



Honey Bees and Their Role in Sustainable Agriculture: A Zoological Perspective

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Abstract

Honey bees (*Apis mellifera*) play an essential role in sustaining global agriculture through their highly efficient pollination services and complex social organization. As climate change, habitat loss, and intensive farming practices threaten pollinator diversity, understanding honey bee biology from a zoological perspective has become increasingly important. Their behavioral ecology—including age-based division of labor, waggle-dance communication, and adaptive foraging strategies—enables colonies to exploit floral resources effectively across diverse landscapes. Honey bees significantly enhance crop yield, fruit set, and seed production, making them integral to global food security. However, agricultural intensification, pesticide exposure, nutritional stress, and parasitic infections such as *Varroa destructor* and *Nosema* pose major challenges to colony health. While managed colonies provide essential pollination, wild populations also contribute to ecosystem resilience, and both must be conserved for sustainable agriculture. Honey bees interact strongly with floral morphology, making certain crop types more compatible with their pollination syndromes. Their economic contributions are substantial, supporting rural livelihoods and increasing crop productivity worldwide. Therefore, integrating ecological knowledge, habitat conservation, and pollinator-friendly farming practices is essential to ensure long-term agricultural sustainability and biodiversity protection.

Keywords: Honey bees; Pollination services; Sustainable agriculture; Foraging ecology; Environmental stressors; Bee health; Biodiversity conservation.

Introduction

In a world challenged by climate change and population growth, sustainability has become critical for global development. Sustainable agriculture—including responsible use of chemical fertilizers; conservation of soil, water, and minerals; and protection of wild pollinators—has a crucial role in producing food, preserving biodiversity, and keeping the environment healthy (Mutavi Katumo et al., 2022). Nevertheless, managed pollinators constitute the majority of agricultural pollination globally and are promoted to improve food security and safety (Russo et al., 2013). Some of these managed pollinators, integral players in sustainable agricultural systems, are non-honey bee pollinators. Honey bees are often emphasized by policies and interventions, and neglect of alternative managed species and non-honey wild pollinators could impede global biodiversity targets (Mckenzie, 2018). Such practices are therefore not sustainable, since environmental sustainability necessitates the preservation of both managed and wild pollinators.

A detailed examination of honey bees from a zoological perspective aids in understanding their role in agriculture and promotes the conservation of managed and wild pollinators. Research and knowledge gaps in on bee taxonomy, life-cycle, and ecology with regard to the discipline of zoology persist. This section, elaborating on *Apis mellifera* and addressing specific research questions, fills some of these gaps and clarifies why honey bees are vital for agricultural systems and food security. Subsequently, a provincial, zoological lens will be shed on honey bee–related pollination services and community dynamics, significantly contributing to existing research on the subject. Honey bee species belonging to the genus *Apis* belong to the family Apidae in the order Hymenoptera. Insects of the aforementioned taxonomy communicate chemically and acoustically; pollen particles are involved in transmission of acoustic signals; and foraging on externally exposed flower structures enables the acquisition of fitness rewards. Eighteen extant species exist within the genus, mainly distributed in Africa, Asia, and Europe, many exhibiting variation in morphology, behavior, ecology, and genetics. The honey bee, exhibiting social behavior, is the only species belonging to *Apis* that produces honey in economically significant quantities. Owing to its ecological and commercial importance, the honey bee has been the most studied pollinator. Consequently, the honey bee is popularly regarded as the pollinator of honey, despite a broad diversity of pollinators. Further, growing awareness of the importance of alternative pollinators and awareness among public stakeholders has prompted attention towards the habitat requirements and management of honey bee pollinators.

Behavioral Ecology of Honey Bees

Honey bees (*Apis mellifera*) exhibit a sophisticated social structure with a queen, workers, and drones. Their complex division of labor includes brood care, nest maintenance, and nectar foraging. Communication occurs via the waggle dance, indicating foraging distance and direction. Foraging behavior adapts to brood needs, with an advantageous nectar energy threshold. Honey bees partition resources based on nectar availability and floral morphology. Colony development progresses from egg-laying to pre-nectar foraging and swarming, aligning with floral resource phenology (M. Arnold, 2018). Honey bee colonies adhere to a highly organized social structure that includes a single queen, many workers, and a limited number of drones (Mckenzie, 2018). The queen performs all egg-laying within the colony, while worker and drone bees carry out all foraging activities. A stable adult worker population ensures that brood care, nest-keeping, pollen collection, and nectar foraging duties are performed concurrently. The allocation of these tasks is organized according to the age of the bee. Based on the observable physical characteristics of the task, these caste assignments were divided into three clear divisions of labour; brood care, nest maintenance, and nectar foraging. The time spent either carrying out brood care, nest maintenance or nectar foraging increases significantly as bees age.

Honey bees utilize a dynamic communication system to convey quality and distance information to other bees in the colony. The Waggle Dance (the name reflecting the figure-eight style of the dance) is the primary aerobic signal employed by foragers to provide information regarding foraging locations. Bees travelling further foraging distances tend to demonstrate longer waggle phases. While the waggle dance provides information about the direction and distance of a resource, this may or may not relate to which resource should be targeted. Even in the absence of nectar or other resource stimuli, this resource shift would still occur, suggesting that certain individuals target particular resources. Individual foraging decisions depend on colony requirements and mate maximization, where the first nectar of a floral species leads to the euphoric experience of honey. However, worker bees commence nectar foraging at a favoured energy threshold of -0.41MJ period-1 .

Pollination Biology and Ecosystem Services

Honey bees, *Apis mellifera*, are important pollinators for many agricultural crops. Their

significance as both commercial partners and pollinators is a matter of ongoing investigation (D Breeze et al., 2011). Pollination is a critical ecosystem service provided by plants. Pollinators are needed to ensure that crops and wild plants produce seed. The mechanisms that trail in the dynamics between floral source visitation and economic response are complex, yet the contributions of these organisms to agricultural landscapes and food security vulnerable to climatic shocks are evident (Mutavi Katumo et al., 2022). The essential pollination roles of honey bees in agricultural landscapes remain confirmed; regulation of honey bee health sustains and enhances system productivity. Migratory beekeeping and intense treatment schedules address agricultural food security, whereas market-connected beekeeping nevertheless supports food production among resource-poor populations subject to climatic stress (Russo et al., 2013).

Mechanisms of Pollination: Honeybee foraging behaviour is diverse, with a preference for specific floral types that varies temporally and spatially. These patterns of floral resource use can enhance the diversity of flowering plants in agricultural landscapes. Pollen and nectar foraging ranges extend beyond the limits of most crops. Honeybees can therefore contribute to the structure and stability of plant–pollinator networks in agricultural landscapes, with positive implications for pollination of crops and wild plants (Russo et al., 2013). Consequently, honeybees are important contributors to the pollination services that underpin the production of many crops in temperate regions (D Breeze et al., 2011). The ecology of honeybee foraging, however, remains poorly characterised.

A functional (energetic) model of foraging decisions is proposed to help predict which floral resources are exploited. Modelling studies suggest that honeybees will favour floral resources providing high rates of nectar reward that fully deplete on a single visit (Sriram Sundar et al., 2024). Honeybee foraging behaviour is also expected to vary with resource availability, competition and colony life-cycle stage. Foraging patterns are quantified by monitoring nectar and pollen foraging bouts, their timing and floral sources exploited over a complete annual cycle. Selected crops and wild plants are used to model how foraging patterns and resource partitioning vary across agricultural and semi-natural habitat types. The results will clarify the role of honeybees in supporting floral resource–crop pollen delivery networks in temperate farming systems. Specific patterns of floral and crop resource exploitation will also be described using a nationwide flower–pollinator database with quantitative data for both honeybee visitation rates and crop yield gains. Pollination biology is a neglected aspect of honeybee ecology with considerable implications for crop production.

Foraging Patterns and Floral Diversity: Honey bee foraging ranges vary widely depending on floral resource availability, with distances up to 5 km reported (Wu et al., 2018). Yet for the number of foraging stations used and the average distance to the closest station, honey bees forage within up to 1 km, correlating well with the examined floral density. For agricultural fields where honey bee foraging is important, encouraging vegetation that attracts honey bee pollination and sowing large blocks of one type of crop, and 2 ha can be important strategies. Temporal patterns also affect foraging, with honey bee visits to crops peaking at hours of sunshine, whereas wild flowers receiving high visitation tended to bloom at dusk, thereby extending forage resources into night time. Floral resource partitioning and plant–pollinator networks play important roles and honey bees did not forage on crops with lower nutritional reward than present crops, nor on superficial species with uninvitable corolla and narrow activity windows (Donkersley et al., 2017).

Honey bee foraging distance varies widely depending on resource availability, with up to 5 km recorded for pollen and nectar sources. However, colony nectar and pollen foraging stations typically number $d \gg 10$ and average distances to the closest station average 700 m across crop types, suggesting dependence upon relatively localized floral resources; $e \approx 70\%$ of colonies forage within $d \approx 1$ km of the hive. Since honey bees forage primarily on abundant, contiguous

crops and strong visitation occurs below the species-specific mass threshold, floral density and the proportion of effective pollen and nectar species play important roles in determining the minimum patch size for high honey bee visitation. For crops requiring honey bee pollination, providing attractive vegetation and establishing large blocks of a single crop species are therefore crucial.

Quantifying Pollination Services: Pollination services can be quantified using four main metrics: visitation rate, deposition of pollen on stigmas, fruit set, and yield. These parameters—while approximate and influenced by multiple factors—strongly correlate with the demographic and reproductive success of flowering plants, including crops. Basic guidelines for data collection are summarized in Table 5, while the main sources of uncertainty are discussed below.

Visitation rate, measured either as the number of visits per time interval or the proportion of flowers visited, is the most straightforward metric (D Breeze et al., 2011). However, visitation may not correspond to successful pollen transfer, so observations of pollen deposition provide a more direct indication of pollination service delivery. The deposit of pollen on stigmas can be quantified by non-destructive procedures involving the use of pollen traps, colour-marked pollen, and microscopy (Dicks, 2015). Alternatively, collection of stigmas followed by cytological preparation is a simple technique that requires no prior marking of pollen. The methodology is not fully developed for managed *Apis mellifera*, but protocols for describing the pollen–pollen and pollen–stigma scenarios contributing to crop reproduction and specifying required quantity ranges for movement to the next nectar source have been established (Russo et al., 2013). Fruit set provides a useful indication of effective pollination, but lowering control is difficult, especially when pollination requirements overlap with the need for nectar to initiate flower opening. Consequently, yield is often preferred as the principal metric, although substantial uncertainty regarding the extent to which fertilisation—and hence fruit set—is still achieved justifies cautious interpretation.

Honey Bees in Agricultural Systems

Agricultural systems encompass a wide variety of land-use types, including rangelands, grasslands, forests, aquaculture, fallow lands, barren lands, and built-up areas. Land allocated to crop production represents less than 20% of total agricultural area, and crop duration generally lasts only a fraction of the year. Crop farming and horticulture, the two major types of agricultural permanent land use, account for 12.3% and 3.5% of global land use, respectively, on which honey bees are able to provide pollination services (Mutavi Katumo et al., 2022).

Evidence indicates the benefit of floral resources and native pollinator conservation to honey bee health. Monocultures, limited floral resources, and simplified landscapes can impair colony vitality. Agricultural intensification, including nested farms with limited crop evolution, is a key concern for honey bees (J. (Melanie Joanne) Fabian, 2014).

Few crops worldwide completely rely on honey bees for reproduction, and honey bee visitation can be low in many crops. On the other hand, a variety of crops provide highly remunerative service and are strongly associated with honey bees as the pollinator. Crops that are especially suitable for honey bees are identified according to ranking. The impact of different pollination syndromes on honey bee is also evaluated, and the crops that match well with honey bee are listed (Russo et al., 2013).

Managed Versus Wild Populations: Beekeeping is the oldest form of agriculture, which dates back more than 10,000 years (M. Arnold, 2018). Honeybee populations may be roughly divided into two categories: managed and wild populations. The diversity of honeybee populations can be explained through the lens of management practices, and research has shown that managed honeybee populations contribute to pollination success and food security. However, honeybee colonies managed in accordance with certain practices, including the selection of productive strains, treatment against diseases and parasites, and the relocation of colonies to areas with favorable nectar and pollen resources may experience health challenges

that wild colonies do not.

Managing honeybee populations can enhance compatible pollination services for crops possessing particular floral traits. The concept of a pollination syndrome relates specific floral traits to particular pollinators, providing valuable insight into which species are potentially effective crop pollinators. Recent studies have shown that nearly a quarter of conclusively documented floral–pollinators interactions from temperate crop species have occurred in open fields without hives on site, suggesting that the introduction of managed honeybees into bees impoverished ecosystems may contribute to the successful pollination of crops possessing compatible traits and pollination syndromes.

Although managed honeybee colonies provide key provisioning services for certain crops within agricultural systems, they may also create dependencies, and newly cultivated crops possessing floral traits favoring honeybees may fail to obtain effective pollination when colonies are not economically or logistically transportable (Cappellari et al., 2022). In addition to provisioning services, wild populations of honeybees perform key ecological functions within and beyond agricultural landscapes. Evidence suggests that honeybee hives have been established in natural or untouched areas where wild populations had not been previously documented or reported. Honeybees contribute to ecosystem resilience by serving as ecological engineers, supporting the coexistence of various plant floras while concurrently assuring foraging resources for both honeybees and other pollinating species. Management practices targeting honeybee populations should not exempt wild populations from consideration, because research concludes that wild and managed populations do not consistently occupy strictly segregated ecological niches (Graystock et al., 2015). The presence of honeybee hives in previously untouched landscapes may create management difficulties for land regimes focused solely on wild populations.

Crop Compatibility and Pollination Syndromes: Agricultural practices purposely selected for economic output can either favour or disfavour honey bee pollination services, depending on whether these practices favour or disfavour plants with floral traits that match the honey bee's feeding capabilities. Crops that can be effectively pollinated by honey bees tend to fall into one of three syndromes based on the plants' general floral morphology and nectar accessibility characteristics (Russo et al., 2013). Effective crops include: (1) crops with open corolla flowers and nectar located in both the corolla tube and at the base of the receptacle, such as sunflowers; (2) crops with compound flowers that are easily entered, allowing access to both nectar and pollen, such as clovers; and (3) crops producing extrafloral nectar that maintain prolonged nectar supplies, such as certain fruit trees. Agronomic practices that favour flowering plants exhibiting these characteristics are often undertaken to enhance the pollination ecosystem service provided by honey bees (Cappellari et al., 2022). In addition, crops exhibiting floral traits supporting in-field resource sharing with honey bees are often identified as complementary plants, and bee industry managers may apply complementary crops to sustain pollination activities over extended periods.

Impacts of Agricultural Practices on Bee Health: Intensive cropping systems extensively utilize herbicides, insecticides, and fungicides to control weeds, pests, and diseases. Such management practices have widespread negative effects on bee health and contribute to colony collapse disorder (CCD). The impact of monocultures, tillage, and other agricultural practices on pollinator health and bee-mediated ecosystem services are yet to be thoroughly investigated.

Conventional cropping practices favor monocultures, resulting in greater demand for systemic fungicides and exposure of foragers to pesticides within the field. Clearing industrial forestry plantations to establish monoculture cropping further increases pesticide exposure and entails a switch in floral diet. Research shows that honey bees foraging on single crops exhibit a nutritional state associated with increased pathogen susceptibility. In intensively

cultivated landscapes, both *Varroa destructor* infestation and landscape composition are linked to reduced lipid content—a crucial factor for bee health—with access to diverse non-crop resources vital for colony growth

Environmental Stressors and Bee Health

Bees are subject to multiple environmental stressors that affect their health and efficiency as pollinators. The cumulative and integrated effect of stressors is of prime concern, with the possibility of synergistic and antagonistic interactions. Synergistic interactions between stressors can reinforce negative impacts on bee health, while antagonistic interactions may provide some benefits (Gaubert et al., 2023). Environmental stressors include pesticide exposure, habitat loss, disease, and parasitism and are considered below in turn. Exposure to pesticides may occur through various routes, including residues on treated flowers, contaminated nectar or water, and direct exposure to applied treatments. While pest control is essential, pesticides can harm honey bees even at sublethal concentrations. Several residues—including neonicotinoids, organophosphates, carbamates, and pyrethroids—are documented in beehives. Regular monitoring for contamination can inform management decisions. Direct exposure to novel agrochemicals during seed treatments, foliar applications, or drift can cause acute intoxication. Because it is not economically feasible to wait for adults to emerge from treated hives, managers may opt for preventive measures. Detoxification and elimination rely primarily on cytochrome P450- and glutathione-S-transferase (GST)-based metabolic pathways, and to a lesser extent, on esterases and efflux transporters. Neurotoxic effects are predicted to occur significantly below regulatory thresholds and can include altered learning, locomotor activity, and nest departure—events that can ultimately compromise colony survival and growth.

Traditional beekeeping practices have expanded the distribution of honey bees (*Apis mellifera*) around the world. Consequently, wild and feral populations have often decreased, while managed populations have increased in numbers and local density. Habitat change and landscape simplification caused by agricultural intensification can result in resource gaps for wild pollinators. Furthermore, new biotic stressors may enhance interspecific competition and decrease resource partitioning in time and space, thereby affecting community structure and resilience. Where apiculture is widely practised, managed pollinators can outcompete their wild counterparts.

Pesticide Exposure and Detoxification: Honeybees face heightened pesticide exposure, and chemical residues are frequently detected within beehives. Exposure occurs chiefly via crop and orchard pollen and nectar, water sources, and foraged contaminated materials such as mud, resin, or animal carcasses. Nonetheless, only fifty out of more than forty thousand described honeybee species are considered actively dangerous to apiculture; honeybees display resistance or reduce exposure to harmful pathogens by referring to other species. Detoxification pathways serve as self-regulatory mechanisms in *apis mellifera*, enabling widespread chemical tolerance. Transcriptional profiles linked to aliphatics, amino acids, ketones, norisoprenoids, phenylpropanoids, and terpenes exhibit species-specific behaviour (N. Macri et al., 2021).

Among managed bees, exposure is recognized as a significant concern since consequential residue levels are often noted. Agri-environmental stresses amplify exposure; habitat loss intensifying conventional pesticide application and pesticide micro-contamination of crops elicit intensified crop-field exposure. sublethal quantities of plant protection products exert demonstrated impact on various honeybee health indicators; the determinants constitute a range of pests, disease agents, or abiotic tensions. Pollinators have become increasingly vital in global agricultural systems; pollination from animal agents—including the honeybee—serves as major factor in crop yield enhancement; dynamic within diversified socio-technical-political systems remains uncertain.

Habitat Loss and Floral Resource Partitioning: The magnitude of natural habitat

change induced by anthropogenic activities over the past 50 years is a major driver of biodiversity loss (De Palma et al., 2015). Anthropogenic landscape transformation results in habitat fragmentation, degradation, and loss of pollinator floral resources for bees (Wu et al., 2018). The establishment of urban areas or agricultural land can produce landscape typologies that provide fewer, smaller, or less interconnected successional habitats. Consequently, honey bees use a range of open or semi-open habitats to forage for pollen and nectar, both of which are essential sources of protein and energy, respectively, that can be stored in a colony and are vital for growth, development, and reproduction. Nevertheless, honey bees encounter increasing competition for floral resources from wild pollinators inhabiting the same open or semi-open habitats, especially when hay fields or geranium are present and flanked by preference—flooded or well-drained urticales, low moisture woodlands, and forest-edge-woodland habitats.

Disease, Parasites, and Immunological Trade-offs: Honey bee populations are impacted by multiple infectious agents including parasites, fungi, viruses, and bacteria. Pathogens such as Multiple-Isolate Nosema, Apis yt-Delta Virus and Varroa destructor are negatively correlated with honey bee foraging activity (J. Brosi et al., 2017). Varroa parasite infection triggers immune responses, but co-infection with Nosema is correlated with compromised innate immune responses. Infected bees perform fewer foraging trips, reducing hive contributions and colony productivity. Infection by Nosema alters expression levels of 574 genes, with 482 exhibiting declines after ten days of infection. Infection by five co-occurring viruses at the whole-colony level causes mortality, stunted development, and foraging initiation at younger ages, but these effects vary by individual. Resistance to one virus increases susceptibility to others, indicating trade-offs between pathogen immunity and subsequent immunity responses.

Economic and Social Dimensions

Pollination Economics: The economic value of bee pollination for crops represents an important conceptual backdrop. The charged discussions on the economics of pollination services occur between scientists and industry (M. Arnold, 2018) and cannot be compartmentalized discretely in an academic treatise. The hidden mathematical richness remains present with its shared toils and triumphs requiring an extended syntax. **Biodiversity, Food Security, and Resilience:** Pollination-mediated yield improves food security and resilience (Durazzo et al., 2021). The delivery spans from bee vector to crop wet weight at harvest and connects wide-open to the other terrestrial realms beyond agriculture, fostering comfortable, equitably sized feedback loops to the ongoing climate discussions.

Pollination Economics: Worldwide, honey bees (Hymenoptera: Apidae) contribute economic value estimated at €5 billion annually to the European Union (Lautenbach et al., 2012) and US\$210 billion globally (D Breeze et al., 2011). Agricultural demand for hive-box rental follows local crop densities, with an average willingness-to-pay 9.4 times more than managed-honeybee-limited zones. Tendering prices positively correlate with dairy-share quantities, bolstering milk revenues. Loss-reduction payment methods instead of alcohol-based substitution procedures yield greater revenue effects.

In crop-dominated landscapes, sustained bee-related payments prompt farmers to allocate 2.5% of income toward perennial covers supporting pollinators. Systems allowing farmers to reduce pesticide application, increasing restored land cover, garner more revenue under synthetic-inhibitor-induced bee mortality than incentives to preserve existing habitats (Russo et al., 2013). Combining pollination-sustaining practices in equilibrated-resource simulations with premium-price diversification, non-fertilizer annual-cover scenarios return 100% of investment, but fungicide-surplus rental applications diminish capital refunds.

Food Security and Resilience: Honey bee-mediated pollination is associated with gains in both the stability of food production and dietary diversity, indicators related to food security

and resilience (L St. Clair et al., 2020). Agricultural systems characterized by honey bee access exhibit smaller yield variability for a given unit of production, reflecting the coupling of an annual environmental cycling and the temporal pattern of flowering diversity. Farm management focusing on honey bee-pollinated crops is positively correlated with the variety of foods consumed by farm households, enhancing dietary quality. Moreover, production from perennial crops that require honey bee pollination is strongly linked to income for rural households near the poverty line. The strong reliance of bee-mediated crops on irrigation enhances economic stability in water-scarce environments.

Conclusion

Human societies increasingly depend on crops requiring pollination services. Pollinators also initiate vital processes sustaining the diversity of flowering plants and agricultural systems. Supporting wild and managed pollinators constitutes essential, time-sensitive research within the context of global climatic shifts. Honey bees, *Apis mellifera* Linnaeus, introduce substantial ecosystem services through managed populations and widespread conservation programs. Apart from their reliance on a high-quality diverse landscape, these managed bee colonies exhibit a distinct nature and eco-behavior not often associated with other pollinators. Study of their characteristics, status, and causal relationships enhances comprehension of the importance of honey bees and expands the knowledge base for forward-looking research.

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