach to female-associated signals can recover when disruptive illumination is removed [17]. Reversibility demonstrates behavioral flexibility, not necessarily learned avoidance. A valid learning test would require prior experience to alter later decisions under comparable cue conditions.

We therefore propose that escape from an insect ecological trap requires three separable opportunities: detectable outcome feedback, experience-dependent cue updating, and access to a usable alternative. Failure at any one stage can preserve the mismatch even when insects possess substantial behavioral flexibility.

Because these conditions determine whether repeated exposure can actually modify future choice, **Table 2** separates mechanisms of apparent persistence from evidence that would be needed to demonstrate genuine avoidance learning.

Table 2. Mechanism–boundary matrix for distinguishing learning, reversible disruption and persistent cue capture in insect ecological traps

Learning or avoidance state	Behavioral context	Repeated-choice evidence	Interpretation and competing explanation	Required update test and state
Persistent versus reversible response				
Persistent cue capture	Recurrent attraction or selection	Similar response despite repeated exposure	Mismatch remains behaviorally expressed Outcome feedback may be unavailable or weak	Track known individuals across repeated choices Proposed synthesis
Reversible disruption	Acute sensory or communication interference	Behavior returns after cue removal	Response is flexible Recovery does not demonstrate learning or memory	Re-expose experienced and naïve individuals under identical conditions Proposed synthesis
Experienced outcome and learned-avoidance candidate				
Outcome experienced but cue not updated	Host, refuge or habitat choice	Inferior consequence occurs after selection	Feedback may be biologically real but unusable for later decisions Consequence can be delayed beyond the decision stage	Test whether prior outcome changes subsequent cue preference Proposed synthesis
Learned avoidance candidate	Repeated-choice system	Experienced insects reduce later selection of the misleading option	Consistent with experience-dependent updating Habituation, fatigue or altered motivation remain alternatives	Separate associative learning from nonlearning explanations Proposed synthesis
Unavailable alternative				
Alternative unavailable	Spatially constrained trap	Harmful cue remains dominant despite possible recognition	Persistence can occur without sensory or cognitive failure Landscape structure constrains corrective choice	Manipulate availability of reliable alternatives Proposed synthesis

Population consequences

Individual mismatches become conservation problems when their consequences accumulate strongly enough to influence recruitment, survival, reproduction, movement or population redistribution. Evidence at these higher levels is valuable, but it cannot retrospectively identify the behavioral mechanism that generated the pattern.

Moth-community studies under artificial light illustrate this scale boundary. Community composition, abundance and richness can vary with light exposure, while the apparent magnitude and structure of those responses may also depend on sampling method [26]. Method-sensitive community patterns therefore cannot be treated as direct reconstructions of individual cue choice.

Species interactions further complicate scaling. Artificial light can modify ecological interactions by changing activity overlap, encounter rates and other behavioral relationships among species [27]. Consequently, an individual cue response could be amplified, weakened or redirected through predators, competitors, mutualists or resource dynamics. Population consequences may therefore emerge from several interacting pathways rather than from a single accumulation of trapped individuals.

This perspective proposes that population-level ecological-trap inference requires a scale-transfer validation step. Evidence becomes stronger when individual selection and biological consequence are linked to demographic rates or repeated redistribution under field conditions. Local abundance decline, community filtering or altered interactions remain important ecological outcomes when that connection is absent, but they should be described at the level actually measured.

The evidential architecture in **Figure 2** therefore makes the scale-transfer boundary explicit rather than depicting population decline as an inevitable final stage of attraction.

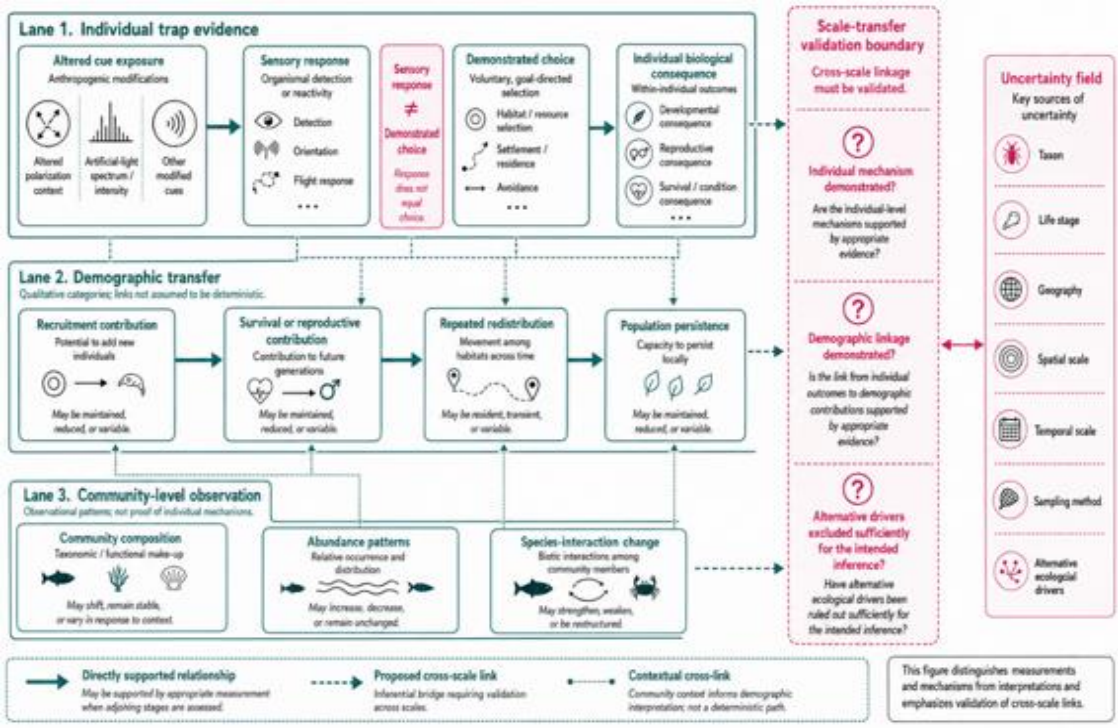


Figure 2. Population evidence cannot identify the ecological-trap pathway unless the individual-to-demographic bridge is demonstrated

Diagnostic framework for insect ecological traps

The evidence considered here supports a stricter distinction between ecological-trap diagnosis and the broader identification of anthropogenic harm. We propose a diagnostic architecture organized around four evidential gates rather than a binary label applied at first observation.

The first gate is cue engagement: does an anthropogenic or altered cue measurably change orientation, attraction or another behavior? Passing this gate establishes sensory or behavioral response only. The second gate is choice displacement: does the cue alter selection among meaningful alternatives? This gate prevents involuntary sensorimotor disruption from being interpreted automatically as habitat preference. The third gate is quality inversion: is the selected option demonstrably inferior to an available alternative for a defensible biological outcome? The final gate is scale transfer: are individual consequences linked to demographic or population processes strongly enough to justify higher-level inference?

This architecture accommodates incomplete cases rather than forcing them into yes/no classification. A contaminated substrate may be preferred while its quality remains context dependent [7]. Restored aquatic habitat may show poorer larval conditions without sufficiently strong adult preference evidence [9]. Conversely, an attractive host can produce a direct developmental failure [10]. These states represent different evidential locations, not simply different “strengths” of the same result.

The framework also protects against false-positive classification when only population or community evidence exists. Community restructuring under light pollution can be substantial [24], yet ecological importance does not eliminate the need to demonstrate the individual pathway when the specific claim is that an ecological trap exists. Accordingly, “confirmed,” “probable,” or numerical certainty categories are not proposed here. The framework is an organizing device for determining which inferential link has been demonstrated and which remains missing. It requires validation across taxa, life stages and field contexts before any prospective diagnostic performance could be claimed.

Table 3 compresses these cross-scale evidential requirements because trap diagnosis depends less on accumulating observations than on identifying which link in the cue–choice–quality chain those observations actually establish.

Table 3. Cross-scale evidence grid for locating where an insect ecological-trap diagnosis is supported, incomplete or overextended

Cue, choice, and quality gates			
Ecological trap comparison dimension	**Cue engagement**	**Choice displacement**	**Quality inversion**
Evidence satisfying the gate	Measured orientation, attraction or behavior change to the altered cue	Selection among ecologically meaningful alternatives	Inferior survival, development, reproduction or other defensible biological outcome in the selected option
Evidence that cannot substitute	Habitat degradation alone	Aggregation around a light without demonstrated choice	Low abundance or poor site condition alone
Biological scale	Sensory/behavioral	Individual decision	Individual performance
Meaning if absent	Trap pathway not initiated evidentially	Cue capture may occur without habitat selection	Preference may remain adaptive, neutral or unresolved
Validation priority and state	Establish cue-specific response Proposed diagnostic gate	Test explicit alternatives under realistic conditions Proposed diagnostic gate	Compare selected and alternative options Proposed diagnostic gate
Linked mismatch and scale transfer			
Ecological trap comparison dimension	**Linked mismatch**	**Scale transfer**	
Evidence satisfying the gate	Choice and inferior outcome demonstrated within a defensible biological pathway	Individual consequences connected to recruitment, survival contribution, redistribution or persistence	
Evidence that cannot substitute	Separate studies retrospectively joined without validation	Community change alone	
Biological scale	Individual/life-history	Population	
Meaning if absent	Candidate trap remains incompletely demonstrated	Ecological harm may be real without population-level trap inference	
Validation priority and state	Link behavior to consequence in the same system Proposed diagnostic gate	Measure demographic linkage and alternative drivers Proposed diagnostic gate	
Boundary validation			
Ecological trap comparison dimension	**Boundary validation**		
Evidence satisfying the gate	Replication across relevant sex, stage, taxon, geography or environmental conditions		
Evidence that cannot substitute	Generalization from one laboratory or field context		
Biological scale	Transferability		
Meaning if absent	Scope remains restricted to tested conditions		
Validation priority and state	Replicate where management decisions require transfer Proposed diagnostic gate		

The principal implication of this perspective is that anthropogenic ecological traps are most usefully treated as failures of ecological information rather than as a synonym for disturbance. Managed colonies, invasive hosts, altered seasonal environments and chemically defended plants can all create misleading conditions, but the biological routes differ markedly [3]. Host-choice mismatch in *A. midea* concerns oviposition and larval performance [4], whereas climate-associated trapping of a migratory moth concerns seasonal movement under changing atmospheric conditions [5]. Their commonality lies at the level of information–quality decoupling, not a shared proximate mechanism.

This distinction also explains why strong attraction can coexist with weak trap evidence. Polarization responses vary spatially and taxonomically [11], ultraviolet polarization does not elicit uniform responses among aquatic-insect families [12], and artificial-light attraction varies with taxon, intensity and wavelength [14]. Susceptibility is therefore conditional on sensory biology and environmental configuration.

The framework deliberately retains null and contradictory cases. Urban monarch gardens can fail to meet either source or trap criteria [6]. Pesticide-contaminated hibernation substrates can be selected even though subsequent

performance effects are treatment- and phenotype-dependent [8]. Such cases prevent the theory from becoming unfalsifiable: if every anthropogenic habitat used by insects were labelled a trap regardless of performance, the concept would lose diagnostic value.

Several evidence gaps remain. Few systems connect experimentally demonstrated choice, biological consequence and population persistence within the same spatial and temporal design. Laboratory behavior can reveal sensory mechanisms without demonstrating field selection, whereas population monitoring can reveal decline without identifying the individual decision pathway. Learning is another unresolved boundary because reversible behavioral disruption is not equivalent to experience-dependent updating.

The proposed framework should therefore be regarded as an inferential discipline rather than an empirically validated diagnostic test. Its value lies in specifying what must be shown before stronger ecological-trap language is used and in allowing harmful anthropogenic effects to remain scientifically important even when the trap pathway is incomplete.

Management implications

Management should target the demonstrated component of a mismatch. For nocturnal insects, tailored and shielded road lighting can reduce immediate attraction relative to conventional configurations [28]. Such reductions are useful intervention endpoints, but they do not by themselves establish improved population persistence.

More generally, evolutionary-trap management can intervene at different leverage points, including modification of misleading cues, restriction of access to harmful options or improvement of the conditions associated with attractive cues [29]. Applying this logic to insects means that management should first identify whether the limiting problem is cue salience, selection, habitat quality or demographic transfer.

The same informational logic can also be exploited deliberately against pests. Engineering cotton to alter emission of the volatile DMNT changes interactions involving mirid bugs and natural enemies [30]. Such manipulation illustrates that attractive or behaviorally active cues can be designed rather than merely mitigated. However, deliberate pest attraction is conceptually different from conservation-oriented trap removal and requires independent assessment of non-target effects and ecological transferability.

Management success should therefore be evaluated sequentially: did the intervention alter the relevant cue, change insect choice, improve the biological consequence of that choice, and—where claimed—produce a defensible population benefit? Failure to distinguish these endpoints risks calling an intervention conservation-effective when it has demonstrated only reduced attraction.

Conclusion

Anthropogenic ecological traps arise when insects continue to use cues that no longer predict the biological value of the habitats, resources or conditions those cues once indicated. The defining problem is therefore not attraction itself but a demonstrable mismatch between information-guided selection and outcome.

The proposed cue–quality framework separates sensory engagement, choice displacement, quality inversion and population-scale transfer. This structure preserves biologically important distinctions among sensory disruption, harmful exposure, preference–performance mismatch and community change while preventing any one of them from substituting automatically for the others.

Ecological-trap research will become more informative when studies connect behavior and consequence within the same system, preserve taxonomic and life-stage boundaries, test realistic alternatives and validate any movement from individual effects to population inference. Such evidence can identify when anthropogenic cues genuinely redirect insects toward poorer outcomes and when a different conservation diagnosis is more appropriate.

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