

Declines in insect abundance and diversity: We know enough to act now

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Abstract

Recent regional reports and trends in biomonitoring suggest that insects are experiencing a multicontinental crisis that is apparent as reductions in abundance, diversity, and biomass. Given the centrality of insects to terrestrial ecosystems and the food chain that supports humans, the importance of addressing these declines cannot be overstated. The scientific community has understandably been focused on establishing the breadth and depth of the phenomenon and on documenting factors causing insect declines. In parallel with ongoing research, it is now time for the development of a policy consensus that will allow for a swift societal response. We point out that this response need not wait for full resolution of the many physiological, behavioral, and demographic aspects of declining insect populations. To these ends, we suggest primary policy goals summarized at scales from nations to farms to homes.

KEYWORDS

climate change, ecosystem function, habitat loss, insect declines, pesticides, pollination, species loss

1 | INTRODUCTION

For variety, abundance and ecological impact, insects have no rival among multicellular life on this planet (Figure 1). In terrestrial and freshwater aquatic ecosystems, insects connect innumerable other organisms in relationships that range from pollination to predation. Just four of the many insect services—dung burial, pest control, pollination, and wildlife nutrition—have an estimated annual value in the United States alone of at least \$57 billion (Losey & Vaughan, 2006). The vast majority of bats, birds, and freshwater fish depend on insects, and humans depend on insect pollination for nutritious fruits and vegetables. Indirect effects of insects are just as consequential, including effects on nutrient cycling and competitive interactions among plants.

Despite the ubiquity of insects and their extensive connections to plants and other animals, declines in insect

diversity and abundance are apparent in studies that include faunal and biomass assessments as well as status reviews of key indicator groups like butterflies and charismatic individual species (Wagner, 2018). While the loss of certain at-risk species has been anticipated and is ongoing based on habitat loss, among other stressors, the situation has potentially become more serious as recent reviews have revealed declines across multiple continents that transcend the loss of individual species in terms of functional and ecological impact (Dirzo et al., 2014; Janzen & Hallwachs, 2019; Sánchez-Bayo & Wyckhuys, 2019; Wagner, 2020). Although less than 1% of described invertebrate species have been assessed for threat by the International Union for Conservation of Nature (IUCN), approximately 40% of those that have been assessed are considered threatened (Dirzo et al., 2014). Among bumble bees, 28% are considered threatened in North America (Hatfield et al., 2015), 41% in

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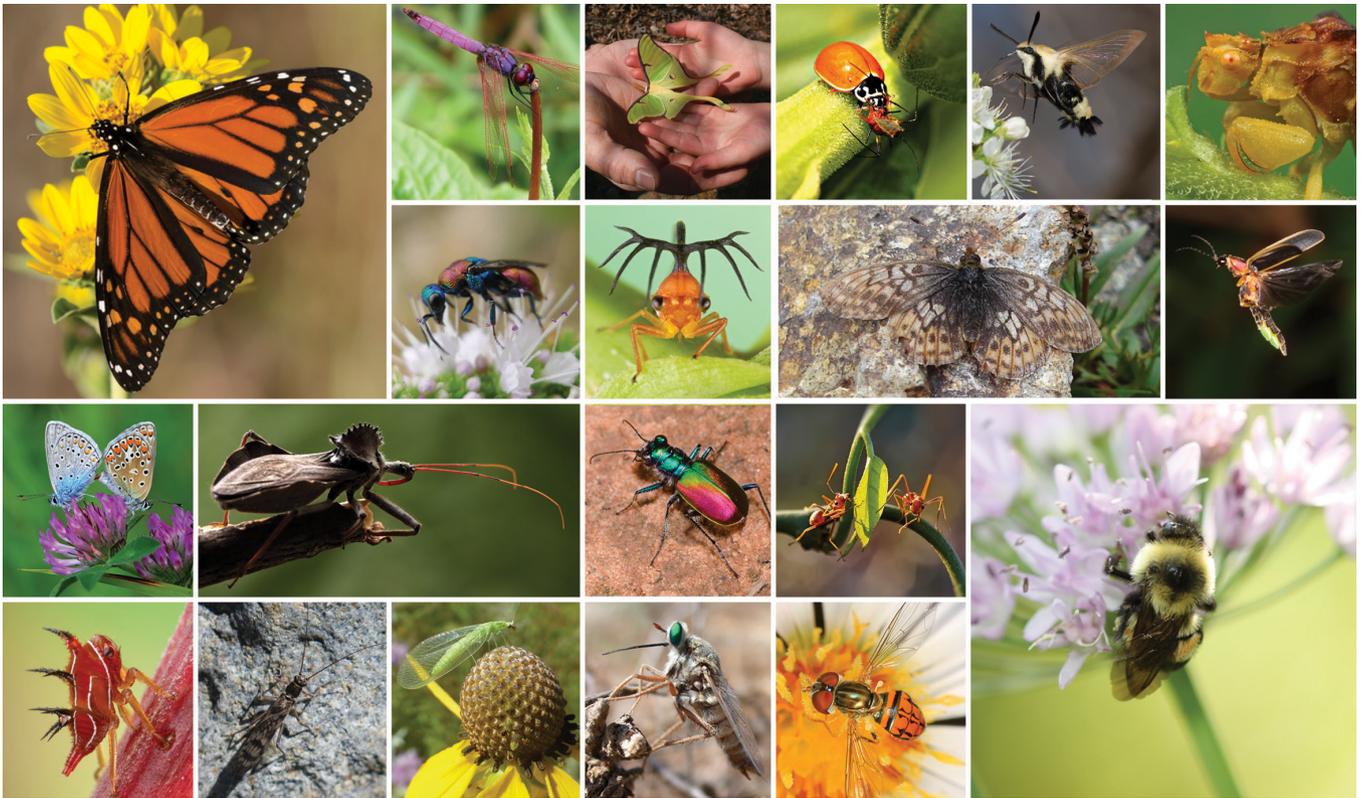


FIGURE 1 With almost 1 million described species, insects eclipse all other forms of animal life on Earth, not only in sheer numbers, diversity, and biomass but also in their importance to functioning ecosystems. A few representatives of that great insect diversity are shown here, as follows: Top row, left to right: monarch butterfly (*Danaus plexippus*), violet dropping dragonfly, (*Trithemis annulata*), luna moth (*Actias luna*), polished lady beetle (*Cycloneda munda*), snowberry clearwing moth (*Hemaris diffinis*), jagged ambush bug (*Phymata* sp.) Second row, left to right: ruby-tailed wasp (*Chrysis* sp.), treehopper (*Umbelligerus woldai*), Uncompahgre fritillary (*Boloria acrocneuma*), eastern firefly (*Photinus pyralis*), Third row, left to right: common blue (*Polyommatus icarus*), wheel bug (*Arilus cristatus*), festive tiger beetle (*Cicindela scutellaris*), ants in Laos (Family Formicidae), rusty patched bumble bee (*Bombus affinis*); Fourth row, left to right: treehopper (genus *Guayaquila*), western willowfly (*Doddsia occidentalis*), green lacewing (*Chrysoperla rufilabris*), Delhi Sands flower-loving fly (*Rhaphiomidas terminatus*), thin-lined calligrapher (*Toxomerus boscii*)

Mesoamerica (IUCN, 2018), and 23.5% of bumble bee species are threatened in Europe (Nieto et al., 2014). In the United Kingdom, 10-year trends show that 52% of butterfly species have declined in abundance at monitored sites and 47% of butterfly geographic ranges in that same region are also reduced (Fox et al., 2015). A monitoring program for butterflies in the Flanders region of Belgium showed that 19 of the original 64 indigenous species have been extirpated (Maes & Van Dyck, 2001). Invertebrate trends for European species that have been evaluated show a much higher proportion of species are in decline compared to a smaller fraction that are increasing (Collen & Baillie, 2010). NatureServe has assessed 636 butterfly species in the United States and Canada and has found that 19% are at risk of extinction (NatureServe, 2019). Roughly one third of tiger beetle species and subspecies in the United States are sufficiently rare to be considered threatened or endangered (Knisley, Kippenhan, & Brzoska, 2014), and Stein (2000) estimated that 43% of stoneflies in the United States are in

an extinction risk category. Declines have been severe in areas highly impacted by human activity, such as industrialized agricultural landscapes, but ongoing insect declines are not restricted to farms or the footprints of suburban sprawl. Fewer butterflies have been observed per year at elevations in the Sierra Nevada Mountains of California high enough to be removed from the most direct effects of development (Forister et al., 2018), and repeated surveys in a protected forest in Costa Rica have found declines in entire genera of tropical moths (Salcido, Forister, Lopez, & Dyer, 2019).

Reductions in total insect biomass in multidecadal studies are similarly being reported from different parts of the globe: a 33% reduction in the abundance of butterflies was observed over 21 years in extensive monitoring in Ohio, United States (Wepprich, Adrion, Ries, Wiedmann, & Haddad, 2019); abundance of 176 moth species decreased by 20% from 1975 to 2014 in Rothamsted insect survey samples in Scotland (Dennis et al., 2019); total flying insect biomass decreased by more than 70% across 63 study

locations over 27 years in Germany (Hallmann et al., 2017) and a more than 10-fold reduction in arthropod biomass was observed from 1976 to 2012 in a resampling study from the Puerto Rican rainforest (Lister & Garcia, 2018). Although there has been some criticism of specific studies (Thomas, Jones, & Hartley, 2019), the overall trend is clear and the broad geographic reach is perhaps the most dire feature of the current crisis, as assessments from all continents except Antarctica reveal declines. Declines have not only been observed among species with narrow habitat requirements, but also among those that are broadly distributed and abundant. The migratory monarch butterfly (*Danaus plexippus plexippus*), for example, has captured recent public attention for its startling population declines. Severe reductions in monarch populations overwintering in Mexico and California have been documented over the last few decades, primarily attributed to changes in land use (Agrawal, 2019; Thogmartin et al., 2017). For instance, the monarch population that overwinters along the Pacific coast has declined by more than 99% compared to the 1980s (Pelton, Schultz, Jepsen, Black, & Crone, 2019). Similarly, another widely distributed species, the rusty patched bumble bee (*Bombus affinis*) was once common throughout the Midwest and Northeastern United States, but has declined by more than 90%—likely due to disease and pesticide use—and became the first bee in the continental United States to be protected under the Endangered Species Act.

2 | MULTIFARIOUS CAUSES OF INSECT DECLINES

Despite the great diversity of ecologies and life histories represented by insects from different regions and habitats, patterns are emerging that point to the primary drivers of insect declines. The most influential factors are habitat loss and degradation, pesticides, and climate change (Deutsch et al., 2008; Sánchez-Bayo & Wyckhuys, 2019) although other factors include disease, invasive species, and light pollution (van Langevelde et al., 2018). Each of those factors is multifaceted. The complexities of habitat destruction have been studied for years by landscape ecologists, and include not only habitat conversion but also homogenization associated with invasive plant species and fragmentation. The complexities of climate change are coming into focus, especially as they involve not only shifting mean conditions but also increasing extremes (Wagner, 2020). A recent study by Warren, Price, Graham, Forstenhaeusler, and VanDerWal (2018) modeled the distributions of multiple taxa under different climate change scenarios. With warming of 1.5°C above preindustrial levels, 6% of invertebrates were estimated to lose at least 50% of their ranges. This increased to 18% of invertebrates at 2°C and 49% of invertebrates at 3.2°C.

Although there are research gaps in our understanding of climate change impacts, it is clear that insects will need high-quality habitat, travel corridors, and stepping stone habitats to move across the landscape in search of new habitats (Black, 2018).

The associations that have been documented between stressors and insect responses point to causal relationships even though our knowledge of the mechanisms that underlie them are imperfect. For example, negative nontarget effects of pesticides are apparent on pollinator populations (Frampton & Dorne, 2007), even as the behavioral consequences of sublethal insecticide exposure on bee foraging are an area of active research (Muth & Leonard, 2019). As a consequence of imperfect knowledge, we cannot always say which stressors or interactions among stressors are more or less important in a given area or for any one species. A firing squad is a useful metaphor for the state of our knowledge, with insects facing a squad made up of those stressors discussed above. In many cases, it will be difficult to identify the killing shot, but we know the bullets are flying and we know where they are coming from (habitat destruction, climate change, etc.). Moreover, we can expect that the next insect species might by chance be hit by a bullet from a different source even though the squad remains the same. None of this is surprising given the complexity of ecological systems and the diversity of insects. In fact, the high complexity of the issue is exactly why action must begin now to mitigate the drivers of insect declines. Basic science will continue (Montgomery et al., ; Saunders, 2019), but to wait for a full understanding of all mechanisms linking drivers to declines risks losing a good number of our subjects along the way.

3 | NEED FOR ACTION

If we hope to stem the losses of insect diversity and the services insects provide, society must take steps at all levels to protect, restore, and enhance habitat for these animals across all landscapes, from wildlands to farmlands to urban cores (see Policy Recommendations section below for a summary of action items, and Table 1 for success stories in insect conservation and management). Protecting existing habitat is an essential step. Large, connected natural areas can act as reservoirs for invertebrate diversity. However, protecting existing natural areas is not enough. Approximately 40% of global land use is devoted to agriculture (Roser & Ritchie, 2019) and over 55% of people live in urban and suburban areas (United Nations, 2019). We must rethink our approach to agriculture and other working lands (Kremen & Merenlender, 2018) to reduce our reliance on insecticides and maximize biodiversity. Also roadsides, parks, urban gardens, and many other landscapes can provide important habitat for insects and other invertebrates and the large number

TABLE 1 Examples of success stories in insect conservation, organized by major categories of threat, and with citations (in the last column) to reviews or meta-analyses with additional examples for each category

Threat	Problem	Solutions	Outcomes	Additional challenges	Country of case study	Additional examples
Habitat loss and degradation	Decline in a habitat-specialist butterfly associated with agricultural intensification.	Agri-environment schemes incentivize habitat improvement (including grazing) on private lands (Brereton, Warren, Roy, & Stewart, 2008).	Population numbers of focal butterfly increase by more than $\times 3$ over approximately 20 years at study sites.	The relative importance of different lands (e.g., farms vs. reserves) merits further investigation.	UK	Habitat restoration benefits native bees (Tonietto & Larkin, 2018).
Pesticides and pollution	Agricultural practices that reduce forage and nesting opportunities for pollinators.	Organic farming with reduced herbicide and insecticide input in more heterogeneous landscapes (Carrié, Ekroos, & Smith, 2018).	Enhanced flower resources support pollinator species richness and increase spatial and temporal stability of pollinator assemblages.	Additional work is needed to parse local versus landscape-level effects on pollinators.	Sweden	Arthropods benefit from reduced pesticide use (Frampton & Dorne, 2007).
Invasive species	Riparian systems impacted by exotic plants lose functional and taxonomic diversity that can be difficult to monitor.	The government operates an invasive plant removal program; odonates monitored as bioindicators (Modiba, Joseph, Seymour, Fouché, & Foord, 2017).	Odonate functional diversity (including body size, hunting mode, etc.) is found to be higher in areas partly or completely cleared of exotics.	Cascading effects on other trophic levels likely but not quantified.	South Africa	Effects of exotic hosts on Lepidoptera behavior, development, abundance and richness (Yoon & Read, 2016).
Climate change	Insects responding to a shifting climate will need increased opportunities for dispersal and movement between habitat patches.	Active management of roadsides for wildlife through planting native vegetation and reduced herbicide use (Hopwood et al., 2015).	Abundance and species richness of pollinators increases along managed roadsides, providing landscape connectivity.	Further work is needed to understand the impact of direct mortality associated with roadside habitats.	USA	Overview of research directions related to insects and climate change (Andrew et al., 2013).

of people in cities and towns can help protect and restore these resources. Although conserving habitat in terrestrial landscapes is vital, protecting and restoring aquatic habitat is perhaps more important and urgently needed, as many of the most at-risk insect groups rely upon freshwater systems.

Insects are resilient and providing habitat for these small animals is often relatively easy compared to many vertebrate species, and the success stories highlighted in Table 1 demonstrate the value (and often rapid return on investment) to be had from habitat restoration for insects. Beyond protection and restoration of habitat, society must reduce land use stressors, including pesticides, overgrazing, and invasive species, as well as curtail the spread of diseases to insect wildlife

(Graystock et al., 2013). More pesticides are used globally than at any time in history and insects and other invertebrates are uniquely predisposed to being negatively impacted by these toxic chemicals. Better regulation and management of pesticides must therefore be a centerpiece of society's response to insect declines, focusing on reducing the availability and use of traditional classes of toxins as well as newer classes including the persistent, systemic neonicotinoids.

4 | POLICY RECOMMENDATIONS

The severity of the insect crisis demands action at many different geographic and political levels. Here, we propose

actions for a variety of societal sectors, acknowledging that implementation will vary by region and country.

4.1 | Nations, states, provinces, and cities

Governments at all levels across the globe need to promote policies that preserve and restore habitat, protect the most vulnerable insect species, reduce pesticide risk to nontarget insects, and address climate change in a meaningful way. Governments should strengthen pesticide regulations to address large-scale contamination of land, air, and water. Specifically, they should ban all use of pest control products to improve the appearance of nonagricultural green spaces such as lawns, gardens, parks, sports fields as well as for use around the home (termed cosmetic use). In Canada, Ontario and Nova Scotia have legislation that significantly reduces cosmetic pesticide exposure (Canadian Cancer Society, 2013). Retail companies should be required to clearly label pesticide products with information on how they might impact nontarget insects (Rihn & Khachatryan, 2016). Subnational policies to conserve insects (Hall & Steiner, 2019) can be enacted before national policies or international agreements are achieved. Governments must create strong incentives to protect, enhance, and restore habitat for insects. Governments can pattern incentives off of existing efforts. For instance, Iowa incentivizes the use of native plants along county and state roadsides (Hopwood, Black, & Fleury, 2016) and there are programs in the United States, Canada, and Mexico at all levels of government to incentivize conservation of monarch butterflies and a broad suite of pollinators (Commission for Environmental Cooperation, 2019). Federal, state, provincial, and local agencies that manage public lands, support conservation efforts of private landowners, or protect species should receive adequate funding, and agencies should prioritize conservation before species are on the brink of extinction (Hochkirch, 2016). In particular, there is a need to focus on water conservation and protection of natural lakes, rivers, streams, and wetlands to ensure water quality and quantity are managed for the benefit of biodiversity. Governments should embrace efforts to minimize carbon use to limit climate warming, and implement robust climate mitigation and adaptation programs to help ecosystems cope with climate changes. Climate mitigation can include promoting renewable energy and public transportation options at all levels, as well as restoring and protecting natural habitats, which efficiently sequester carbon. Climate adaptation can include restoring and protecting natural areas and habitats across all landscapes including farms and urban centers, as well as working to increase habitat connectivity (Griscom et al., 2017). These adaptation efforts can be tailored to improve conditions for a broad range of insects as well as for general biodiversity.

4.2 | Working lands

Management of farms, ranches, and forests can incorporate conservation of beneficial insect biodiversity as a goal equally important as the management of other natural resources. Society can support agricultural systems that move away from monocultures, toward a mosaic of low water use, climate friendly crops that supply both humans and animals with vital, healthy nutrition and include (as part of the farm mosaic) nectar resources to support local pollinators and other beneficial insects. Fencerow-to-fencerow farming, pesticides, and chemical fertilizers, soil degradation and the conversion of natural habitat to agriculture should be minimized or replaced by ecological intensification, regenerative farming and agroecology (Kremen & Merenlender, 2018). Specifically, farmers and other land managers need to reduce the use of insecticides, herbicides, and fungicides and adopt practices to manage pest insects using more ecologically based approaches such as Integrated Pest Management and organic methods. As part of an IPM approach, the prophylactic use of pesticides (timing of insecticide sprays that corresponds to plant, rather than pest, phenology) should be curtailed.

Farmers should be rewarded for adopting these practices with a robust set of price incentives, technical support and encouragement. The practice of rewarding environmentally degrading farming with subsidies and crop insurance should end. Food companies can prioritize use of low-input crops and the use of a higher diversity of hardy, pest-resilient plant species in manufactured food.

4.3 | Natural areas

Managers of natural areas, parks, roadsides, and rights of way should include conservation of native insect diversity as a goal for land management on sites large and small. Managers should work with university researchers, nonprofits, and community scientists to better understand the insect fauna that is found in both terrestrial and aquatic habitats. This understanding will help guide management. In general, vegetation management and restoration should maximize the diversity of native floral resources, but understanding insect communities will help maximize restoration and management potential. Grazing, fire management, mowing, invasive species removal, and recreation can all be done in a way that minimizes impacts and maximizes benefits to insect diversity. Consideration of how restoration and management of streams, rivers and wetlands will impact insects should be incorporated into planning. Managers should consider how to connect habitat across the landscape so that species can move to new areas as the climate changes (Black, 2018). Managers of natural areas can also play a crucial role in educating the public about the importance of insect diversity.

4.4 | Gardens, homes, and other private property

Even small patches of habitat are important; the many small areas available in urban and suburban yards and parks as well as parking strips could be restored and managed in such a way that they collectively benefit a great number and variety of insect species (Hall et al., 2017) and allow for movement of species across landscapes (Crone, Brown, Hodgson, Lutscher, & Schultz, 2019). Eliminating or minimizing pesticide use in these areas will help both terrestrial and aquatic insects. Purchasing food grown using organic or sustainable methods will help foster change in the agricultural sector. Advocacy is also needed to encourage governments to protect and restore parks, natural areas, and local waterbodies.

5 | CONCLUSIONS

It has not been our primary goal to argue that recent reports of insect declines do or do not represent a global phenomenon in which the many stressors of the Anthropocene are pushing insects over the edge of population viability. We agree with others who have stressed the need for greater investment in basic science and further analyses of existing data (Saunders, 2019; Thomas et al., 2019). However, it is our belief that the severity of reported insect declines is nevertheless sufficient to warrant immediate action. A simple application of the precautionary principle tells us that it is in our best interest to improve natural habitats and act for the benefit of insects. Even if further research finds that declines are not as widespread as they might appear, building more well-connected and toxin-free open areas is in the interest of all. Similarly, we can take action without understanding the complexities of all species- and region-specific drivers of decline: nontarget pesticide impacts, for example, can be minimized without understanding the diversity of physiological effects on individual species (Goulson, Nicholls, Botías, & Rotheray, 2015). Acting with imperfect knowledge is something that we all do all of the time, in our personal and professional lives, and (in the case of insect declines) it is a rational response to reductions in insect abundance and diversity. Similarly, the idea that basic science should proceed in parallel with pragmatic problem solving is not controversial. In modern medicine, for example, there are many pathologies for which mechanisms are poorly resolved, yet causal agents are sufficiently well understood that we can act to avoid the disease despite imperfect knowledge. The approach we suggest to insect declines is no different. We must act to ameliorate the drivers of declines while basic research proceeds. Along the way, basic and applied work will undoubtedly illuminate each other.

All species are worth protecting and preserving for their own sake, but the current crisis is much larger than individual species and rises to the level of losing key functions in terrestrial and aquatic ecosystems. If we do not take action now to address declines in insect abundance and diversity, we will very likely face problems, including food shortages because of pollinator limitation, that will make many previous challenges faced by human civilization seem tame by comparison. The good news is there is hope because insects are resilient and established methods in conservation biology and management can produce positive outcomes for insect populations over reasonable time scales of decades or less (Table 1).

While government and legislative action is most definitely needed (see Policy Recommendations section above), it is also the case that the actions of individual humans can have an immediate impact. Even a backyard or apartment balcony can be an important stopover for the smallest of animals upon which we all depend.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

AUTHOR CONTRIBUTIONS

All authors conceived of the initial idea for the manuscript and contributed to writing.

DATA ACCESSIBILITY

Data were not analyzed as part of this work; any numbers included in the text are taken from cited papers.

ETHICS STATEMENT

Research was not conducted that would have required approval.

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