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Pollinator Evolution in Response to Agricultural Practices: Insights from Bee Populations

Jia Xing, Xueyan Chen
Tropical Animal Resources Research Center, Hainan Institute of Tropical Agricultural Resources (HITAR), Sanya, 572025, Hainan, China
Corresponding author: xueyan.chen@hitar.org
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Abstract This study analyzes how modern agricultural practices drive adaptive evolution of honey bee populations in terms of genomic detoxification ability, foraging behavior, and population genetic structure. The study found that long-term pesticide exposure may prompt honey bees to evolve detoxification gene mutations to improve survival, while crop monoculture forces honey bees to adjust their foraging strategies or behavioral rhythms to cope with the nutritional pressure brought about by resource homogeneity. Large-scale landscape changes and habitat fragmentation reduce the genetic diversity of honey bees and aggravate local population isolation. In addition, pathogen spillover and genetic disturbance caused by commercial beekeeping activities also have a negative impact on wild bees. To mitigate the adverse effects of agricultural practices on honey bee evolution, this study discusses strategies such as reducing pesticide use, enriching farmland landscape diversity, and promoting diversified agricultural systems. It also looks forward to future research directions, including the use of genomics technology to monitor honey bee adaptive changes and the importance of integrating pollinator protection concepts in agricultural management. This study aims to deepen the understanding of the evolutionary adaptation of honey bee populations in agricultural ecosystems and provide a reference for the formulation of pollinator protection and sustainable agricultural management strategies.
Keywords Bees; Pollinators; Agricultural practices; Evolutionary adaptation; Genetic diversity; Ecological management

1 Introduction

Pollinators provide indispensable ecological services for agricultural production. Many major food and cash crops in the world rely on insect pollination to improve yield and quality (Katumo et al., 2022; Reilly et al., 2024). Pollinators such as bees promote crop fruiting through pollination, so that about 75% of global crop yields benefit from animal pollination to varying degrees. Studies have shown that when pollination services are insufficient, the yield of some crops will be limited, which has been confirmed in the United States and other places. Not only crops, but also the reproduction of wild plants is highly dependent on the activities of pollinators. The presence of pollinators maintains the plant diversity and function of many ecosystems. Therefore, pollinators are known as the key functional group of agricultural ecosystems, and their diversity and abundance directly affect food production and ecological balance.

However, in recent years, many parts of the world have reported a decline in the population of pollinating insects, which has raised concerns about agricultural production and ecological stability. In particular, as the main pollinator, the health of bees is closely related to food security. Ensuring the diversity and function of pollinators is of key significance to maintaining the sustainability of agricultural ecosystems. Honey bees (including farmed honey bees and wild solitary bees, bumble bees, etc.) are particularly important among many pollinating insects and are often used as model organisms to study pollination ecology and evolution (Hristov et al., 2020; Osterman et al., 2021). On the one hand, the Western honey bee (*Apis mellifera*) is a widely raised pollinating insect worldwide and has been introduced to various places to provide pollination services for a variety of economic crops. Due to its easy breeding and management and significant pollination benefits, honey bees have become the focus of attention when studying agricultural pollination issues. On the other hand, honey bees have complex social behaviors and navigation and foraging abilities, which are unique in behavioral ecology and evolutionary biology research (Quigley et al., 2019; Papa et al., 2022).

Honey bees are highly efficient in spreading pollen, maintaining plant mating and genetic communication, and their pollination behavior and efficiency are often used as one of the indicators for evaluating ecosystem health and agricultural productivity. In addition, the bee genome has been sequenced and its genetic mechanisms have been studied in depth, making bees an ideal model for studying how environmental stresses (such as pesticides) drive evolutionary changes in insects. Because bees are sensitive to environmental changes and easy to monitor, their population dynamics can reflect the status of agricultural ecosystems. Therefore, using bees as model pollinators to explore the impact of agricultural practices on pollinators is not only of theoretical significance, but also helps to provide reference for other pollinating species (Requier et al., 2022).

This study aims to summarize the research progress on agricultural practices driving bee evolutionary adaptation in recent years, outline the key driving factors in agricultural practices that may affect pollinator evolution, discuss the role of bees in agricultural ecosystems and the current problems they face, focus on the ecological and genetic mechanisms of agricultural practices driving bees to produce evolutionary responses, and analyze the impact of pesticides, organic agriculture and genetically modified crops on the adaptive evolution of bees through specific cases. This study will also explore how to mitigate the adverse effects of agricultural practices on bee populations through management and protection strategies, and look forward to future research trends in the field of bee evolutionary adaptation and agricultural practices. This study hopes to deepen the understanding of the relationship between agricultural practices and pollinator evolutionary dynamics, and provide necessary guidance for agricultural policy making and pollinator conservation.

2 Key Evolutionary Drivers in Agricultural Practices

2.1 Pesticide use pressure

Chemicals such as insecticides, fungicides and herbicides widely used in modern agriculture not only directly cause poisoning and death of pollinators such as bees, but also have hidden effects at sublethal doses, weakening their immunity, navigation and reproductive capabilities (Nicholson et al., 2023; Kita et al., 2024). For example, neonicotinoid insecticides are widely used in seed coating and plant protection due to their high efficiency and broad spectrum, but studies have found that they have strong toxicity and behavioral interference effects on bees, which can lead to impaired learning and memory, decreased disease resistance and abnormal foraging behavior. This type of chronic stress will have a selective effect on the population: resistant individuals may be relatively dominant in the population, thereby promoting changes in the frequency of detoxification-related genes.

Experiments by Tsvetkov et al. (2023) have shown that the survival rate of honey bee workers after acute chlorfenapyr exposure is about 38% genetically inherited, and some detoxification genes (such as the CYP9Q family) in surviving bees carry specific mutations that can effectively metabolize pesticides. This finding means that pesticide application is acting as a selection factor for the bee population, with sensitive individuals being eliminated and tolerant individuals relatively increasing, thereby causing changes in the genome composition of the population. In addition to the genetic level, pesticide pressure may also induce behavioral adaptation, such as bees changing their foraging time to avoid the peak of pesticide application, or preferring non-treated flower sources.

2.2 Crop monoculture and resource homogenization

Crop monoculture and large-scale intensive farming in agricultural landscapes have led to the homogenization of flower sources and nutritional resources available to pollinators. Large areas of monoculture (such as rapeseed, sunflower, etc.) provide a large amount of single pollen and nectar during the flowering period, but "food deserts" often appear after the flowering period, which puts pollinating insects under the pressure of resource scarcity. Studies have shown that when the nectar source is single and the nutrition is unbalanced, bees have a shorter lifespan, lower immunity, and are more susceptible to pathogens (Branchiccela et al., 2019). This provides a selection advantage for individual bees with stronger nutrient utilization efficiency or stress resistance.

Some bee populations may adapt to long-term single-flower source environments by changing their demand for specific nutrients in pollen or improving their nectar storage capacity. Pollinators specializing in specific crops may prosper. Pope et al. (2023) analyzed the genome of the North American pumpkin bee (Eucera pruinosa) and found that the widespread cultivation of pumpkins and other cucurbit crops by humans has significantly changed the evolutionary trajectory of this pollinator in the last thousand years: the pumpkin bee population has expanded rapidly, and chemical perception-related selection sweeps have appeared in the genome, which is presumably the result of adapting to the single floral fragrance environment of crops.

2.3 Habitat fragmentation and landscape change

Agricultural reclamation and urban expansion have led to the fragmentation of pollinator habitats, with habitat patches separated by farmland and artificial landscapes. This change in landscape scale has a significant impact on the gene flow and genetic structure of bee populations (Panziera et al., 2022). When habitat fragmentation is severe, bee populations are often confined to smaller habitat patches, and individual communication between populations is hindered, which in turn leads to inbreeding and decreased genetic diversity in local populations.

From the perspective of genetic evolution, when the landscape hinders gene flow, each isolated population may evolve independently under the action of natural selection and genetic drift, leading to genetic differentiation. Espregueira Themudo et al. (2020) analyzed the genome of European honey bees and found that under the influence of human activities in the last century, the nucleotide diversity of its two major lineages (Western European M lineage and Central European C lineage) was significantly reduced, and some functional genes (such as the royal jelly protein gene family) showed signs of selection, which may be related to the genetic homogenization caused by the introduction and breeding of beekeeping.

2.4 Commercial beekeeping and population genetic disturbance

Commercial beekeeping has a dual impact on bees and other pollinators: on the one hand, it improves crop pollination, but on the other hand, it may also disrupt the genetic structure and health of wild populations. Large-scale mobile beekeeping and cross-regional transportation of bee colonies have broken the original geographical isolation of bee populations and mixed the genetic backgrounds of bees from different regions. This artificial introduction and hybridization may lead to a reduction in the genetic purity of local bee subspecies or strains, and the unique adaptive genome is diluted by foreign genes. For example, after the introduction of excellent varieties such as Italian honey bees and Carniola honey bees, the native black bees (*Apis mellifera mellifera*) in many parts of Europe have undergone extensive hybridization, and the genetic characteristics of local bee species have gradually been lost (O’Neal et al., 2018).

In addition, commercial beekeeping generally adopts artificial breeding, tending to select high honey production and docile traits, resulting in a relatively narrow genetic base for queen bees used in the global beekeeping industry. Over time, the genetic diversity of farmed bee colonies will decrease, which not only increases the vulnerability of bees to diseases and environmental changes, but also further reduces the diversity of wild populations through intermarriage with wild bees. On the other hand, commercial beekeeping may also affect wild pollinators through the spread of pathogens (Belsky and Joshi, 2019). Bees raised in high density in beehives often carry pathogens such as viruses and fungi. Mobile beekeeping can cause these pathogens to spread between regions and spill over to infect wild bees and bumblebees.

3 The Importance of Bees in Agricultural Ecosystems and the Problems They Face

3.1 The ecological role of bees as pollinators

Bees have irreplaceable ecological functions in agricultural ecosystems. As pollinators, bees help a large number of crops complete the pollination process, improve the fruit set rate and fruit quality. Research statistics show that bees contribute a considerable proportion of crops that mainly rely on animal pollination. For example, in field trials of economic crops such as fruits, nuts, and oilseeds, bee pollination can increase yields by more than 20% to 50%. The efficient foraging behavior of bees enables them to visit many flowers in a short period of time, promote the transfer of pollen between different flowers or plants of the same plant, and thus increase the fruit set rate and fruit size of crop seeds (Gazzea et al., 2023). Bees promote plant fruiting through pollination, which not only benefits vegetation renewal, but also provides food resources for other fruit-eating and seed-eating animals.

Therefore, bee pollination forms a key link in maintaining the structure and function of the ecosystem. When bee populations decline, it often leads to limited plant reproduction and changes in species coexistence, and ecosystem functions may be weakened (Jarpla et al., 2024; Puvača and Brkić, 2024).

3.2 Current threats to global bee populations

In recent decades, reports of bee population declines and colony losses have occurred frequently around the world, indicating that bees are facing multiple environmental threats. The harm of pesticides, especially neurotoxic insecticides, to bee health has attracted widespread attention. Field experiments and laboratory studies have confirmed that exposure to pesticides such as neonicotinoids can cause abnormal bee behavior, shortened lifespan, and reduced fertility. The reduction and degradation of pollination habitats are also an important reason for the decline of bees. With the development of agricultural intensification and urbanization, the landscape structure of traditional farmland has been simplified, large-scale monoculture and herbicide use have made wildflower resources scarce, and the nutrition sources and nesting sites of bees have been limited. Surveys show that in areas with fragmented landscapes and poor flower resources, bee colonies are significantly weaker and their overwintering survival rates are also reduced (Branchiccela et al., 2019).

In addition, pests and pathogens pose a serious threat to bee populations. The most notorious of these is the Varroa destructor parasite and the viruses it carries. Microsporidia (such as Nosema) and a variety of RNA viruses also threaten bee health, often synergizing with other factors under malnutrition or pesticide pressure. The stress brought by climate change is also beginning to emerge. Climate warming and seasonal disruptions may cause a mismatch between plant flowering and bee activity, resulting in a shortage of nectar sources or the inability to collect high-quality pollen. Soroye et al. (2020) analyzed more than 100 years of data and found that bumblebee species in North America and Europe have experienced a significant contraction in their habitat range, which is closely related to the increased frequency of extreme high temperature events.

3.3 Changes in the ecological environment of bees due to agricultural practices

While modern agricultural practices have increased production, they have also profoundly changed the ecological environment on which bees depend for survival. High-intensity pesticide use creates an environment full of chemical risks for bees. Pesticide residues on flowers, polluted water sources and soil may all become ways for bees to be exposed to pesticides. Motta et al. (2022) showed that after bees were exposed to glyphosate, the expression of antimicrobial peptide genes in their bodies decreased and the melanization reaction of body fluids was inhibited, indicating that glyphosate can induce innate immune disorders in bees (Figure 1).

The homogenization of farmland structure has changed the nutrition and habitat pattern of bees. Traditional agricultural landscapes include a mixture of cultivated land, woodland and semi-natural habitats, providing bees with a continuous source of food and nests. Intensive agriculture is often a large area of homogeneous land, lacking flowering wild plants and nesting sites. It is difficult for bees to find sufficient and diverse pollen outside the flowering period of crops, resulting in a single nutrition, which in turn affects their reproduction and immunity (Branchiccela et al., 2019).

Modern commercial beekeeping methods themselves have also changed the living environment of bees. For example, frequent honey collection and sugar feeding to increase honey production will affect the bee colony's regulation of nutrition; long-distance migration pollination keeps bees in a state of constant stress and prone to disease outbreaks. In addition, around high-density apiaries, large-scale feeding by honey bees may lead to competition with wild pollinators, reducing the latter's food source (Grozinger and Flenniken, 2019; Willcox et al., 2023).

4 Ecological and Genetic Mechanisms of Agricultural Practices Driving Bee Evolution

4.1 Evolutionary impact mechanisms of pesticide use

The impact of pesticides on bee populations is not only reflected in individual toxicity, but also in the physiological and genetic adaptation of bees through selection pressure. The evolutionary response of bees to pesticides mainly involves detoxification metabolism, resistance behavior and population genetic structure. At the level of detoxification metabolism, bees have a complex detoxification enzyme system, including P450 enzymes, carboxylesterases and glutathione-S-transferases, etc., which are used to decompose foreign toxins. At the level of detoxification metabolism, bees have a complex detoxification enzyme system, including P450 enzymes, carboxylesterases and glutathione-S-transferases, etc., which are used to decompose foreign toxins. However, there are variations in the sequence of CYP9Q enzymes between different bee populations, which can affect the binding efficiency of the enzymes and pesticide molecules, thereby causing differences in tolerance. Tsvetkov et al. (2023) found that surviving bees often carry specific non-synonymous mutations in the CYP9Q1 and CYP9Q3 genes, which increase the enzyme's affinity and metabolic capacity for chlorothiazide, enabling bees to detoxify lethal doses of pesticides.

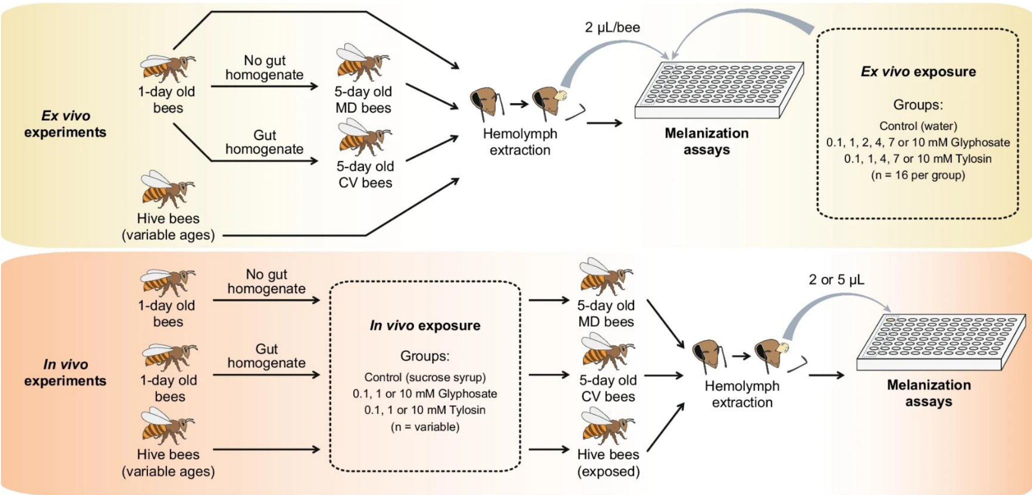

Figure 1 Glyphosate induces immune dysregulation in honey bees (Adopted from Motta et al., 2022)

Image caption: Ex vivo and in vivo experiments to investigate the effects of glyphosate and tylosin on melanization in honey bees. Ex vivo experiments were performed with 1-day old bees, 5-day old bees lacking or containing a normal microbiota, and hive bees; 2 μL of hemolymph were extracted from individual bees and used along with variable concentrations of glyphosate or tylosin (0, 0.1, 1, 2, 4, 7 or 10 mM) in melanization assays. In vivo experiments were performed with 5-day old bees lacking or containing a normal microbiota and hive bees previously exposed to different concentrations of glyphosate or tylosin (0, 0.1, 1 or 10 mM) for 5 days. 2 μL or 5 μL of hemolymph were extracted from exposed bees and used in melanization assays; MD microbiota-defective, CV conventional microbiota (Adopted from Motta et al., 2022)

In terms of behavior and physiology, bees may also evolve adaptive strategies to pesticide pressure. From a population perspective, the selective effect of pesticides on bees may lead to the death of a large number of sensitive individuals, thereby reducing the effective size and genetic diversity of the population, and even forming a population bottleneck of resistance. In a highly pesticide-applied environment, if only a few resistant individuals survive and reproduce, the gene pool of the offspring will be dominated by resistance alleles, showing a tendency towards genetic uniformity. However, this evolution of resistance usually takes a long time and intergenerational accumulation. In species with a long lifespan and relatively low reproduction rate such as bees, the speed of population evolution to pesticide resistance is limited. When pesticide pressure is too strong, the evolutionary response often cannot keep up with the rate of population decline.

4.2 Monoculture system and evolutionary adaptation of bee foraging strategy

Monoculture system significantly changes the foraging environment of bees, which may drive evolutionary adjustments in their foraging behavior and strategy. In a natural environment with high diversity, bees have developed flexible foraging patterns: worker bees communicate the location of multiple flower sources through "dance language" and can selectively collect pollen from different plants with complementary nutrition to meet the comprehensive nutritional needs of the bee colony (Branchiccela et al., 2019). The highly pulsed and homogenized environment of resources poses new challenges to the foraging strategy of bees and may also trigger adaptive changes. On the one hand, bees may evolve stronger preferences and efficient utilization capabilities for the flowers of major crops. On the other hand, for general pollinators (such as bees and bumblebees), long-term nutritional imbalance caused by monoculture may promote changes in their nutritional physiology. In addition to nutrient utilization, the evolutionary adjustment of foraging behavior is also worthy of attention. In an environment with monotonous flower sources, bees may reduce the motivation to explore new flower sources and focus on familiar crop flowers; or evolve synchronized reproduction and activity rhythms with the annual crop flowering cycle.

4.3 Landscape structure changes and genetic diversity of honey bee populations

Changes in agricultural landscapes, including habitat fragmentation, farmland expansion, and contiguous monoculture, have had a profound impact on the genetic structure of honey bee populations. Habitat fragmentation limits gene flow between honey bee populations. Wild bees (such as solitary bees and bumblebees) often need semi-natural habitats to nest and reproduce. When these habitats are divided into isolated islands, the population becomes isolated and the probability of inbreeding increases. Large-scale monoculture and frequent migration of bee colonies have changed the genetic composition of honey bees. In order to meet pollination needs, the beekeeping industry often transports bee colonies across regions, resulting in gene exchange between bee populations from different regions. This increases the surface diversity of bees in certain areas at the artificial level, but it may also cause global genetic homogeneity.

The homogenization of agricultural landscapes also reduces the opportunities for gene exchange between pollinator species. For social insects such as honey bees, their gene exchange mainly depends on the nuptial flight of queen bees and drones. Tanasković et al. (2021) analyzed the mitochondrial DNA of Serbian bees and found that the genetic diversity of local bees has declined in recent decades, which is attributed to changes in the gene pool caused by human introduction and management methods. Landscape changes also affect the retention and loss of bee adaptive genes. Local bee colonies in natural environments often accumulate unique disease resistance or climate adaptation genes through long-term selection, but in an agricultural context, these genes may be at risk of loss due to genetic mixing or changes in selection pressure.

5 Specific Case Analysis of Pesticides on the Evolutionary Adaptation of Bees

5.1 The impact of neonicotinoids on the adaptive evolution of bee populations

Neonicotinoids are one of the most widely used pesticides in the world in the past two decades, and their potential impact on bees has attracted much attention from researchers. These pesticides act on the nicotinic acetylcholine receptors in the insect central nervous system, causing nerve signal disorders and death. Bees are not target pests for neonicotinoids, but they are exposed to them when they feed on treated pollen, nectar or drink medicated dew. Tsvetkov et al. (2023) selected bee strains that were sensitive and tolerant to chlorothiazide for comparison and found that the survival rate of worker bees in the tolerant strain was significantly higher after exposure, accompanied by specific mutations in the CYP9Q detoxification gene (Figure 2). This shows that in areas of high-intensity use, neonicotinoids may act as a selection pressure to screen out bee individuals carrying favorable mutations, increasing their proportion in the population. In addition to genetic variation, bees may also reduce the toxicity of neonicotinoids by regulating their behavior. For example, experiments have shown that after multiple exposures to sublethal doses, worker bees will reduce their desire to feed on the smell (flowers treated with pesticides) and show a certain degree of learning to avoid it. This behavior essentially increases the chance of survival.

5.2 The impact of organic farming practices on the evolution of bee populations

Organic farming creates a relatively friendly living environment for pollinators by not using chemical synthetic pesticides and fertilizers and promoting biodiversity. For bee populations, this not only reduces toxicological pressure but also increases nutritional sources, which is believed to contribute to the recovery and stability of bee populations. Pluta et al. (2024) conducted comparative experiments at 16 sites in Germany. The results showed that in areas with a higher proportion of organic farming, the parasitism rate of Varroa mites in bee colonies was lower, and the reproduction rate and group strength indicators of bee colonies were significantly improved. This shows that organic practices can alleviate the environmental pressure on bees, allowing them to invest more energy in growth and reproduction rather than detoxification and immunity. This reduction in pressure may have a cumulative effect on evolution: selecting traits that are more conducive to growth and reproduction. Bee populations that have been in an organic environment for a long time may tend to retain genotypes that perform well under low pesticide conditions, such as strategies that invest more resources in reproduction. On the contrary, in a high-pressure pesticide environment, they may prefer to retain genotypes that are more resistant to toxicity but slightly inhibited in reproduction.

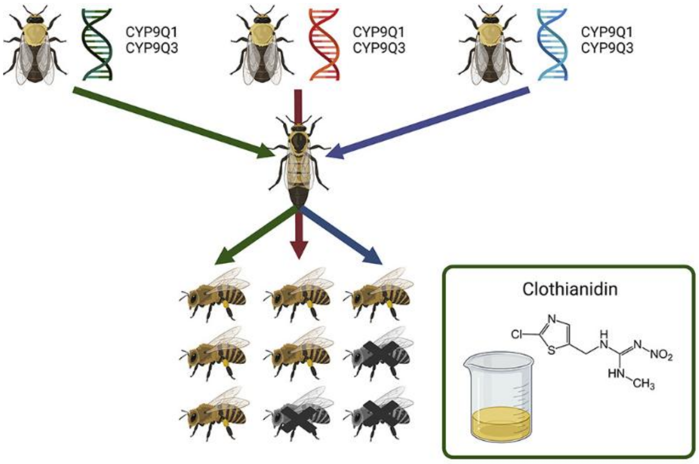

Figure 2 Genetic variation in metabolic resistance to clothianidin in honey bees (Adopted from Tsvetkov et al., 2023)
Image caption: Metabolic differences in the response to clothianidin exposure between two P450 genotypes of honey bee CYP9Q1 and CYP9Q3; bees with different genetic backgrounds (represented by green, red, and blue DNA strands) produce offspring through hybridization. When exposed to clothianidin, the offspring exhibit varying survival abilities: some survive while others die (Adopted from Tsvetkov et al., 2023)

5.3 Research on the impact of transgenic crop planting on bee genetic diversity

With the large-scale promotion of transgenic insect-resistant and disease-resistant crops, people are also concerned about their potential impact on pollinating insects. Transgenic crops mainly affect bees in two ways: one is the direct effect, that is, bees ingest exogenous products expressed in pollen and nectar of transgenic plants; the other is the indirect effect, that is, transgenic crops change agricultural production methods, thereby affecting the habitat and resources of bees. For example, Bt crops (transgenic varieties expressing Bacillus thuringiensis toxins) can kill lepidopteran pests that feed on their tissues, but whether bees are affected by feeding on Bt pollen has been controversial. Compared with direct effects, the indirect ecological effects of transgenic crops may be more worthy of attention. For example, the large-scale application of herbicide-resistant genetically modified crops is often accompanied by more herbicide use, which eliminates weeds and wildflowers in the fields. This undoubtedly reduces the non-crop flower sources for bees, which is equivalent to amplifying the nutritional pressure of monoculture on bees. In the vast genetically modified soybean and corn belts in the United States, due to the widespread use of herbicides, weed flowers in fields and ridges are almost extinct, which is considered to be one of the reasons for the decline in monarch butterflies and pollinating insects. Similarly, for bees, the continued lack of flower sources will exert nutritional selection pressure on their populations, which may force bees to adjust their reproductive strategies (such as reducing the number of overwintering bees) to adapt to the resource-scarce season.

6 Conservation and Management Strategies for the Impact of Agricultural Practices on the Evolution of Bee Populations

6.1 Strategies to reduce the evolutionary pressure of pesticide use on bees

Given that pesticides are one of the primary pressures faced by pollinators such as bees, reducing the selection pressure exerted by pesticides on bees is one of the key goals of conservation strategies. First, the reduction and precision of pesticide use should be promoted. Through methods such as integrated pest management (IPM), the number and dosage of unnecessary broad-spectrum insecticide sprays should be reduced as much as possible, and alternative methods such as biological control, trapping and insect-resistant varieties should be adopted instead (Zhang et al., 2022; Gebhardt et al., 2025). Secondly, the selection of low-toxicity agents and the optimization of application methods are also important measures. For example, pesticides with low toxicity or short duration of action to bees can be used first, and the pesticides can be applied during the low peak period of pollination activity (such as at night and before and after flowering) to avoid the peak period of bee collection. In addition, the development and promotion of more bee-friendly plant protection technologies is also one of the long-term strategies. For example, for application methods such as seed coating and soil treatment that may cause bee exposure, the formulation can be improved to reduce dust drift. Finally, it is also very important to strengthen education and cooperation with farmers and beekeepers. Farmers can understand the value of pollinators and the impact of pesticides through training, so that they are willing to adjust their drug use habits in actual operations; beekeepers can establish a communication mechanism with farmers, know the application plan in advance and temporarily relocate the beehives to avoid poisoning incidents (Bloom et al., 2021).

6.2 Suggestions for improving agricultural landscape diversity and ecological corridor construction

In response to the problems caused by habitat fragmentation and resource homogeneity, improving agricultural landscape structure and diversifying farmland habitats are effective strategies to protect pollinators and support their evolutionary adaptability. Specific measures include: adding habitat corridors, retaining semi-natural habitat patches, and optimizing land use layout. The construction of ecological corridors aims to connect separated habitat patches and provide mobile channels for pollinators such as bees. Corridors can be continuous flower belts at the boundaries of farmlands, vegetation buffers on ridges, or flowering plant belts planted along roads and canals. Protect and restore semi-natural habitats in farmlands. This includes retaining forest edges, shrubs, grasslands, etc. around farmland to provide nesting sites and non-crop flower sources for bees. Diversified planting at the landscape scale. Encourage farmers to adopt intercropping, crop rotation and diversified crop layout to avoid large-scale long-term single planting. Diverse crop composition not only disperses the flowering period and prolongs the nectar supply time, but also reduces the use of continuous large-scale herbicides through different crop requirements. It is also necessary to strengthen the management of habitat corridors and patches. For example, plant local perennial flowering plants to ensure continuous flowering throughout the growing season; corridor width and plant configuration should fully consider the flight habits of bees (Piaopiao et al., 2015; Rundlöf et al., 2022).

6.3 Diversified agricultural systems and ecological management strategies for pollination services

In order to protect pollinators while ensuring agricultural output, it is necessary to develop diversified and pollinator-friendly agricultural systems and comprehensively consider the maintenance of pollination services in management. Promote the concept of agricultural biodiversity, that is, introduce multiple biological elements in and around farmland to form ecological mutualism. Develop crop rotation and symbiotic systems. Avoid long-term absence of flowers in a certain season through crop rotation. For example, crop rotation with rapeseed can ensure nectar sources in different seasons. Use symbiotic systems, such as mixing flowering green manure in the orchard, to improve the soil and provide nectar for pollinating insects. Furthermore, encourage the combination of bee pollination management and agronomic measures. In addition, supporting wild pollinators is also an important part of the diversified system. Wild pollinators include bumblebees, solitary bees, and aphid flies, which make unique contributions to crop pollination under certain conditions. Implement economic incentives for pollination services. Through policies or market means, such as subsidizing farmers who adopt pollination-friendly measures and incorporating pollination services into organic certification indicators, agricultural producers are encouraged to take the initiative to create good conditions for pollinators (Faure et al., 2023).

7 Challenges and Future Research Trends in the Study of Evolutionary Adaptation of Honey Bee Populations in Agricultural Ecosystems

7.1 Limitations and challenges of current research

Although research on agricultural practices and honey bee evolutionary adaptation has made some progress in recent years, there are still many limitations and challenges. For example, it is difficult to observe long-term evolutionary effects. Evolutionary changes in pollinators such as honey bees often take several or even dozens of generations to manifest, while the time scale of conventional experiments and monitoring projects is limited, making it difficult to directly observe evolutionary processes such as changes in gene frequency. Evolutionary changes in honey bee populations are intertwined with multiple pressures, making it difficult to distinguish causal relationships. There are also species and regional differences that have not been fully considered. Honey bee evolutionary responses may vary depending on species (Western honey bees vs. Eastern honey bees vs. wild bees) or genetic backgrounds (Guichard et al., 2023; Lin et al., 2025). There are also technical challenges in research methods. For example, analyzing the big data of honey bee genomes requires separating adaptive mutation signals, and it is quite difficult to detect natural selection imprints from massive neutral variants. At the practical level, there is uncertainty in generalizing laboratory or simulation research findings to real agricultural situations. The behavior and gene flow of bees in the natural environment are more complex than those in experimental conditions, and there are many external interference factors, so some experimental results may not be verified in the field.

7.2 Future research trends and key technology development

In the face of the above challenges, future research needs to innovate in methods and technologies to more comprehensively understand the evolutionary adaptation dynamics of bee populations. It will become a trend to use population genomics and long-term data to monitor the genetic changes of bees. The combination of multiple omics will also help to analyze the adaptation mechanism of bees. Genomics reveals variation, while transcriptome, proteome and metabolome can depict functional responses (Trapp et al., 2017). Experimental evolution and quasi-natural experiments will provide direct evidence. Semi-natural enclosure experiments can be designed to allow bee populations to reproduce for multiple generations in a controlled agricultural environment and observe their traits and genetic changes. Advanced individual tracking and behavior analysis technologies will help discover new patterns of behavioral adaptation. Using RFID radio frequency tags, computer vision tracking, etc., high-resolution recording of bee collection, dance communication, migration and other behaviors can quantify how agricultural disturbances change bee behavior. Model simulation and big data will play a role in comprehensive prediction. In addition, emerging gene editing and synthetic biology technologies may open up new paths for studying pollinator adaptability.

7.3 Future agricultural ecological practices and prospects for bee protection research

Future agricultural practices need to become more eco-friendly and sustainable, not only to protect pollinators such as bees, but also to maintain human well-being. The development of sustainable agricultural models will profoundly affect the fate of pollinators and provide a "natural experiment" for scientific research. Research on agricultural pollinators in the context of climate change will become increasingly urgent. As the global climate continues to warm, the mismatch between flowering and pollinator activity periods may intensify, and new pest and disease pressures will emerge. The protection of native pollinator diversity will become a key topic. In the past, more attention has been paid to bees (especially Western honey bees). In the future, more attention should be paid to the role of local wild pollinating insects, such as stingless bees and solitary bees, in agricultural ecology, and how they adapt to environmental changes. In terms of protection practices, pollinator monitoring with the participation of all people may emerge. Murphy et al. (2022) have quantified the potential impact of pollination decline on global trade and food prices, suggesting that countries must pay attention to pollinator protection to avoid food security risks. This will encourage countries to invest more resources in policies and promote international cooperation.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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