

The role of insects in sustainable agriculture and integrated PEST management

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Abstract: Insects occupy a paradoxical position in agricultural systems, functioning simultaneously as some of agriculture's most damaging pests and as indispensable allies in crop production. Focusing on their incorporation into Integrated Pest Management (IPM) systems, this research delves into the many ways in which insects contribute to sustainable agriculture. Beneficial insects contribute to pollination, biological pest control, soil health, and nutrient cycling, while harmful species necessitate careful management strategies that minimize ecological disruption. The paper explores how IPM, as a holistic and ecologically informed approach, leverages insect biology and behavior to reduce dependency on synthetic pesticides, lower production costs, and preserve biodiversity. Through an analysis of pollinator services, natural enemy dynamics, IPM components, and emerging technologies, this paper argues that the strategic understanding and conservation of insect populations is fundamental to achieving long-term agricultural sustainability and food security.

Keywords: paradoxical, pollination, ecological disruption, Integrated Pest Management (IPM)

1. INTRODUCTION

Agriculture has historically been shaped by a complex and evolving relationship with the insect world. For much of the twentieth century, agricultural policy and practice treated insects predominantly as adversaries—organisms to be eradicated through increasingly potent chemical interventions. In recent decades, however, a more nuanced understanding has emerged, recognizing that insects are not monolithically harmful but instead represent a vast and diverse group of organisms, many of which provide essential services to agricultural productivity. Because of their roles in pollination, pest control, and nutrient cycling, insects play an important role in both human and environmental health, and they provide a wide range of services to ecosystems, including providing, regulating, supporting, and cultural functions. (Tonelli, Youngsteadt, & Frank, 2022). This recognition has given rise to sustainable agricultural paradigms that seek to work with insect ecology rather than against it, most notably embodied in Integrated Pest Management.

The term "sustainable agriculture" encompasses a wide range of agricultural methods that aim to provide for current social and food demands without jeopardising future generations' capacity to do the same. Insects' functions within this system go much beyond their common perception as nuisances. Consideration of the hazards connected with insect usage and management should be part of any comprehensive knowledge of the socio-ecological functions of insects, according to recent theoretical work. These functions include provisioning, regulation, support, and cultural services. (Barragán-Fonseca et al., 2025). The term "sustainable agriculture" encompasses a wide range of agricultural methods that aim to provide for current social and food demands without jeopardising future generations' capacity to do the same. Understanding and harnessing these ecological services is central to reducing the agricultural sector's reliance on synthetic inputs and to building resilient farming systems.

Integrated Pest Management represents the operational framework through which this ecological understanding is translated into practice. The foundational publication that introduced this approach, "The Integrated Control Concept," described in detail the fundamental ideas of integrated control along with the concepts of economic injury levels and economic thresholds that continue to underpin pest management decision-making today (Stern, Smith, van den Bosch, & Hagen, 1959). To manage pest populations in a way that minimises harm to human health, non-target organisms, and the environment, integrated pest management (IPM) integrates multiple complementary strategies, including biological, cultural, mechanical, and chemical approaches. This approach is guided by ecological knowledge and economic thresholds, rather than relying on a single control method (Tudi et al., 2024). This paper delves into the paradoxical nature of insects as both a problem and a solution in agricultural systems, how beneficial insects contribute to sustainability, and how integrated pest management (IPM) principles and practices help farmers control pest populations wisely while protecting beneficial insect biodiversity.

2. INSECTS AS POLLINATORS: FOUNDATIONS OF CROP PRODUCTIVITY

One of the most important things that insects do for agriculture, both commercially and environmentally speaking, is pollinate plants. Insect pollination plays a key role in the reproduction of both wild and domesticated plants, and roughly seventy percent of flowering plant species rely on insect pollinators, a substantial proportion of which are directly involved in agricultural production (Khalifa et al., 2021). One of the most important things that insects

do for agriculture, both commercially and environmentally speaking, is pollinate plants, and pollinators additionally support broader ecosystem functions such as biodiversity maintenance, erosion prevention, and improved water quality (U.S. Fish & Wildlife Service, n.d.). Although honeybees are not native to the United States, they are said to have contributed as much as \$5.4 billion to agricultural production. Other natural pollinators, such as bumblebees, butterflies, moths, and ants, are also important for pollinating crops nationwide (U.S. Fish & Wildlife Service, n.d.).

In addition to its social significance and manageability, the honeybee (*Apis mellifera*) is highly regarded as a bioindicator of environmental contaminants like pesticide residues, heavy metals, and airborne particulate matter. As a result, it continues to be the most extensively managed pollinator species. (Tonelli et al., 2022). However, an increasing body of research has highlighted the importance of wild and native pollinators, which often provide pollination services that are equal to or more effective than those of managed honeybees for certain crops, and whose diversity in foraging behavior and climatic tolerance buffers pollination services against the loss or decline of any single species. Furthermore, studies have shown that crops reliant on pollinators benefit from insect pollination because it increases production stability between growing seasons, underscoring the resilience benefits that diverse pollinator communities confer on agricultural production (Garibaldi et al., 2021, as cited in EcoEvoRxiv review).

The decline of pollinator populations represents one of the most pressing threats to sustainable agriculture in the contemporary era. Long-term monitoring in protected areas has documented declines exceeding seventy-five percent in total flying insect biomass over a 27-year period, a finding that has alarmed both the scientific community and the public regarding the broader trajectory of insect biodiversity loss (Hallmann et al., 2017, as cited in EcoEvoRxiv review). Such declines pose a direct threat to the ecosystem services that insects provide, including pollination (Dangles & Casas, 2019, as cited in EcoEvoRxiv review). Sustainable agricultural practices that support pollinator health—such as reducing pesticide use during bloom periods, maintaining floral diversity, and preserving semi-natural habitat patches within and around farmland—are therefore essential components of long-term agricultural resilience, illustrating how insect conservation and agricultural productivity are mutually reinforcing rather than competing objectives.

3. BIOLOGICAL CONTROL: NATURAL ENEMIES AS AGENTS OF PEST SUPPRESSION

Beyond pollination, insects contribute to agricultural sustainability through their role as natural enemies of crop pests. Biological control can be defined as the decline in pest density resulting from the presence of natural enemies, a category that includes predators, parasitoids, pathogens, and competitors, all of which suppress pest populations through different mechanisms such as predation, parasitism, and disease transmission (Pacific Northwest Pest Management Handbooks, 2015). This form of pest regulation is not a modern invention but an ancient ecological process: natural enemies have preyed upon and parasitized insect pests for hundreds of millions of years, shaping ecological interactions across terrestrial habitats long before human intervention (Naranjo & Ellsworth, 2009, as cited in *Frontiers in Agronomy*, 2025).

Three supplementary approaches are often used to preserve and improve natural enemy populations. The goal of conservation biological control is to improve agricultural conditions by, for example, increasing biodiversity in natural habitats, judicious and selective pesticide use, and reduced disturbance—to support existing populations of natural enemies already present in the landscape, and represents the primary mechanism through which biological control is successfully sustained in most agricultural systems (University of California IPM Program, n.d.). Periodic releases of mass-reared natural enemies, either inoculative to build a population or inundative for fast, are used in augmentative biological control, short-term suppression, and has been successfully applied against numerous pests in both open-field and greenhouse cropping systems (Pijnakker et al., 2020). The first of the three methods is classical biological management, which has been around the longest. It entails bringing predatory ladybird beetles and other natural enemies of pests to new areas in order to keep them in check. *Rodolia cardinalis* in the early 20th century to rein in the cottony cushion scale, a citrus pest that had made its way to Mediterranean Europe by mistake. (Greathead, 1976, as cited in Bale, van Lenteren, & Bigler, 2008).

The economic and ecological advantages of biological control are considerable, though they require careful management of natural enemy populations to be realized. Field studies have demonstrated that flowering field margins and other conservation measures can support natural enemy populations effective enough to reduce pest densities tenfold or even a

hundredfold, enabling participating farmers to reduce insecticide applications by seventy percent while simultaneously increasing yields by approximately five percent (Wikipedia contributors, 2023, citing field-margin research). The importance of biological control often becomes most visible when it fails: broad-spectrum, residual pesticides that persist for days or weeks frequently cause secondary pest outbreaks or pest resurgence precisely because they eliminate the natural enemies that would otherwise have kept those secondary pests in check (University of California IPM Program, n.d.). This dynamic illustrates why the conservation of natural enemy populations is treated as a foundational, rather than supplementary, component of Integrated Pest Management.

4. INTEGRATED PEST MANAGEMENT: PRINCIPLES AND COMPONENTS

The ecological and economic problems with chemical-intensive pest management that was based on a calendar came to light in the middle of the twentieth century, leading to the rise of Integrated Pest Management. After some initial discussion between Smith and Allen in 1954, the notion of integrated control was explicitly developed in a 1959 study that established the economic harm level and economic threshold as the core ideas of the field. (Stern et al., 1959, as cited in Wikipedia contributors, 2023). The economic injury level, when the cost of damage surpasses the cost of management, is defined as the population density at which control actions must be undertaken to prevent an expanding pest population from crossing the economic threshold. (Seiter, 2018). This threshold-based logic replaced reflexive, schedule-based pesticide application with a more deliberate, monitoring-based approach in which an insect control action is only justified once a pest population reaches a level where intervention is economically warranted, since, as one analysis notes, It would be irresponsible to treat a whole field with pesticide only because one bug was detected. (Seiter, 2018).

Cultural control practices form a foundational component of IPM, encompassing modifications to farming practices that make the agricultural environment less favorable to pest establishment. IPM frameworks classify management responses into three broad categories: a "do-nothing" approach when pest populations remain below the economic or aesthetic threshold; a "reduce-numbers" approach implemented through pesticides, natural enemy releases, or cultural practices once the threshold is reached; and a "reduce-susceptibility" approach that modifies the host plant or ecosystem itself to raise the threshold at which damage becomes economically significant (Utah State University Extension, 2023).

These practices, while often requiring greater planning and management complexity than monoculture systems, provide durable and low-cost suppression of pest populations.

Biological control, as discussed in the preceding section, is typically prioritized within IPM frameworks as a first line of defense, with farm management practices designed to conserve and enhance natural enemy populations before resorting to other interventions. Microbial control agents, including entomopathogenic fungi, bacteria, viruses, and nematodes, offer additional biologically based tools that target specific pest species while leaving beneficial insects largely unaffected (Tudi et al., 2024). Chemical control remains a component of IPM, but its application is fundamentally reconceived relative to conventional pest management: insecticides are applied only after regular monitoring indicates that a pest population has reached the economic threshold, and are selected and timed to be as compatible as possible with ongoing biological control efforts, since the term "integrated" in the original 1959 framework was conceived as synonymous with "compatible" (Wikipedia contributors, 2023). In order to reduce the negative impact on the environment caused by chemical treatments without sacrificing their effectiveness, IPM programs are increasingly using newer formulation technologies including controlled-release pesticide formulations and nanoemulsions. (Tudi et al., 2024).

5. MONITORING, IDENTIFICATION, AND DECISION SUPPORT IN IPM

Because Integrated Pest Management is based on educated, threshold-based decision-making instead of reflexive action, accurate and timely monitoring of pest and beneficial insect populations is crucially important for its successful implementation. The crop, the biology of the pest, the economic toleration of damage, and the larger management context are all elements that must be considered when determining the action threshold for a certain pest. (Seiter, 2018). IPM programs require correct identification of the insect or pest in question and careful consideration of relevant biological factors before a control or no-control decision can be made, and they combine multiple management approaches for greater overall effectiveness (West Coast Nut, 2025).

Comprehensive IPM reviews emphasize that the discipline's economic, environmental, and social dimensions are interdependent: successful adoption depends not only on technical monitoring tools but also on participatory approaches and effective knowledge exchange among farmers, extension agents, and researchers (Tudi et al., 2024). Case studies across

diverse agroecological contexts have demonstrated that well-implemented IPM programs can simultaneously promote biodiversity conservation, ensure food safety, and maintain crop protection efficacy, though widespread adoption continues to require transdisciplinary research, capacity building, and supportive policy frameworks (Tudi et al., 2024). This underscores that monitoring and decision support in IPM are not purely technical exercises but are embedded within broader systems of farmer education and institutional support.

6. INSECTS, SOIL HEALTH, AND NUTRIENT CYCLING

Insects play an important part in nutrient cycling and soil health beyond their functions as pollinators and pest suppressors. The dung beetle is a prime example of an organism that plays an important role in ecosystem engineering; it burys cattle faeces, which in turn drives extensive nutrient cycling, with controlled studies showing that dung beetle activity increases soil concentrations of potassium, phosphorus, and nitrogen relative to manure left undisturbed on the surface (Sannino et al., 2024). In addition to enriching nutrients, dung beetles speed up the breakdown of dung deposits and transfer nutrients from the topsoil to the bottomsoil. In semiarid pasture systems, studies have shown that tunnelling species can increase organic matter, total nitrogen, and phosphorus in the soil profile by up to 50%. (Maldonado et al., 2019, as cited in Torabian, 2024).

The activity of dung beetles also delivers benefits that extend beyond soil chemistry into pasture management more broadly. Their tunneling behavior increases the soil's capacity to absorb and retain water, with some studies recording up to a threefold increase in water infiltration rates as a result of beetle activity, which in turn improves hydrological functioning and supports plant productivity (Keller et al., 2022, as cited in Torabian, 2024). Because cattle tend to avoid grazing near dung piles, manure accumulation can reduce usable pasture acreage by five to ten percent; by rapidly burying and processing this waste, dung beetles significantly enhance grazing efficiency while simultaneously reducing populations of dung-breeding flies and parasites that would otherwise persist in undisturbed manure (ATTRA Sustainable Agriculture Program, n.d.). Maintaining and enhancing the diversity of dung beetle communities is therefore recognized as a key element of sustainable pasture management, illustrating how soil-dwelling insects, though often overlooked relative to pollinators and predators, are equally integral to the ecological foundations of sustainable agriculture (Sannino et al., 2024).

7. CHALLENGES AND TRADE-OFFS IN INSECT-BASED SUSTAINABLE AGRICULTURE

Despite the considerable promise of insect-centered approaches to sustainable agriculture, several challenges complicate their implementation. Knowledge gaps in ecological interactions, the costs of habitat management and augmentative releases, and ongoing environmental pressures like pesticide exposure and habitat loss erode beneficial insect populations despite efforts to conserve them are the constraints on effectively integrating beneficial insects into farming systems. (Patel, 2025, *Journal of Experimental Agriculture International*). Sustainable practices such as crop rotation and intercropping can help increase habitat heterogeneity and support beneficial insect diversity. Other strategies to address these constraints include establishing flower strips and hedgerows, pursuing conservation biological control, and augmentatively releasing natural enemies (Patel, 2025).

A further structural challenge is the frequent disconnect between insect conservation efforts and agricultural or food policy, because environmental authorities often develop conservation programs independently of agricultural activity; as a result, protected habitat for pollinators may exist immediately adjacent to cropland that continues to rely on intensive agrochemical use, limiting the practical conservation benefit of such measures (Barragán-Fonseca et al., 2025). Furthermore, scientists have warned that conservation efforts often overlook less apparent but functionally important taxa, such as parasitoid wasps, decomposers, and dung beetles, despite the fact that these organisms play an essential role in agroecosystems. (Barragán-Fonseca et al., 2025). Classical biological control introductions, while historically responsible for notable successes, are also subject to increasing scrutiny, because native species that aren't intended targets run the danger of suffering adverse impacts from intentionally introduced non-native natural enemies, requiring rigorous risk assessment before implementation (Follett & Duan, 2012, as cited in Gurr, Wratten, Landis, & You, 2017).

8. FUTURE DIRECTIONS AND CONCLUSION

The future of insect-based sustainable agriculture and Integrated Pest Management lies in the continued integration of ecological knowledge with technological and institutional innovation. Emerging formulation technologies in pesticide delivery, participatory extension models, and a growing conceptual emphasis on the full range of socio-ecological roles that insects play—provisioning, regulating, supporting, and cultural—suggest that future frameworks will

increasingly treat insect conservation and agricultural productivity as complementary rather than competing goals (Tudi et al., 2024; Barragán-Fonseca et al., 2025). Continued research into pest–natural enemy population dynamics, pollinator decline, and the under-recognized contributions of soil-dwelling insects such as dung beetles will further refine the tools available for sustainable pest management and ecosystem service provision.

In conclusion, insects occupy a position of profound importance within agricultural systems, serving simultaneously as agents of crop damage and as indispensable contributors to pollination, pest suppression, and soil health. The recognition of this dual role has catalyzed the development of Integrated Pest Management as a holistic, ecologically grounded framework for agricultural pest control, one that prioritizes the conservation and strategic deployment of beneficial insect populations over reflexive chemical intervention. As global agriculture confronts the intersecting challenges of food security, biodiversity loss, and climate change, the strategic understanding and management of insect populations will remain central to the pursuit of sustainable, resilient, and productive farming systems.

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