

Entomology in the Anthropocene: Challenges and Opportunities for Insect Science: A Review

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Abstract: The Anthropocene era is marked by profound environmental transformations that are reshaping insect diversity, abundance, and distribution. Insects, which underpin critical ecosystem functions such as pollination, nutrient cycling, pest regulation, and food web stability, are experiencing unprecedented declines driven by habitat loss, climate change, pollution, invasive species, and agricultural intensification. This review synthesizes current evidence on the scope and drivers of insect declines while highlighting emerging tools and strategies to address them. Technological innovations including artificial intelligence, radar entomology, environmental DNA, and citizen science platforms are revolutionizing the scale and resolution of insect monitoring. Concurrently, policy initiatives such as the European Union's Farm to Fork Strategy demonstrate growing recognition of the need to integrate insect conservation into sustainability agendas. We argue that securing insect biodiversity in the Anthropocene requires a coordinated global framework that combines advanced monitoring, taxonomic capacity building, evidence-based policymaking, and public engagement. Such an integrated approach is essential not only for preserving insect diversity but also for safeguarding the ecological services upon which human societies depend.

Keywords: Insect decline, Anthropocene, biodiversity conservation, AI monitoring, environmental policy, entomology, ecosystem services, monitoring technology conservation.

Introduction

The Anthropocene, our current geological epoch, is defined by the profound and accelerating influence of human activity on global ecosystems. Insects, comprising the most diverse group of terrestrial animals, perform indispensable roles: pollination, decomposition, soil formation, nutrient cycling, and supporting food webs. Yet mounting empirical evidence signals widespread declines across insect communities around the world.

Recent studies provide compelling evidence of widespread insect declines globally, with potentially catastrophic consequences for ecosystems. Long-term data from various regions indicate an average 37% decline in insect species populations, with aquatic insects particularly affected [23]. Some studies report even more dramatic reductions, such as a 76% decline in insect biomass over 26 years in Germany [7]. These declines are attributed to multiple factors, including habitat loss, pesticide exposure, climate change, and agricultural intensification [7,13]. The consequences are severe, as insects play crucial roles in pollination, pest control, nutrient recycling, and as a food source for many animals [7,13]. To address this crisis, researchers recommend implementing long-term population monitoring, reducing synthetic insecticide use, preserving natural habitats, and fostering a more positive human-insect relationship [13].

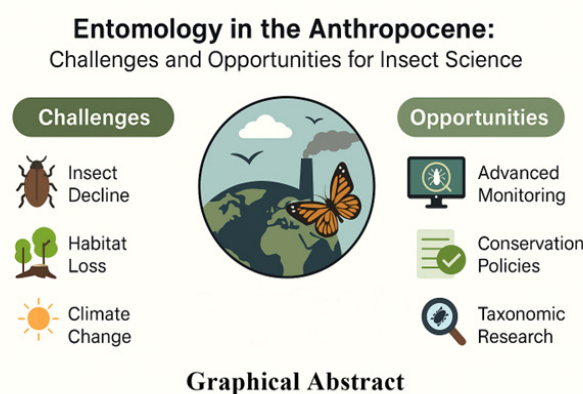


Figure 1: Entomology in the Anthropocene: Challenges and Opportunities for Insect Science.

There are concerning declines in insect populations globally, though trends vary across habitats and regions. In a study, widespread declines in flying, ground, and aquatic insects across Western and Northern Europe, North America, and the Neotropics was reported [33]. In a meta-analysis [31], it was found that terrestrial insect abundance decreased by 9% per decade, while freshwater insect populations increased by 11% per decade. However, a study [14] cautions that total abundance alone may not accurately reflect ecosystem health. A study provides further evidence of global insect declines, reporting an average 37% of species declining across major insect orders [23]. They note more pronounced changes in aquatic communities, with 42% of species declining.

Worldwide alarming declines in insect populations across various regions have been observed. In Germany, a 27-year study reported a 76% decrease in flying insect biomass across protected areas, regardless of habitat type [10]. This decline is corroborated by other research, with some studies estimating reductions of 75-98% over 35 years in Puerto Rico. The causes are likely multifaceted, including habitat loss, pesticide exposure, and climate change [7]. Temperature plays a significant role, with insect biomass generally increasing with monthly temperature, except during extremely hot summer months. Land cover type also influences insect abundance and phenology, with grasslands harboring higher biomass [35]. These declines have far-reaching consequences for ecosystems, as insects are crucial for pollination, pest control, and as a food source for many species [7,32]. These studies emphasize the urgent need for comprehensive monitoring efforts to better understand the extent and causes of insect population changes [33,31].

Evidence of Insect Declines

Long-term Biomass Loss

In a landmark 27-year study in Germany, documented alarming declines in flying insect biomass. The study found a 76% seasonal decline and an 82% mid-summer drop in flying insect biomass across 63 protected areas [10]. A follow-up study confirmed that insect biomass remained at low levels in 2020-2021, with no significant recovery observed [20]. Land cover heterogeneity was identified as a key factor influencing insect biomass and diversity, with low-vegetation habitats supporting higher richness of pollinators and threatened species [27]. Temperature also plays a crucial role, with insect biomass generally increasing with monthly temperature. However, this relationship becomes negative during exceptionally hot summer months [35]. These findings highlight the urgent need for improved protection and management of diverse habitats, particularly unforested areas, to sustain insect biodiversity in the face of ongoing environmental changes.

Shrinking in Protected Areas Worldwide

Observations from Costa Rica's Guanacaste Reserves revealed dramatic declines in insect populations, including an 83% reduction in beetles over 45 years and a 60-fold decline in Puerto Rico, signaling pervasive trends even in nominally intact ecosystems [15]. These trends are attributed to climate change, habitat loss, and pesticide exposure. The consequences of insect decline are severe, as they are crucial for ecosystem functioning, serving as food for various species and performing vital roles like pollination and nutrient recycling [7]. Despite the importance of insects, there are significant gaps in research on their conservation within protected areas, with most studies focusing on species representation rather than threat assessment or management effectiveness [4].

Global Synthesis

A comprehensive review indicates, particularly well-documented in Western and Northern Europe, with reports of up to 76% reduction in flying insect biomass over 27 years in protected areas [10]. Similar trends are emerging worldwide, including North America, Asia, and the Neotropics [33].

The causes of these declines are multifaceted, including habitat destruction, agricultural intensification, climate change, and invasive species [33]. While the extent and magnitude of insect declines are not fully understood, the available evidence is sufficient to warrant immediate action to protect insect biodiversity [19]. Researchers emphasize the need for comprehensive monitoring efforts across ecological gradients to identify causal factors and develop effective conservation strategies [33,6].

Driving Forces behind Decline

Agricultural Intensification

Agricultural intensification and landscape simplification have been linked to insect decline and increased insecticide use, though the relationship is complex. Landscape structure changes, including grassland management intensification and shifts in arable land use, are identified as significant factors in insect decline [8]. Butterfly communities, particularly specialist species, are negatively impacted by intense conventional agriculture and benefit from extensively managed grasslands [9]. Some studies have found a positive correlation between landscape simplification and insecticide use [18]. However, this relationship is not consistent across years, with varying effects observed in different time periods [16]. The impact of agricultural intensification on insect populations and pesticide use appears to be context-dependent, influenced by factors such as crop type, landscape composition, and temporal variations. These findings highlight the need for multiyear studies and targeted land management strategies to address insect decline and promote sustainable agriculture.

Climate Disruption

Experts in tropical reserves emphasize that climate change, especially extended dry seasons and disrupted ecological cues, has become a dominant force in insect collapse. In Costa Rica, long-term observations reveal a gradual decrease in insect species richness and density since the late 1970s, with climate change identified as the primary driver [15]. Similarly, research in Puerto Rico's Luquillo rainforest found a 10 to 60-fold reduction in arthropod biomass over 30 years, coinciding with a 2.0°C rise in forest temperatures [17]. These declines are not isolated, with reports of insect losses from Europe, North America, and elsewhere [33]. Factors contributing to this "insect apocalypse" include habitat destruction, agricultural intensification, pesticide use, and climate change [7]. The consequences of these declines are severe, as insects play crucial roles in ecosystem functioning, including pollination, pest control, and nutrient recycling. Their loss could lead to the collapse of terrestrial and freshwater ecosystems [7].

Monitoring and Expertise Gaps

The decline in taxonomic expertise, particularly in entomology, poses significant challenges for biodiversity monitoring and conservation. Global disparities exist, with expertise concentrated in economically rich countries while biodiversity hotspots lack sufficient specialists [21,22]. This "taxonomic impediment" is exacerbated by funding disparities, infrastructure deficits, and socio-economic factors in the Global South [22]. In Europe, efforts to profile taxonomists and assess expertise gaps have revealed the need for prioritizing taxonomy in biodiversity conservation [5]. The synergy between professional and amateur taxonomists is crucial for entomological research but faces challenges including declining numbers of specialists and financial resources [1]. To address these issues, strategies such as community engagement, global collaborations, and integration of diverse disciplines are proposed to enhance monitoring capacity and foster sustainable insect biodiversity research [22].

Emerging Opportunities

Advanced Monitoring Technologies

Technological advances are transforming insect monitoring and ecology. Deep learning models like Insect Net can accurately identify over 2,500 insect species using citizen science imagery, offering potential for early detection of invasive species [3]. Low-cost, multisensory systems such as Insects combine cameras, optical sensors, and environmental data for AI-based insect classification [28]. Computer vision and deep learning enable efficient, continuous, and non-invasive entomological observations, providing estimates of insect abundance, biomass, and diversity [12]. Emerging technologies like computer vision, acoustic monitoring, radar, and molecular methods are revolutionizing insect ecology and monitoring, offering unprecedented possibilities for studying these diverse animals [30]. However, challenges remain, including the need for validation of image-based identification, generation of sufficient training data, and development of public reference databases [12].

Policy Momentum and Awareness

Recent studies highlighting insect declines have garnered significant media attention, leading to concerns about an "insect apocalypse" [24,26]. However, researchers caution against overgeneralization, noting geographical and taxonomic limitations in existing data [24]. Despite these constraints, evidence suggests widespread insect declines pose a global risk to ecosystem functions, including pollination, pest control, and nutrient cycling [29]. The scientific community emphasizes the need for immediate action, proposing policy measures to address factors contributing to insect losses [6].

Current conservation efforts are deemed insufficient, with calls for increased research, monitoring, and international cooperation [29]. Experts advocate for a balanced approach in science communication to maintain public support for insect conservation while acknowledging the complexity of the issue [24,26].

Future Directions & Recommendations

To mitigate ongoing insect declines and their ecological consequences, a multi-faceted approach combining advanced monitoring, policy reform, and interdisciplinary collaboration is essential.

Below are Key Focus Areas and Actionable Recommendations Supported by Recent Research

Focus Area	Recommended Actions	Supporting Evidence
Monitoring Expansion	Deploy tech-aided, long-term insect surveillance globally, especially in underrepresented regions (e.g., tropics, Global South).	The gaps in tropical insect data; remote sensing can help [34].
Technology Integration	Use AI, radar (e.g., entomological lidar), and sensor networks for real-time, large-scale monitoring.	About 98.7% accuracy in stored product insect ID using optimized YOLOv5 models was observed [2]
Policy Engagement	Advocate for policies that tie insect conservation to ecosystem services (e.g., EU’s Farm to Fork Strategy).	Analysis of legal frameworks for sustainable food systems [25]
Interdisciplinary Collaboration	Integrate entomology with climate science, agriculture, and public health to address cascading impacts.	The study demonstrated 42% improvement in prediction accuracy when combining disciplines [36]
Capacity Building	Reverse the decline in taxonomic expertise through education, funding, and citizen science programs.	The study quantified the loss of taxonomists [11]

Conclusions

The Anthropocene has brought unprecedented challenges for insect science, as rapid environmental change drives widespread declines in insect diversity, abundance, and distribution. Yet, it has also created unparalleled opportunities for innovation in research, monitoring, and conservation. Harnessing advances in artificial intelligence, remote sensing, molecular ecology, and citizen science can transform how we understand and safeguard insect populations. At the same time, embedding entomological knowledge into global sustainability policies while strengthening taxonomic expertise and long-term surveillance will be critical to mitigating biodiversity loss. Insects are the foundation of terrestrial ecosystems; protecting them in the Anthropocene is not just a scientific priority but an ecological necessity.

References

1. Audisio, P., 2017. Insect taxonomy, biodiversity research and the new taxonomic impediments. *Fragmenta entomologica*, 49(2), pp.121-124.

2. Badgujar, C.M., Armstrong, P.R., Gerken, A.R., Pordesimo, L.O. and Campbell, J.F., 2023. Real-time stored product insect detection and identification using deep learning: System integration and extensibility to mobile platforms. *Journal of Stored Products Research*, 104, p.102196.

3. Chiranjeevi, S., Sadaati, M., Deng, Z.K., Koushik, J., Jubery, T.Z., Mueller, D., Neal, M.E., Merchant, N., Singh, A., Singh, A.K. and Sarkar, S., 2023. Deep learning powered real-time identification of insects using citizen science data. *arXiv preprint arXiv:2306.02507*.

4. Chowdhury, S., Jennions, M.D., Zalucki, M.P., Maron, M., Watson, J.E. and Fuller, R.A., 2023. Protected areas and the future of insect conservation. *Trends in Ecology & Evolution*, 38(1), pp.85-95.

5. De Nolf, M., Meeus, S., Fichtmueller, D., Lundin, K., Tilley, L. and Groom, Q., 2023. European taxonomists in profile: a data-driven approach. *Biodiversity Information Science and Standards*, 7, p.e111534.

6. Forister, M.L., Pelton, E.M. and Black, S.H., 2019. Declines in insect abundance and diversity: We know enough to act now. *Conservation Science and Practice*, 1(8), p.e80.

7. Goulson, D., 2019. The insect apocalypse, and why it matters. *Current Biology*, 29(19), pp. R967-R971.

8. Grevé, M.E., Marx, M.T., Eilmus, S., Ernst, M., Herrmann, J.D., Baden, C.U. and Maus, C., 2024. Insect Decline—Evaluation of Potential Drivers of a Complex Phenomenon. *Insects*, 15(12), p.1021.
9. Habel, J.C., Ulrich, W., Biburger, N., Seibold, S. and Schmitt, T., 2019. Agricultural intensification drives butterfly decline. *Insect Conservation and Diversity*, 12(4), pp.289-295.
10. Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T. and Goulson, D., 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PloS one*, 12(10), p.e0185809.
11. Hopkins, G.W. and Freckleton, R.P., 2002, August. Declines in the numbers of amateur and professional taxonomists: implications for conservation. In *Animal conservation forum* (Vol. 5, No. 3, pp. 245-249). Cambridge University Press.
12. Høy, T.T., Årje, J., Bjerger, K., Hansen, O.L., Iosifidis, A., Leese, F., Mann, H.M., Meissner, K., Melvad, C. and Raitoharju, J., 2021. Deep learning and computer vision will transform entomology. *Proceedings of the National Academy of Sciences*, 118(2), p.e2002545117.
13. Jactel, H., Imler, J.L., Lambrechts, L., Failloux, A.B., Lebreton, J.D., Le Maho, Y., Duplessy, J.C., Cossart, P. and Grandcolas, P., 2020. Insect decline: immediate action is needed. *Comptes Rendus. Biologies*, 343(3), pp.267-293.
14. Jähnig, S.C., Baranov, V., Altermatt, F., Cranston, P., Friedrichs-Manthey, M., Geist, J., He, F., Heino, J., Hering, D., Hölker, F. and Jourdan, J., 2021. Revisiting global trends in freshwater insect biodiversity. *Wiley Interdisciplinary Reviews: Water*, 8(2), p.e1506.
15. Janzen, D.H. and Hallwachs, W., 2021. To us insectometers, it is clear that insect decline in our Costa Rican tropics is real, so let's be kind to the survivors. *Proceedings of the National Academy of Sciences*, 118(2), p.e2002546117.
16. Larsen, A.E., 2013. Agricultural landscape simplification does not consistently drive insecticide use. *Proceedings of the National Academy of Sciences*, 110(38), pp.15330-15335.
17. Lister, B.C. and Garcia, A., 2018. Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences*, 115(44), pp. E10397-E10406.
18. Meehan, T.D., Werling, B.P., Landis, D.A. and Gratton, C., 2011. Agricultural landscape simplification and insecticide use in the Midwestern United States. *Proceedings of the National Academy of Sciences*, 108(28), pp.11500-11505.
19. Montgomery, G.A., Dunn, R.R., Fox, R., Jongejans, E., Leather, S.R., Saunders, M.E., Shortall, C.R., Tingley, M.W. and Wagner, D.L., 2020. Is the insect apocalypse upon us? How to find out. *Biological conservation*, 241, p.108327.
20. Mühlethaler, R., Köthe, S., Hörren, T., Sorg, M., Eichler, L. and Lehmann, G.U., 2024. No recovery in the biomass of flying insects over the last decade in German nature protected areas. *Ecology and Evolution*, 14(3), p.e11182.
21. Rodrigues, A.S., Gray, C.L., Crowter, B.J., Ewers, R.M., Stuart, S.N., Whitten, T. and Manica, A., 2010. A global assessment of amphibian taxonomic effort and expertise. *BioScience*, 60(10), pp.798-806.
22. Sánchez Herrera, M., Forero, D., Calor, A.R., Romero, G.Q., Riyaz, M., Callisto, M., de Oliveira Roque, F., Elme-Tumpay, A., Khan, M.K., Justino de Faria, A.P. and Pires, M.M., 2024. Systematic challenges and opportunities in insect monitoring: a Global South perspective. *Philosophical Transactions of the Royal Society B*, 379(1904), p.20230102.
23. Sánchez-Bayo, F. and Wyckhuys, K.A., 2021. Further evidence for a global decline of the entomofauna. *Austral Entomology*, 60(1), pp.9-26.
24. Saunders, M.E., Janes, J.K. and O'Hanlon, J.C., 2020. Moving on from the insect apocalypse narrative: engaging with evidence-based insect conservation. *BioScience*, 70(1), pp.80-89.
25. Schebesta, H., Bernaz, N., Macchi, C., Zuniga, F.R., Nsour, M.F., Ali, A.N.M.A. and Solaiman, S.M., 2021. The European Union Farm to Fork Strategy: Sustainability and Responsible 420 Business in the Food Supply Chain.
26. Simmons, B.I., Balmford, A., Bladon, A.J., Christie, A.P., De Palma, A., Dicks, L.V., Gallego-Zamorano, J., Johnston, A., Martin, P.A., Purvis, A. and Rocha, R., 2019. Worldwide insect declines: An important message but interpret with caution. *Ecology and evolution*, 9(7), pp.3678-3680.
27. Sinclair, J.S., Buchner, D., Gessner, M.O., Müller, J., Pauls, S.U., Stoll, S., Welti, E.A., Bässler, C., Buse, J., Dziok, F. and Enss, J., 2024. Effects of land cover and protected areas on flying insect diversity. *Conservation Biology*, p.e14425.
28. Tschakner, M., Brandt, D., Schmidt, H., Bießmann, F., Chiaburu, T., Schrimpf, I., Schrimpf, T., Stadel, A., Haußer, F. and Beckers, I., 2023, October. Multisensor data fusion for automatized insect monitoring (KInsecta). In *Remote Sensing for Agriculture, Ecosystems, and Hydrology XXV* (Vol. 12727, p. 1272702). SPIE.

29. Van Der Sluijs, J.P., 2020. Insect decline, an emerging global environmental risk. *Current opinion in environmental sustainability*, 46, pp.39-42.
30. Van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., Høye, T.T., Jongejans, E., Menz, M.H., Miraldo, A. and Roslin, T., 2022. Emerging technologies revolutionise insect ecology and monitoring. *Trends in ecology & evolution*, 37(10), pp.872-885.
31. Van Klink, R., Bowler, D.E., Gongalsky, K.B., Swengel, A.B., Gentile, A. and Chase, J.M., 2020. Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*, 368(6489), pp.417-420.
32. Vogel, Gretchen., 2017. Where have all the insects gone?: 576-579.
33. Wagner, D.L., 2020. Insect declines in the Anthropocene. *Annual review of entomology*, 65(1), pp.457-480.
34. Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R. and Stopak, D., 2021. Insects decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences*, 118(2), p.e2023989118.
35. Welti, E.A., Zajicek, P., Frenzel, M., Ayasse, M., Bornholdt, T., Buse, J., Classen, A., Dziöck, F., Engelmann, R.A., Englmeier, J. and Fellendorf, M., 2022. Temperature drives variation in flying insect biomass across a German malaise trap network. *Insect Conservation and Diversity*, 15(2), pp.168-180.
36. Young, S.L., Goldowsky-Dill, N.W., Muhammad, J. and Epstein, M.M., 2019. Connecting experts in the agricultural and meteorological sciences to advance knowledge of pest management in a changing climate. *Science of The Total Environment*, 673, pp.694-698.