Evidence and Uncertainty in the Future Pathways of Insects Under Global Change

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Abstract

Insects are essential for life on Earth, yet anthropogenic environmental changes have led to declines in insect biomass, abundance, and species richness. Projecting future insect trajectories can inform conservation and policy but is complicated by variation in life histories and traits, nonlinear population dynamics, extreme population fluctuations, and interacting natural and anthropogenic drivers. Limited long-term, spatially representative data further constrain the accuracy of projections, while human-driven factors such as land-use change and policy shifts add layers of uncertainty. Understanding these uncertainties is essential for interpreting current evidence, prioritizing research, and developing robust policies that remain effective under a range of plausible future scenarios. This synthesis integrates evidence on insect responses to global change, bounding outcomes under plausible best- and worst-case scenarios of greenhouse gas emissions, environmental change, and social and economic pathways over 10- and 50-year horizons. Across case studies of functionally diverse taxa with conservation, economic, and public-health relevance, uncertainty is a central feature, reflecting variation in species traits, environmental drivers, and social systems. We identify five pathways—agricultural deintensification, increasing food-system efficiency, urban greening, mitigation of light pollution, and landscape restoration—that can alter future trajectories of insect populations while providing benefits for humans. Combined with rapid climate mitigation and habitat protection, these interventions offer the greatest potential to stabilize and restore insect populations and their ecological functions. Recognizing insects as central to biodiversity planning and explicitly addressing uncertainty are critical for effective conservation, policy design, and long-term sustainability.

Introduction

Insects, and the contributions they make to society (Grames 2026), are under threat from many anthropogenic stressors (Halsch 2026), resulting in declines in abundance, species richness, and biomass across taxonomic groups, ecosystems, and regions (Wagner 2026). Policy action is needed to halt or reverse these declines as climate change accelerates and its impacts on biodiversity and human societies intensify (Allan et al. 2021). Continued planetary change will drive turnover in community composition, with some insect species adapting while others do not (Neupane et al. 2024). Some insects, including many species considered to be pests, are expected to thrive (to be 'winners') under climate change (Jactel et al. 2019), whereas many other species may decline and disappear (be 'losers'), leading to increased biotic homogenization and loss of ecosystem function as communities become dominated by a subset of surviving species (Jackson et al. 2022, Finn et al. 2023). Projecting how, and in what form, insects will persist through the Anthropocene is essential to policy and ultimate mitigation of negative impacts on insects and humans. Meeting this challenge requires an understanding of which traits make species vulnerable or resilient to change, how insects respond to global change, and how the drivers of global change are themselves changing and interacting. By projecting future responses of insects to global change, it is possible to inform policy changes that conserve insects and the contributions insects make to humanity (Ware 2026).

It is logical for global assessments and conservation frameworks to place insects at the forefront given that they constitute the majority of animal species and underpin essential ecological processes that support human societies (Ware 2026). Incorporating insects into planning and management is necessary not only to conserve insects, but to mitigate and reverse the adverse effects of global change on nature as a whole. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services' (IPBES) global assessment helps to inform changes in

global policy and guide international, national, and local action on biodiversity conservation (Ruckelshaus et al. 2020). The Kunming-Montreal Global Biodiversity Framework set 23 targets to implement by 2030 as a means of recovering natural systems by 2050 (Affinito et al. 2024). Meeting these targets requires recognizing insects as a central component of global biodiversity.

Barriers to incorporating insects into global policy include taxonomic uncertainty and data deficiency around diversity, ecology, and population trends. Insects' short generation times, ecological complexity, and sensitivity to environmental change can produce rapid and unpredictable responses, complicating management and conservation (Arribas et al. 2012). Numerous insects, such as those that function as crop pests and disease vectors, have negative impacts on humanity. Therefore, it is necessary to consider not only the conservation of insects and the variety of species they encompass, but also the management of insect pests under future scenarios. Responses of insects to anthropogenic change also vary across geographic extents. Climate and land use are likely the primary drivers of changes in insect communities over large areas (Outhwaite, McCann, et al. 2022), whereas disturbance, non-native species, and pathogens drive local changes (Kaunisto et al. 2016, Fortuna et al. 2022). These drivers rarely occur in isolation and often interact in non-uniform ways, increasing uncertainty in insect population projections (Halsch et al. 2025).

In this synthesis, we integrate recent literature and expert opinion on the responses of insects to global change drivers and projections of future change across social, economic, and natural systems. We do not attempt to be exhaustive, selecting only a small subset of taxa and guilds that we consider to be representative of core issues relating to insect biodiversity change, and a subset of alternative futures. Given the hyperdiversity of insects, we recognize that many other such assessments are needed to fully capture the possible consequences of global change on

insects and the services they provide. We also identify potentially transformative pathways for insect conservation and the benefits insects provide to humanity. We emphasize uncertainty in future insect trajectories arising from unpredictable changes in biotic responses, environmental conditions, and social and economic systems over the next century. We bound our projections of insect responses to plausible future scenarios with 'best-case' and 'worst-case' outcomes with respect to emissions of greenhouse gases, resulting environmental change, and the social and economic pathways affecting land use over 10 and 50 years. We generally consider climate as a core driver in this synthesis, recognizing its interaction with other drivers where supported by the literature. We focus our discussion on insect taxa for which data are generally rich, and which may serve as indicators of how other taxonomic groups, for which less data exist, may respond. The selected taxa are of economic, cultural, or public health relevance, and represent distinct functional groups expected to respond differently to global change drivers. We then emphasize five potentially transformative pathways—agricultural deintensification, increasing food-system efficiency to reduce land needs, urban greening, mitigation of light pollution, and landscape restoration—that could moderate the impacts of future change while benefiting both insects and people, and highlight successful examples of conservation interventions. Throughout, we use the confidence framework developed for IPBES assessments to identify certainty in key messages and points of agreement within the scientific community (IPBES 2019). In this framework, knowledge is classified as "well-established" if it reflects both substantial evidence and high expert agreement, "established but incomplete" if there is limited evidence but high agreement, "unresolved" if there is substantial evidence but the evidence conflicts or experts are not in agreement, and "inconclusive" when evidence is insufficient and experts do not agree.

Uncertainty in future scenarios

There is substantial uncertainty in the status of insects, their risk of decline or extinction, and their likely responses to future change (Roeder, Roeder, et al. 2021). Insects are hyperdiverse, with extraordinary taxonomic and functional diversity (Stork 2018) that varies regionally, making future insect abundance, population viability, and species interactions exceptionally difficult to project with precision or generalize across taxa (Bahlai 2023). The extent and magnitude of impacts on insects may also depend on species traits, which often define the winners and losers under anthropogenic change (Roeder, Bujan, et al. 2021). Future trends are particularly difficult to project for insects with complex life histories, high sensitivity to environmental change, or distributions in regions experiencing rapid or unpredictable global change (Ebi et al. 2016, Halsch 2026). Furthermore, species traits are not necessarily fixed and environmental changes may lead to adaptive responses (Outhwaite et al. 2024). These challenges reflect multiple sources of uncertainty, including data limitations, methodological choices, and the inherent variability of insect populations. Characterizing these uncertainties is essential for interpreting current evidence, identifying priority knowledge gaps, and developing robust policy responses where information is incomplete. Although the magnitude and trajectory of insect responses remain uncertain, there is broad agreement that proactive measures are needed to conserve insects (Forister et al. 2019, Wagner et al. 2021).

Nonlinear population dynamics with multifactorial drivers complicates reliable projection of changes in abundance (well established). Insect population sizes can fluctuate by orders of magnitude over time even in stable environments (Bahlai 2023), and are simultaneously influenced by multiple, interacting external drivers (Halsch et al. 2025). Population dynamics can range from noncyclical, where population sizes appear random over time, to strongly cyclical over return intervals from seasons to decades. Complicating accurate predictions of population abundances, fluctuations in abundance arise from interactions among density-dependent and density-independent responses, which are often nonlinear (Hunter et al. 1997, Hastings 2010,

Royama 2012, Jactel et al. 2019, Rumohr et al. 2023). High-amplitude, regional fluctuations are typical of irruptive species, including many forest and agricultural pests, and these species' population dynamics are expected to become increasingly unpredictable under global change (Pureswaran et al. 2018, Ma et al. 2025).

Beneath these observed fluctuations, interacting traits and ecological processes combine with density-dependent and stochastic effects to generate nonlinear population trajectories that challenge projection of future dynamics (Turchin 2003). When abiotic and biotic drivers interact, a population's apparent density-dependent characteristics often change directly in response to shifts in abiotic conditions (Bahlai and Zipkin 2020). Life-history parameters such as fecundity, generation time, and thermal tolerance interact with demographic stochasticity and density-dependent feedbacks to produce trajectories that are highly sensitive to initial conditions (Jactel et al. 2019). Short generation times allow rapid demographic or evolutionary responses, whereas dispersal mediates spatial coupling among local populations, creating metapopulation-level dynamics that can amplify or dampen fluctuations (Haynes et al. 2014). These multifactorial interactions give rise to emergent, non-additive effects, meaning that the combined impact of abiotic and biotic drivers is often qualitatively different from what would be expected by summing individual effects.

The available long-term data documenting insect population responses are incomplete or subject to biases that compromise generalizability (well established). Given that insect population dynamics are highly variable across years and species, the paucity of historical baseline data on insects for model training and testing makes projecting future changes difficult (Montgomery et al. 2026). Although hundreds of studies have reported time series quantifying insect abundance, most are short in duration or geographically restricted. A recent synthesis identified only 166 long-term insect surveys worldwide suitable for estimating trends (van Klink

et al. 2020). Many of those surveys were concentrated in Europe and North America, with limited data from the tropics (van Klink et al. 2020). By contrast, vertebrate monitoring programs collectively track tens of thousands of populations across thousands of species, with the Living Planet Database alone incorporating more than 30,000 population time series from over 5,000 vertebrate species (Ledger et al. 2023). In addition, many insect datasets are spatially limited (Burke and Lauenroth 1993) and may be affected by changes in sampling protocols, specimen loss, or other changes in methods that influence detectability across taxa (Welti et al. 2021, McNamara Manning et al. 2024). Long-term monitoring sites are frequently located in protected areas or research stations that may buffer populations from anthropogenic pressures such as habitat loss, creating conditions that differ fundamentally from those experienced by many insect populations (Forister et al. 2023). Moreover, projections based on abundant, well-studied species may have limited value for projecting responses across insect populations given that most species are rare and poorly studied, with life histories and traits that differ from those of common taxa (Zhang et al. 2020). Consequently, projections of future insect population trajectories remain highly uncertain (Kellermann and Van Heerwaarden 2019).

Uncertainty in both natural systems and human-driven factors makes future insect population trajectories more difficult to project (well established). Insect population dynamics are often strongly affected by environmental changes (Müller et al. 2024). Therefore, rapid or unpredictable changes in environmental conditions will likely result in rapid and unpredictable changes in insect populations. For instance, some climate variables that affect insect movements, such as wind patterns or locations of storm tracks (Lv et al. 2023), are inherently difficult to project. Insect responses to a given environmental driver are not always predictable even when the environmental changes can be projected with certainty (Thompson et al. 2021). With continued anthropogenic pressures, there is substantial uncertainty in the speed, location, and extent of future land-use change (Riahi et al. 2017). How land-use change may interact with

climate change and other environmental drivers to impact biodiversity is difficult to project because the mechanisms that underpin these interactions are not well understood (Schulte to Bühne et al. 2021). Furthermore, global social and political instability create considerable uncertainty in future land-use scenarios. For instance, human migration and conflict are among the key causes of land-use change, yet are often unpredictable and interact with heterogeneous policies across geopolitical regions (Crawford et al. 2024, Yin et al. 2025).

Plausible future scenarios

The Shared Socioeconomic Pathways (SSPs), described in the sixth and most recent assessment of the Intergovernmental Panel on Climate Change (IPCC), reflect assumptions about future social, demographic, technological, and economic growth that will affect emissions and land-cover change (Riahi et al. 2017). Although drivers of change vary across SSPs, especially at regional and local scales, these scenarios offer an opportunity to project the impacts of interconnected drivers on insect biodiversity. Eight plausible future scenarios were included in the models that informed the IPCC's sixth assessment. Here, we consider two of these scenarios, the lowest level of carbon dioxide emissions (SSP 1-2.6) and the highest level of emissions (SSP 5-8.5), effectively best and worst-case climate and land-use change scenarios, as the bookends of plausible futures. We make no judgment about the most likely future climate scenario because likelihood depends heavily on changes in social, economic, and political systems that are beyond the scope of this review.

SSP 1-2.6 scenario: anthropogenic carbon dioxide emissions reach net zero by the mid-twenty-first century and warming could be limited to 1-2˚C above pre-industrial levels, although there will be spatial heterogeneity in realized temperature increases (Lee et al. 2023). This scenario falls within the natural range of climatic variability over recent evolutionary history, so many

organisms may be resilient to this magnitude of change. Adaptive responses to changing climate under this scenario may reflect phenotypic plasticity, e.g., changes in behavior or physiology in response to changing environmental conditions (Gibert et al. 2019, Urban et al. 2026).

SSP 5-8.5 scenario: anthropogenic carbon dioxide emissions continue to increase unabated and global mean temperature warms by 3-5˚C by 2100, which may exceed the thermal tolerances of many species. This scenario is expected to drive extreme weather, climate-related disturbances such as wildfire, and social and economic shifts resulting in land-use change (Riahi et al. 2017). A sharper divergence between species thriving or declining is anticipated under this scenario, with the greatest risk to species that have limited adaptive capacity (that is, those with lower resilience), including ecological specialists, or are already disproportionately affected by global change (Hoveka et al. 2022, Weaving et al. 2022). The uncertainty in which groups will be most affected under this scenario underscores the need to refine understanding of the role of traits in conferring resilience, or vulnerability, to global change and to improve region-specific projections of shifts in populations and communities in coming decades (Cardoso et al. 2025).

Insect responses to future change

Insect responses to climate change and other forms of global change will vary across taxa, regions, and time scales, and considerable uncertainty remains about which groups will be most affected (Warren et al. 2018). To illustrate projections of insect responses to global change, we focus on ten taxa with diverse functional and life-history traits that are relevant to conservation, economic activity, and public health, whether positively or negatively, and that provide insight into insect responses under different global change scenarios. Although our focal taxa do not

represent the full breadth of insect diversity, they cover a variety of ecosystem functions and roles.

The selected taxa are sufficiently well-studied that it is generally possible to speculate on their responses to future scenarios, and we used the IPBES framework to characterize the strength of our expectations. Our focal taxa include species, genera, and other taxonomic groups, each restricted to a single family or lower taxonomic group. More expansive case studies of a subset of these exemplar taxa, bumblebees (*Bombus* spp.; selected for their role in pollination), *Anopheles* mosquitoes (selected for their effect on human health), monarch butterflies (*Danaus plexippus;* selected for their visibility as conservation icons), and dung beetles (Scarabaeidae, selected for their role in decomposition) are below. Drawing on the available literature, we develop qualitative, evidence-informed expectations of how these groups may respond to different global change scenarios (**Table 1**). We gave syntheses and consensus studies the greatest weight, followed by integrative models and then empirical studies that were long term or geographically extensive. We consulted empirical studies that were shorter and encompassed smaller areas when more-comprehensive studies were not available.

We project responses over 10 years (to 2035) and 50 years (to 2075) under the best case (SSP1-2.6), and worst case (SSP 5-8.5) scenarios and characterize the uncertainty and confidence associated with these projections. We selected these time periods because they are relevant for changes in population dynamics and extinction risk (Cardillo et al. 2026) and also human interventions, conservation actions, and changes to global conservation policy that could mitigate the worst impacts of anthropogenic change on biodiversity (Saunders et al. 2020). Consistent with assessment-based approaches, confidence assignments reflect the authors' evaluation of the quantity, quality, consistency, and agreement of available evidence. As such, they should be interpreted as qualitative judgments rather than quantitative estimates.

<u>Bumblebees</u>

Bumblebees (*Bombus* spp.) are a charismatic and ecologically important group that pollinate wild plants and crops, including the 8% of the world's plants that require buzz-pollination (Potts et al. 2010, De Luca and Vallejo-Marín 2013). In Europe, North America, and Asia, bumblebees have experienced population declines and range reductions (Grixti et al. 2009, Williams et al. 2009, Cameron et al. 2011) The causes of declines in bumblebee populations are multifaceted, but climate change is believed to be a key driver (Goulson et al. 2015). Bumblebees may rely on a tight phenological match with their floral resources. Shifts in flowering timing or duration under changing climate conditions can disrupt this coupling (Kudo et al. 2025), potentially exacerbating declines even when bumblebee activity windows themselves remain unchanged.

The distributions of many bumblebee species are shrinking and will continue to do so under all climate scenarios (established but incomplete). Bumblebees are physiologically adapted to cooler climates, making them highly vulnerable to rising global temperatures and extreme weather events (Soroye et al. 2020). On the basis of their climatic niches, species are expected to decline at the southern edges of their ranges as distributions respond to climate change (Williams and Osborne 2009). Observations over the past century from Europe and North America reveal widespread range losses, contractions at southern range boundaries, and shifts to higher elevations of many bumblebee species, although northerly populations remain poorly documented due to limited data (Kerr et al. 2015). Climate projections under multiple SSPs indicate that even species currently classified on the International Union for Conservation of Nature's Red List as "Least Concern" may lose 30–76% of their habitat by mid-century, with montane species facing the greatest reductions under high-emissions trajectories (Ghisbain et al. 2024).

Although many bumblebee species are at risk of extinction, a subset of species may remain widespread under the high emissions climate change scenario (unresolved). Although range reductions of many bumblebee species have been documented, not all bumblebees are currently in decline. Bumblebees appear to be differentially impacted by anthropogenic stressors, as some species are declining while others remain abundant (Banaszak-Cibicka and Żmihorski 2012, Colla et al. 2012). For example, in the eastern United States, populations of the common eastern bumblebee (*Bombus impatiens* Cresson) have remained widespread, while the distribution of *B. affinis* has declined substantially from its historic distribution (Cameron et al. 2011). These differential responses to environmental change depend on species traits such as dispersal capacity, physiological tolerances, diet breadth, and phenology (Martén-Rodríguez et al. 2025). It is projected that climate change will favor species with generalist diets, long activity periods, and behavioral and physiological adaptations for warmer, more variable environments.

Social insects such as bumblebees may be buffered through colonial behavior, which stabilizes nest microclimates and supports resource gathering under environmental stress. Additionally, bumblebees have plastic and adaptive responses that increase resilience to climate change and other environmental stresses (Maebe et al. 2021, Menzel and Feldmeyer 2021). However, species dispersal rates may not be sufficient for bumblebees to track temperature changes over larger scales (Sirois-Delisle and Kerr 2018). Although there are still many unknowns that limit projection of bumblebees' responses to climate change under a high emissions scenario (SSP 5-8.5), we suggest that future research prioritize identification of the traits that confer vulnerability or resilience to climate change and evaluation of how trait-based species loss may drive community homogenization. Such work is needed to gauge whether shifts in community composition could degrade pollination services and ultimately threaten food security (Vasiliev and Greenwood 2021).

Anopheles mosquitoes

Mosquitoes in the genus *Anopheles* are among the most consequential insects for global public health because they are vectors of *Plasmodium,* which causes malaria. Malaria is one of the most prevalent and deadly human diseases on the planet, responsible for up to 600 000 deaths per year (World Health Organization 2026). Therefore, *Anopheles* spp. have often been referred to as the deadliest animals in the world (Kamerow 2014). Consequently, *Anopheles* are well-studied, and their population dynamics are tightly linked to climate and hydrology (Afrane et al. 2012).

Net malaria burden decreases under the most optimistic climate scenario (unresolved). Under SSP 1-2.6, projected disease transmission by *Anopheles* mosquitoes will likely increase at current range margins and in highlands due to expansion of climatic suitability as temperatures in those areas warm to the optimal malarial transmission band (Ryan et al. 2023, Klepac et al. 2024). Urban-associated species (e.g., *Anopheles stephensi*) may not drive increased prevalence of malaria due to limited urban expansion (Ryan et al. 2023). Disease transmission may decline in the hottest lowland tropics where temperatures exceed physiological optima for mosquitoes or *Plasmodium* (Li and Managi 2022, Klepac et al. 2024). Moderate increases in the human population at risk under SSP 1-2.6 are likely to be offset by improvements in health care, secure housing, and vector control (Sellers and Ebi 2017, Li and Managi 2022).

Rapid climate change will likely lead to increased malaria prevalence (established but incomplete). *Anopheles* ranges are projected to expand, particularly into highlands and cooler subtropical regions, and transmission seasons may lengthen by 1–2 months in these zones (Ryan et al. 2023, Klepac et al. 2024). Transmission depends not just on temperature but also on sufficient rainfall and humidity to support mosquito breeding and parasite development. By

2075, more than 30% of Earth's land could be climatically suitable for *Anopheles*, exposing 56% of the global human population to diseases for which *Anopheles* serve as vectors if other environmental and social conditions allow (Ryan et al. 2023). Although extremely hot lowland areas may become unsuitable, the net effect of expansion into newly suitable regions is likely to outweigh these losses (Li and Managi 2022, Klepac et al. 2024). Even in currently cooler regions, local *Anopheles* species may have the capacity to carry malaria if *Plasmodium* can survive. Without substantial interventions in public health, disease risk will remain high or increase due to warming, extreme events, rapid urbanization, and stresses on health systems (Sellers and Ebi 2017, Li and Managi 2022).

Monarch butterflies

Monarch butterflies, *Danaus plexippus* (Linnaeus), are among the most familiar and charismatic insect species (Ware 2026) and are a species known for their regular, predictable migration (Reppert and De Roode 2018). They receive substantial interest from researchers, policymakers, and the public (Gustafsson et al. 2015, Harris et al. 2023) and are the subject of several large scale, coordinated monitoring and conservation efforts (Cariveau et al. 2019, Diffendorfer et al. 2023). Monarch butterflies are often used as flagship species in conservation efforts. The long history of data on monarch butterfly populations can be used to infer some of the impacts of conservation policy on their population dynamics (Gustafsson et al. 2017).

Migratory dynamics are a key point of vulnerability for monarch butterflies under future climate scenarios (well established). Monarch butterflies are subject to the cumulative effects of varied global change drivers across the large spatial extent of their migratory range (Zylstra et al. 2021). Southward monarch migration is triggered in part by seasonal declines in temperature and day length. If winters become sufficiently mild, the selective pressure for long-distance

388 migration may weaken, potentially leading to shorter distance migrations or shifts in the location
389 of overwintering areas (Sánchez-Cordero et al. 2026). In addition, monarch migration is multi-
390 generational, requiring host plants and other elements of breeding habitat to support successive
391 generations across the migratory route. Changes in the distribution or phenology of their host
392 plant, milkweed (*Asclepias* spp.), and nectar resources along this route could therefore disrupt
393 the timing and success of migration even if suitable conditions remain at the endpoints (Zylstra
394 et al. 2021). Population trajectories also differ between the eastern and western migratory
395 populations. Western monarch butterfly populations that overwinter along the California coast
396 have declined more sharply in recent decades than the larger eastern population that
397 overwinters in central Mexico (Harris et al. 2023). These regional differences highlight how
398 variation in land use, habitat availability, and climate exposure across migratory routes can
399 produce divergent outcomes within a single species.
400
401 *Habitat conservation can mitigate the impacts of climate change on population persistence, but*
402 *only below an unknown threshold of climate change and above an unknown threshold of habitat*
403 *amount and quality (unresolved)*. Regardless of the future scenario, the net abundance of
404 monarch butterflies is projected to decrease, with the greatest losses associated with changes
405 in precipitation and land cover rather than with temperature alone (Ragab et al. 2025). These
406 declines may be partially offset by localized habitat conservation. If local habitat amount and
407 quality are sufficient, moderate levels of warming may accelerate development from larvae to
408 adults (Lemoine et al. 2015), and the number of adults may increase as a result (Zaya et al.
409 2017). Alternatively, the current ranges and abundances of host plants may contract or
410 decrease, respectively (Lemoine 2015), reducing the stability of breeding populations.
411 Temperatures in hotter southern lowlands will likely exceed current physiological optima for
412 monarch butterfly flight, egg survival, and host plant nutritional quality (Rich et al. 2025). In
413 these regions, warming may lead to range contractions, reduced reproduction, and disruptions

to migration, with the most substantial declines projected in the southern portion of the species' range (Ragab et al. 2025).

Habitat restoration, including roadside and agricultural conservation initiatives, and protection of overwintering sites could help stabilize populations, especially over 10 years (Gu and Shen 2022), although impacts of these activities will scale with area restored. These changes could help to offset decreases in habitat quality within most of the present breeding range of monarch butterflies, which are likely given high levels of warming (Zylstra et al. 2021). Over longer periods of time, abundance of monarch butterflies is likely to become more variable and declines will be more difficult to reverse (Ragab et al. 2025). By the late twenty-first century, more frequent heatwaves, altered storm tracks, and more frequent wildfire and drought may increase mortality during migration, reduce physiological condition, and decrease overwintering survival (Barve 2012). For populations to persist under these changing conditions, and given their current physiology, the distribution of host plants and habitat must keep pace with changes in climate suitability as temperatures consistent with breeding shift poleward or to higher elevations (Svancara et al. 2019).

Dung beetles

Dung beetles (i.e. primarily beetles in the family Scarabaeidae that feed on dung) are ecosystem engineers, contributing to essential functions such as nutrient cycling, maintenance of soil structure, trophic regulation, dung removal, plant growth, bioturbation, and secondary seed dispersal (Anderson et al. 2024, Hasan et al. 2024). These functions are especially critical in livestock grazing systems where dung beetles are responsible for processing and burying

dung, suppressing livestock parasites, and reducing greenhouse gas emissions (Nichols et al. 2008, Slade et al. 2016). Population declines have been documented in response to both landscape-level changes, such as land use conversion, habitat loss, and fragmentation; and local factors, including habitat modification, vegetation structure, and dung quality; across temperate and tropical regions (Lobo 2001, Verdú et al. 2018, López-Bedoya et al. 2022). Because their activity, survival, and reproduction are strongly temperature-dependent (Verdú et al. 2018), climate change is projected to alter dung beetle community structure and composition (Dortel et al. 2013, Carreón et al. 2025). However, many species' behavioral and ecological traits, such as burrowing into soil and dung, allow them to buffer short-term temperature and moisture extremes, providing some resilience to environmental variability (Batilani-Filho and Hernandez 2017).

Activity of widespread thermophilous dung beetle species may increase under the most optimistic climate scenario (unresolved). Under SSP1-2.6, increased temperatures in cooler and temperate regions are projected to lengthen seasonal activity and accelerate dung decomposition, enhancing the beetles' role in ecological function where their thermal limits are not exceeded (Slade et al. 2016). Cooler temperate regions in the northern hemisphere are expected to see increased species richness and turnover in community composition as distributions of thermophilous species shift northward, with concurrent reductions in species richness expected at southern range limits (Dortel et al. 2013). Similarly, upward elevational range shifts have been observed among dung beetle species in the Alps and Sierra Nevada mountain ranges, with further warming expected to compress ranges given species' thermal tolerances (Menéndez et al. 2014).

Extreme heat events and elevated baseline temperatures projected under the high emissions scenario may reduce adult performance and larval survival of dung beetles, negatively affecting populations of most species (established but incomplete). Smaller, heat-tolerant species are expected to be favored under high-emissions warming consistent with SSP5-8.5, whereas large-bodied tunneling species that contribute most to nutrient incorporation and parasite suppression are expected to decline (Piccini et al. 2018, Carreón et al. 2025). These changes are projected to reduce functional capacity even where species richness remains moderate, with net outcomes including slower manure breakdown, higher parasite loads, reduced pasture productivity, and increased emissions from surface dung (Nichols et al. 2008, Slade et al. 2016). Although most species' ranges are expected to become smaller, shifts in the distributions of dung beetles will hinge on fecundity, habitat availability, and synchronous shifts in dung resources (Menéndez and Gutiérrez 2004, Dortel et al. 2013). Widespread species are projected to have a greater capacity to adapt to climate change than species with restricted geographic ranges (Lim et al. 2024). Restoration of disturbed habitat, especially pastures in temperate regions and primary forests in tropical regions, can provide adequate resources and climatic refugia to support dung beetle populations (Dortel et al. 2013, López-Bedoya et al. 2022), and the mammal species upon which they depend for dung (Nichols et al. 2009, Schweiger and Svenning 2018), in the future.

Transformative pathways

The most impactful pathways for insect conservation into the future are rapid climate change mitigation and the protection of habitat. Stabilizing global temperatures and preventing further loss, fragmentation, and degradation of natural land cover address the primary drivers of long-term insect declines (Wagner 2020, Forister et al. 2023). These pathways are deeply

intertwined, with the effectiveness of intervention greatly enhanced when both are pursued simultaneously (Segan et al. 2016). Increased restoration of lost and degraded habitat could also create opportunities to reverse past declines (Tudor et al. 2023). Insects are sensitive to fine-scale microhabitat conditions and structural complexity, so even small shifts in temperature, moisture, or vegetation can have rapid and profound impacts on local populations (Arribas et al. 2012). Without these structural and climate-level changes, local or sector-specific interventions are unlikely to fully reverse negative trajectories at regional to global scales (Leather 2013).

Some existing programs and policies can meaningfully improve future conditions for insects regardless of future scenarios (Harvey et al. 2020, Chowdhury et al. 2023). In the context of ongoing climate change and development, these interventions act as evidence-based buffers, redirecting insect population trajectories toward more favorable outcomes at regional extents. Examples include agricultural deintensification to enhance agroecosystem sustainability; reducing the need for additional farmland by increasing efficiencies in the food system; urban greening policies that prioritize green space and land uses that support native species; mitigation of light pollution in terrestrial and freshwater systems; and conservation and restoration of native land cover. These interventions are not exhaustive, but are selected to highlight examples of feasible actions and their implementation and impacts (see Elphick. 2026 for a more comprehensive compilation of potential actions). These pathways generate co-benefits for biodiversity and human well-being by improving habitat quality, supporting resilient insect communities, regulating pest populations, and establishing positive ecological trajectories over decades.

Agricultural deintensification

Encouraging adoption of semi-natural habitat and diverse vegetation structure in croplands is a practical strategy to support insect diversity without reducing agricultural yields (unresolved).

Agricultural production has rapidly expanded and intensified over the past half century, often at the expense of natural and semi-natural ecosystems (Dudley and Alexander 2017). Sustainable agricultural practices that integrate local ecological knowledge and maintain structural complexity of vegetation offer a pathway to support insect biodiversity while sustaining productivity (Outhwaite, Ortiz, et al. 2022, Campera et al. 2024). For example, farmers can be provided with incentives to incorporate perennial or semi-natural elements such as field margins, hedgerows, or patches of native vegetation within crop systems rather than clearing land for the cultivation of monocultures. These practices create habitat for insects and other animals, improve pollination and pest regulation, and provide additional products or ecosystem services without reducing overall yields (Tscharntke et al. 2012, Paul et al. 2017, Kuyah et al. 2019).

One approach to deintensification is converting marginal cropland from intensive annual production to perennial grasses and forbs that mimic historic native grassland communities. These plantings can also be used for other purposes, such as biofuels or wildlife habitat (Khanna et al. 2021, Shortall and Helliwell 2021). Marginal lands have relatively low productivity when used for row crops compared to adjacent cultivated areas, and they are often managed intensively with supplemental inputs and mechanization to maximize yields (Li et al. 2021). When marginal lands are taken out of crop production and cultivated with perennial grasses and forbs, they mimic native grasslands that historically covered central North America, creating permanent insect habitat (Gardiner et al. 2010). Planting perennial grasses also provides net benefits for farmers given that these areas can reduce nutrient runoff by over 70% (Blanco-Canqui et al. 2004), improve growing conditions for adjacent crops (He et al. 2022), and increase insect-mediated ecosystem services such as pollination, seed dispersal,

decomposition, and pest regulation by natural enemies (Werling et al. 2014, Grames 2026). Even small-scale plantings can double wild pollinator abundance and flower visitation rates in nearby crops, increasing yield and reducing reliance on managed pollinators (Blaauw and Isaacs 2014). There is evidence that native habitat remnants can similarly benefit insect biodiversity in tropical ecosystems (Gray et al. 2016).

A well-studied implementation of this approach is the Science-based Trials of Rowcrops Integrated with Prairie Strips (STRIPS) program. STRIPS was developed to help farmers, educators, and researchers collaboratively test ecological responses to increasing the proportion of herbaceous perennial land cover in agricultural areas (Mayer 2023). Initially limited to Iowa State University research stations, the program has since expanded to commercial farms across the midwestern United States, enrolling over 60,000 hectares. When participating farmers converted roughly 5% of their row-crop fields to perennial cover and received compensation (Luther et al. 2022), insect species richness doubled, bee abundance more than tripled, soil erosion declined, and water quality improved (Gray et al. 2014, Schulte et al. 2017). **Focal taxa most likely to be impacted:** non-crop spaces provide habitat and resources like food, prey and nesting sites to directly support bumble bees, Monarch butterflies, dung beetles, lady beetles and fireflies. Some non-crop plants may act as alternate hosts for field crop aphids.

<u>Reduce agricultural land needs</u>

Strategies that reduce the amount of land required for food production can complement agricultural deintensification by enabling habitat restoration and reducing pressure on insect biodiversity (inconclusive). Agricultural deintensification on land currently in use reduces pressures on insects through a ‘land-sharing’ ethos. ‘Land-sparing’ approaches that reduce the area of agriculture needed to feed a human population can be used in conjunction with

564 deintensification (Kremen 2015). Agriculture is the dominant global land-use, with cropland and
565 pasture accounting for 45% of Earth's habitable surface (Ritchie and Roser 2019). Halting the
566 further expansion of agricultural land, and exploring opportunities to restore farmland to more
567 natural or semi-natural states, is essential for conserving many insect species.
568
569 One of the most effective ways to reduce pressure for continued agricultural expansion while
570 feeding a growing human population is to shift global diets away from meat. Although animal
571 protein remains an important source of nutrition for many people worldwide, the land footprint of
572 vertebrate animal protein is 10-50 times greater than that of plant protein (Poore and Nemecek
573 2018). Such dietary shifts reduce the amount of land required for food production. This change
574 would provide opportunities to restore farmland through natural succession enriched with
575 targeted plantings (Aide et al. 2000) and to reduce pressure for agricultural expansion, which is
576 the largest contributor to habitat loss and deforestation (Pendrill et al. 2019). Policies to
577 encourage movement toward plant-based diets are rare (Davis et al. 2025), and individual
578 preferences and behaviors present barriers to adoption (Rickerby and Green 2024). One such
579 policy was initiated in Germany, where the Advisory Council on the Environment recommended
580 government action to encourage the adoption of plant-based diets through increasing access to
581 vegetarian food while removing subsidies that reduce meat prices, increasing environmental
582 awareness, and cultivating social norms around lower levels of meat consumption (Schleicher
583 and Töller 2024). Although these policy instruments have not yet become law, proponents
584 contend that as consumer behaviors change, the overall agricultural footprint will be reduced.
585 **Focal taxa most likely to be impacted:** all focal taxa may exhibit some response to large-
586 scale changes in food consumption, including through climate change mitigation via reduction in
587 agriculturally-associated greenhouse gas emissions.
588
589 <u>Urban greening</u>

Cities can support substantial insect biodiversity when urban greening efforts create connected networks of functional habitat (unresolved). Municipally coordinated urban greening can substantially increase species richness of insects in cities (Turo and Gardiner 2019). For example, the municipal government of Toronto, Canada, recognized its ~360 native bee species and over 100 other native insect species in its biodiversity plans (Marshman 2023). Through the PollinateTO grant program, community groups have created hundreds of insect-friendly gardens, collectively adding many hectares of insect habitat across neighborhoods (Minaei 2022). These gardens provide nectar, pollen, nesting sites, and overwintering shelter for bees, butterflies, moths, and other insects while moderating the urban heat island effect. The program creates incentives and social norms for including green spaces, community gardens, and pollinator-friendly landscaping in urban areas while restricting pesticide use (Nalepa and Colla 2023). Functional green spaces, such as green roofs, street-side patches of nectar- and pollen-producing plants, and restored urban riparian systems, form networks that support insect movement, foraging, and reproduction (Colla et al. 2009, Conflitti et al. 2022). In this way, urban greening becomes more than a cosmetic or recreational amenity: it is a tangible conservation strategy that enhances insect diversity, stabilizes native pollinator populations, and builds ecological resilience under changing climate conditions (Marshman 2023). Because human preferences influence urban greening, scaling up implementation will likely require incentives, education, and efforts to encourage creation and maintenance of species-rich, functional green spaces in cities (Turo and Gardiner 2019).

Focal taxa most likely to be impacted: urban greening provides habitat and resources to directly support bumble bees, Monarch butterflies, stingless bees, lady beetles and fireflies. Habitat patches may also be used by pest taxa such as *Anopheles* spp. mosquitoes, fire ants and aphids, so these areas should be monitored and maintained to favor beneficial taxa.

615

616 Reducing artificial light at night

617

618 *Policies and management that reduce artificial lighting can mitigate the impacts of light pollution*
619 *on insects while maintaining human nighttime activities (established but incomplete).* Light
620 pollution from artificial light at night has significantly altered the nighttime environment and
621 poses a threat that disproportionally affects insects (Owens et al. 2020, Halsch 2026). The most
622 widely recognized impacts are mortality and disruption of normal foraging or mating activities
623 due to insects' attraction to light (Owens and Lewis 2018). Light pollution also can influence
624 insect fitness through its effects on physiology, development, and behaviors such as feeding
625 and mating (Owens et al. 2020, Boyes et al. 2021) and by affecting interactions with plants,
626 vertebrates, and other arthropods (Seymoure et al. 2023). Modifications to the structure of
627 fixtures, timing of lit periods, and properties of the light emitted can dramatically reduce the
628 impacts of artificial outdoor lighting while maintaining its functions for humans (Fristrup et al.
629 2024).

630

631 Owens et al. (2024) developed a set of recommendations to reduce the impacts of artificial night
632 light on insects. First, use light only if and when needed. Second, limit direct light only to where
633 it needs to go and no further. Third, modify the properties of the light used: reduce the
634 brightness of light and limit levels of short-wavelength light. For example, fixtures applied to
635 lights in a park in Germany that were designed to limit illumination to only targeted areas
636 reduced attraction of flying insects to nearly dark sky levels, indicating strong potential for
637 spatially optimized lighting to mitigate adverse impacts (Dietenberger et al. 2024). Despite some
638 uncertainty in the effects of artificial light on insects, wide application of these principles could
639 mitigate the known consequences for sensitive taxa (Van Koppenhagen et al. 2026). Mitigation

actions are shaped by social and economic context, yet increasing access to data and modeling tools can help identify approaches that are more likely to deliver positive outcomes for people and ecosystems (Tardieu et al. 2025).

Focal taxa most likely to be impacted: reducing disruption by artificial light reduction most clearly benefits groups like fireflies which rely on lighting conditions for reproductive behavior. However, because many insects use light for timing life events or movement, this intervention would likely have widespread impacts.

Land protection and restoration

Strategic habitat protection and restoration provide refugia that safeguard insects and mitigate the impacts of environmental stressors (well established). Land protection and restoration can be an effective strategy to preserve insects by providing habitat and refugia that buffer against other environmental stressors (Percel et al. 2025). Conservation of insect diversity necessitates both the restoration of degraded habitats and the protection of high-quality habitats. Despite the significance of insects to ecosystem processes, vertebrates and plants are the dominant taxa considered when designating protected areas. Chowdhury et al. (2023) called for strategic designations for protected areas on the basis of insect conservation as part of a multifaceted approach to enhance insect conservation into the future. However, restoring or reclaiming sites affected by human activities, such as retiring land from agriculture as more efficient practices reduce land demand, represents an opportunity for insect conservation. Although dispersal limited and highly sensitive species do not benefit as strongly from restoration efforts (Brederveld et al. 2011), and restoration cannot provide the same level of conservation as intact

protected areas (Parkhurst et al. 2022), restoration can create refugia and prevent ongoing loss of insects (Tonietto and Larkin 2018).

A study in southwest Costa Rica examined the impact of restoring cattle-grazed pastures to lowland wet forest (Pinto et al. 2025). Dung beetle communities in the restored plots were initially more species-poor and highly distinct from the reference sites, but became much more species-rich and more similar to intact reference sites over three years of sampling. Similarly, the large-scale restoration of Cumberland Plain Woodland on formerly cleared agricultural land near Sydney, Australia, aimed to bring back locally native trees, shrubs, and the structural complexity of a critically endangered grassy eucalypt ecosystem. Vegetation composition lagged behind that of remnant woodland after a decade of planting (Wilkins et al. 2003), but initial signs of insect recovery were observed. Butterfly species richness was substantially higher in revegetated areas than in unrestored pastures, and restored sites supported more diverse lepidopteran assemblages, showing that habitat restoration can increase insect diversity even if convergence with reference conditions takes longer (Lomov et al. 2006). These results suggest that many insect communities can recover quickly–potentially more quickly than communities of other, longer-lived organisms–when remediation actions are well-designed.

Focal taxa most likely to be impacted: preservation and restoration will generally benefit all focal taxa when applied to the habitats and regions they occur in. Naturalized habitat could offer more resistance to invasion by range-expanding taxa like fire ants, and would support insects at higher trophic levels like lady beetles, potentially limiting eruptive dynamics in pests.

Conclusions

Insects will experience divergent and uncertain trajectories under ongoing anthropogenic change. Their trajectories are driven by interacting shifts in climate, land use, biotic interactions, and social and economic systems. Our synthesis demonstrates that these dynamics are projected to play out differently across taxa, and that both risks and opportunities emerge under future scenarios. Although uncertainty in ecological responses and human pathways complicates projection, it does not preclude action. Across the case studies examined, targeted interventions, such as agricultural deintensification, increasing food-system efficiency, urban greening, mitigation of light pollution, and landscape restoration–are promising ways to mitigate losses and, in some cases, enhance insect populations while providing benefits for human well-being. By integrating scenario-based projections with an explicit treatment of uncertainty, this work underscores that future insect outcomes are not fixed but contingent on near-term decisions. Embedding insects within policy frameworks will be critical for navigating uncertainty and sustaining both species and ecosystem function in a rapidly changing world. The use of scenario building approaches to project the future status of insects and the services they provide remains an underutilized practice. Expanded use of expert elicitation and quantitative methods across a broader collection of taxa would enhance future conservation planning.

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Table 1: Anticipated population trends of ten insect taxa of conservation, economic, and public-health relevance under SSP 1-2.6 (low emissions, sustainable development) and SSP 5-8.5 (high emissions, fossil-fuel driven development) scenarios for 2035 and 2075. Arrows indicate expected population trends on the basis of current evidence, whereas stars show confidence in projections (0 = inconclusive, 1 = unresolved, 2 = established but incomplete, 3 = well-established, as defined in the text). This synthesis highlights both the risks and opportunities for targeted conservation and management actions under different future scenarios. Taxonomic illustrations are from Phylopic, with full citations in the footnotes.

Insect group	2035	2075	Projected outcomes
Bumblebees Pollination of crops and natural systems 	↘ ★★☆	→ ☆☆☆	**SSP 1-2.6** Temperate bumblebees have already undergone range compression due to temperature change. These trends are expected to continue, but can be mitigated in the longer term with intentional habitat management to provide climate refugia (Williams and Osborne 2009, Kerr et al. 2015)
	↘ ★★☆	↘ ☆☆☆	**SSP 5-8.5** Rare and sensitive species are at risk of extinction, but some generalist species with more plastic responses to temperature and diet will persist in areas where climates remain suitable (Vasiliev and Greenwood 2021, Ostwald et al. 2024)
***Anopheles* mosquitoes** Disease vector 	↗ ★★☆	→ ★☆☆	**SSP 1-2.6** Slight temperature increases expand area of climate suitability near range margins, but disease transmission is managed due to improvements in public health resources (Sellers and Ebi 2017, Li and Managi 2022)
	↗ ★★☆	↗ ★★☆	**SSP 5-8.5** Geographic expansions of suitable range are combined with longer disease transmission seasons. Urban expansion in these areas without public health interventions puts more than half the world's population at malaria risk (Ryan et al. 2023, Klepac et al. 2024)
***Colias* butterflies** Model taxon for ecophysiological research 	→ ★★☆	→ ★★☆	**SSP 1-2.6** Moderate warming is expected to drive gradual upslope shifts and modest changes in thermoregulatory traits, but evolutionary responses may lag behind increasing climate variability, leading to greater demographic fluctuations at range margins (Kingsolver and Buckley 2015, MacLean et al. 2016)

	↘ ★★☆	↘ ★★☆	**SSP 5-8.5** Rapid warming and more frequent thermal extremes produce range contractions at lower elevations and substantial population declines over 50 years (Buckley and Kingsolver 2012)
Monarch butterflies Conservation icon 	↘ ★☆☆	↘ ☆☆☆	**SSP 1-2.6** Precipitation and land cover change reduce overall abundance, but losses may be somewhat mitigated by restoration of large areas of habitat (Gu and Shen 2022, Ragab et al. 2025)
	↘ ★★★	↘ ★★☆	**SSP 5-8.5** Temperatures exceed physiological optima in southern portion of range, breeding habitat contracts, overwintering grounds subject to extreme events at greater frequency (Barve 2012, Ragab et al. 2025)
Fire ants Invasive pest, ecosystem disruption 	↗ ★★☆	→ ☆☆☆	**SSP 1-2.6** Slight temperature increases expand climatically suitable habitat near northern range margins, but spread and establishment remain constrained by climatic variability and land use (Morrison et al. 2004, Sung et al. 2018)
	↗ ★★☆	↗ ☆☆☆	**SSP 5-8.5** Rapid warming and milder winters drive accelerated northward expansion hundreds of kilometers beyond present ranges, higher colony densities, and widespread establishment over 50 years, increasing ecological impacts and management challenges (Morrison et al. 2004, Li et al. 2024)
Dung Beetles Decomposition 	↗ ★☆☆	→ ★☆☆	**SSP 1-2.6** Slight temperature increases lead to longer seasonal activity and increased dung decomposition rates. Some species may shift up elevational and latitudinal gradients (Dortel et al. 2013, Slade et al. 2016)
	↘ ★★☆	↘ ★★☆	**SSP 5-8.5** Widespread range reductions expected in larger, functionally important species as temperatures exceed thermal tolerances and thermal refugia become limited (Piccini et al. 2018, Carreón et al. 2025)
Stingless Bees Pollination, economic security in indigenous communities	→ ★★☆	→ ★★☆	**SSP 1-2.6** Slight temperature increases expand climatically suitable habitat into subtropical and elevational margins, but colony performance remains sensitive to changes in precipitation and floral resource phenology (Dew et al. 2019, Hrncir et al. 2019)

	↘ ★★☆	↘ ★★☆	**SSP 5-8.5** Rapid warming combined with more frequent droughts and heat extremes drives range contractions in lowland tropical areas and disrupts bee behavior and plant–pollinator synchrony over 50 years, increasing colony losses and reducing pollination (Toledo-Hernández et al. 2022, Da Silva et al. 2025)
Lady Beetles Pest control in agriculture, cultural significance 	→ ★★☆	↗ ★☆☆	**SSP 1-2.6** Invasions leading to increasingly non-native-dominated communities in the near-term, but intentional landscape management improves connectivity and provides refugia for preserving native species (Gardiner et al. 2021, Soares et al. 2023, Bahlai and Landis 2026)
	↘ ★★☆	↘ ★★☆	**SSP 5-8.5** Increased temperatures, extreme events, and landscape simplification stress physiological tolerances of temperate species while reducing climate-moderated refugia (Sloggett 2021, Hyder et al. 2025)
Field crop aphids Ubiquitous pests of staple food crops 	↗ ★★☆	→ ☆☆☆	**SSP 1-2.6** Near-term slight warming increases reproductive rates without exceeding physiological tolerances of most pest taxa. As temperature changes stabilize, so does aphid growth rate. Interactions with crop physiology and natural enemy responses increases uncertainty (Derocles et al. 2018, Wang et al. 2024)
	↗ ★☆☆	↗ ☆☆☆	**SSP 5-8.5** Population growth rates are increased by warming, but thresholds for physiological heat stress may be exceeded in this scenario. With markedly higher temperatures, aphid growth rates and behavior will strongly interact with crop physiology associated with plant stress, increasing yield loss (Newman et al. 2003, Ma and Ma 2012)
Fireflies Cultural significance 	↘ ☆☆☆	→ ☆☆☆	**SSP 1-2.6** Some climate stressors and light pollution disrupt reproduction but by mitigating landscape change and adopting less disruptive lighting technologies, losses are stabilized in the long term (Hermann et al. 2016, Vaz et al. 2021)
	↘ ★★☆	↘ ★★☆	**SSP 5-8.5** Environmental signals regulating phenology become decoupled; activity patterns change under more frequent extreme events and soil disturbance from agricultural intensification compromise life history and reproduction (Hermann et al. 2016, Vaz et al. 2021)

Projected population change	**Level of certainty**
↘ Decreasing	★★★ Well established

→ Stable	★★☆ Established but incomplete
↗ Increasing	★☆☆ Unresolved
	☆☆☆ Inconclusive

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