Natural Enemies, Farmer Cognition, and Pesticide Use: Micro Evidence from China's Pear Producing Regions

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Abstract

Purpose- This paper examines how natural enemies, as ecological control agents, influence farmers' pesticide use decisions, and how this effect is conditioned by farmers' cognitive understanding of pest–enemy dynamics and their risk attitudes.

Design/methodology/approach- Drawing on original data from 327 pear farmers in three of China's major producing provinces (Hebei, Shandong, and Hubei), this study integrates three data sources: ecological monitoring of orchard level predator populations, incentivized experiments on farmer risk preferences, and structured household surveys. Interaction models are estimated to assess how farmers' cognition moderates the relationship between natural enemy density and pesticide use, measured in terms of both expenditure and spraying frequency.

Findings- Results show that farmers with greater ecological awareness, specifically, better recognition of pests, natural enemies, and their interrelations apply pesticides less frequently and at lower cost. This cost reducing effect of cognition is significantly amplified under higher natural enemy densities, suggesting a synergistic relationship between ecological assets and behavioral responses. In contrast, farmers with higher risk aversion tend to spray more often, though not necessarily at greater expense, indicating a quantity-over-quality behavioral pattern in risk management.

Originality/value- This study makes several novel contributions. First, it moves beyond perception based proxies by incorporating field-measured predator densities into behavioral modeling. Second, it identifies a micro-level mechanism whereby ecological conditions and farmer cognition jointly shape input behavior. Third, it highlights how natural enemies are underutilized in current farmer decision-making due to low awareness, providing concrete evidence for targeting ecological extension services. The findings have practical relevance for advancing sustainable pest control in perennial systems such as orchards and for promoting nature-based solutions in developing country contexts.

Key words: Natural enemies, Farmer cognition, Pesticide use, Risk attitude, Field experiment, Interaction effect, China

1. Introduction

Excessive reliance on chemical pesticides has become a major challenge in modern agriculture, especially in high-value crops like fruits and vegetables. Although pesticides are essential for controlling pests and diseases, their intensive application has resulted in severe ecological degradation, higher production costs, and mounting food safety risks ((Liu and Huang, 2013; Munir *et al.*, 2024a)). In fruit production, pesticide intensity is estimated to be 7.7 times that of staple crops[1], and limited post-harvest processing increases the likelihood of residues entering the food chain, thereby elevating risks of foodborne exposure and public health concerns (Munir *et al.*, 2024b; Wahab *et al.*, 2022). Broad-spectrum insecticides further compound the problem by killing not only pests but also beneficial organisms, notably natural enemies that help regulate pest populations(Wilson, 2012). This disrupts ecological balance, weakens the resilience of agroecosystems, and accelerates biodiversity loss(Pimentel *et al.*, 1992). Additionally, pesticide overuse contributes to non-point source pollution and poses long-term threats to environmental and human health (Goulson, 2014; Landrigan *et al.*, 2018; Tang *et al.*, 2021; Zhang *et al.*, 2015). These challenges underscore the urgent need for more sustainable, ecology-based pest management strategies, particularly for high-value crops, where chemical dependence is excessive and the potential of natural enemies remains largely underutilized.

Pesticide use is also a behavioral response to production risk. In the face of uncertainty, risk averse farmers often overapply pesticides as a precautionary measure (Ellis, 1993;

[1] According to the National Bureau of Statistics (2025), the average pesticide expenditure per mu in 2023 was 422.5 CNY for orchards, 191.5 CNY for vegetables, and 54.8 CNY for grain crops.

Liu and Huang, 2013; Mi et al., 2012). This pattern is especially common in developing countries where smallholders lack effective risk transfer mechanisms. In addition to risk preferences, farmers' cognitive abilities, particularly their knowledge of pest ecology and pesticide use are critical determinants of pesticide behavior. Studies show that farmers with higher ecological cognition apply pesticides more judiciously(Chen *et al.*, 2013; Grogan, 2014). Other factors such as farm size, pesticide prices, access to extension services, and pest pressure also influence farmers' decisions (Chen *et al.*, 2013; Liu and Huang, 2013; Mi *et al.*, 2012; Pemsl *et al.*, 2005; Zhang and Swinton, 2012). However, most existing studies rely on generalized proxies for cognition, which limits the precision of empirical insights.

Natural enemies are a vital part of agricultural ecosystems and, when properly utilized, can help reduce pesticide dependence through ecological pest suppression. A growing body of natural science and economic research has confirmed the ecological and economic value of natural enemies in pest control (Gallardo *et al.*, 2016; Zhang and Swinton, 2009, 2012). Yet, most assessments are based on experimental plots, biological models, or hypothetical scenarios, often failing to incorporate farmers' behavioral responses or heterogeneous field conditions (Huang *et al.*, 2018). Consequently, the value of natural enemies remains underappreciated by farmers and is rarely factored into their pest management decisions.

This study seeks to bridge the gap between ecological pest control potential and farmers' pesticide behavior by examining how natural enemy density and farmers' ecological cognition jointly influence pesticide use at the micro level. Drawing on unique data from China's main pear-producing regions, we integrate ecological field monitoring, household surveys, and behavioral modeling to quantify how natural enemies affect pesticide application costs and frequency, and how these effects are moderated by farmers' knowledge and risk preferences. By explicitly incorporating natural enemies into farmers' decision-making models and considering behavioral heterogeneity, this paper contributes to the literature on sustainable agriculture in three key ways. First, it provides rare empirical evidence of how the presence of natural enemies shapes real-world pesticide behavior rather than relying on simulation-based estimates. Second, it constructs a fine-grained measure of farmer cognition based on field surveys and pest identification tests rather than relying on coarse proxies. Third, it highlights the behavioral conditions under which natural enemies can meaningfully reduce pesticide reliance, offering new insights into the role of cognition and risk attitudes in ecological input adoption.

The remainder of the paper is organized as follows: Section 2 presents the theoretical framework and research design; Section 3 outlines the methodology and empirical model; Section 4 describes the data and sample; Section 5 reports the empirical results; and Section 6 concludes with policy implications.

2. Theoretical Framework and Research Design

2.1 Farmers' Cognitive Awareness and Pesticide Use

Farmers' understanding of agricultural pests and their natural enemies plays a critical role in shaping pesticide use behavior. Cognitive awareness influences how farmers perceive the threat of pests, the effectiveness of control strategies, and the potential value of natural enemies. Studies have shown that higher farmer knowledge is associated with more rational and targeted pesticide application, reducing both overuse and misuse (Chen *et al.*, 2013; Grogan, 2014). In particular, awareness of the ecological interactions between pests and predators is essential for internalizing the benefits of natural enemies. However, existing literature often adopts a generalized approach to cognition, lacking specific assessments of farmers' ability to recognize pest–natural enemy dynamics. This study contributes to the literature by incorporating a detailed cognition index based on farmers' recognition of orchard insects and understanding of their ecological roles. Based on this, we propose

Hypothesis 1: Farmers with higher cognitive awareness of pests and natural enemies are more likely to reduce pesticide use.

2.2 Farmers' Risk Attitudes and Pesticide Use

Pesticide use also reflects farmers' behavioral responses to production uncertainty. In environments with weak insurance coverage and limited public risk mitigation mechanisms, farmers often rely on pesticides as a form of production protection. The literature suggests that risk-averse farmers tend to overapply pesticides to avoid the uncertain consequences of pest damage (Ellis, 1993; Liu and Huang, 2013; Mi et al., 2012). While this behavior may seem cost inefficient from an input optimization perspective, it aligns with risk minimization strategies. This psychological dimension of production behavior is particularly relevant in the context of pest outbreaks, which are difficult to predict and manage. Farmers with higher degrees of risk aversion are more likely to increase application frequency or dosage to feel secure about yield outcomes. Therefore, we propose

Hypothesis 2: Farmers with higher levels of risk aversion are more likely to apply pesticides more frequently, regardless of ecological pest control conditions.

2.3 Moderating Role of Natural Enemy

Natural enemies represent a vital biological control force in orchard ecosystems, offering a cost-effective and environmentally sound alternative to chemical pesticides(Huang *et al.*, 2018; Letourneau *et al.*, 2009; Zhang and Swinton, 2012). The presence of natural enemies can suppress pest populations and thus reduce the need for chemical inputs (Bell *et al.*, 2016; Letourneau *et al.*, 2009). However, their actual influence on pesticide use depends on whether farmers recognize and respond to their ecological function. The role of natural enemies is not independent of farmer cognition. Even when enemy populations are ecologically sufficient, their pest control potential may be ignored or underutilized if farmers lack the knowledge to perceive and trust their effectiveness. Thus, the interplay between cognition and enemy density is key. Therefore, we propose *Hypothesis 3: Natural enemy density positively moderates the relationship between farmer cognition and pesticide use.*

2.4 Proxy Strategy for Natural Enemy Population Density

A key empirical challenge is the potential endogeneity in measuring natural enemy density, especially if current pesticide use has already affected local enemy populations. To mitigate this, the study adopts a proxy based strategy. Instead of directly measuring natural enemies in each farmer's plot, population densities are derived from nearby organic or green-certified orchards. These reference orchards, managed without chemical pesticides in accordance with China's "green production" standards, reflect stable agroecological baselines. Since they are minimally affected by the sampled farmer's own practices, they offer a credible estimation of regional natural enemy densities. Monitoring locations were chosen to be as close as possible to the surveyed farmers' orchards, ideally adjacent, to ensure ecological comparability. This strategy reduces simultaneity bias and improves the internal validity of the empirical model by treating natural enemy density as an exogenous ecological condition rather than an outcome of farmer decisions.

Figure 1 summarizes the conceptual framework of this study. It illustrates how natural enemy density, as an ecological input, influences farmers' pesticide use behavior through two behavioral mediators: cognitive awareness and risk attitudes. Farmers with greater ecological cognition are more likely to recognize the pest suppressing function of natural enemies and reduce pesticide application accordingly. Risk averse farmers, by contrast, tend to overapply pesticides to guard against uncertainty. The effectiveness of natural enemies in reducing pesticide use is conditional on farmers' awareness, and their moderating effect becomes more salient when enemy density is within a viable range. This framework integrates ecological, behavioral, and economic dimensions to guide the empirical analysis and hypothesis testing.

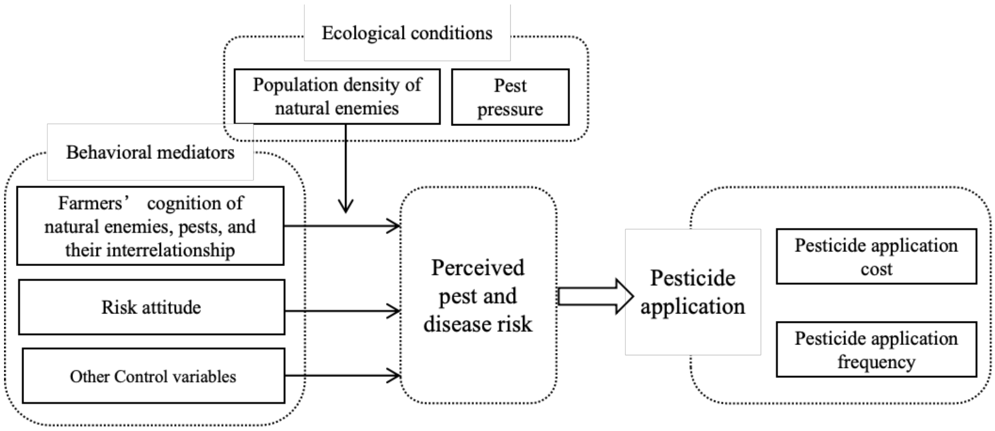

Figure 1. Framework for Natural Enemies and Farmers' Pesticide Application Behavior.

3. Methodology

3.1 Econometric Model

Building on the theoretical framework, we specify the following econometric models to estimate the determinants of pesticide application cost and frequency:

$$Controlcost = a_0 + a_1 risk + a_2 enemy + a_3 cognition + \sum_{k=1}^{K} b_k X_k + a_4 enemy * cognition + \mu \quad (1)$$

In this model, the dependent variable $Controlcost$ represents the pesticide application cost per mu. The variable $risk$ denotes the farmer's degree of risk aversion; $enemy$ measures the population density of natural enemies in pear orchards; $cognition$ captures the farmer's level of knowledge regarding pests, natural enemies, and their interactions. The interaction term $enemy * cognition$ examines how natural enemies and farmer cognition jointly influence pesticide use behavior.

X_k denotes a vector of control variables including orchard disaster status, pest incidence, degree of non-agricultural employment, farmer's age, education level, health condition, orchard size, and regional dummies. μ is the random error term. a_0 is the intercept, and a_1 through a_4 , and b_k are the parameters to be estimated.

$$Controltimes = \mathrm{a}_0 + \mathrm{a}_1 risk + \mathrm{a}_2 enemy + \mathrm{a}_3 cognition + \sum_{\mathrm{k=1}}^{\mathrm{K}} b_k X_k + \mathrm{a}_4 enemy * cognition + \mathrm{\mu} \quad (2)$$

In this model, the dependent variable $Controltimes$ indicates the number of pesticide applications. Given the diversity of pesticide types and the difficulty of collecting precise application quantities by type, average pesticide costs are used to reflect usage intensity. Additionally, pesticide application frequency serves as a proxy for pesticide usage volume, providing further insight into farmers' pesticide application behavior.

3.2 Measurement of Risk Attitude

Farmers' risk attitudes are key psychological traits that influence pesticide application decisions under uncertainty. In this study, we employ a multiple price list (MPL) lottery experiment to measure the degree of risk aversion, following the method proposed by Holt and Laury (2002). The experiment is based on a constant relative risk aversion (CRRA) utility framework, and individual risk coefficients are estimated according to the switching point between safe and risky lottery options.

To maintain brevity, the detailed design of the experiment, the specification of the utility function, and the classification of risk preferences are not repeated here. For a full account of the procedure and methodology, please refer to Section 4.1 in our previous paper (Liu *et al.*, 2022). The complete set of experimental tables and classifications is provided in the **Appendix** of this paper.

3.3 Measurement of Farmers' Cognition

Farmers' cognitive levels were assessed through responses to four targeted questions designed to evaluate their ability to identify pear orchard pests and natural enemies and understand their ecological relationships:

1) Does an increase in natural enemy populations contribute to pest control? (Options: ① Not clear; ② Agree; ③ Strongly agree) 2) How many pest species in the provided pear orchard images can you identify? (Correct identification of pest names required for scoring). 3)Which of the following are not pear orchard pests? (Options:

① *Coccinellidae* (lady beetles); ② *Grapholita molesta* (oriental fruit moth); ③ *Cacopsylla pyricola* (pear psylla); ④ *Aphididae* (aphids); ⑤ *Phyllonorycter ringoniella* (pear leaf miner); ⑥ *Syrphidae* (hoverflies); ⑦ *Nabis spp*. (damsel bugs); ⑧ *Phyllotreta spp*. (flea beetles); ⑨ *Trichogramma spp*. (parasitic wasps); ⑩ *Chrysopidae* (green lacewings); ⑪ *Araneae* (spiders); ⑫ Not clear). 4)Can *Trichogramma spp*. (parasitic wasps) control *Grapholita molesta* (oriental fruit moth) in pear orchards?

Questions 1 and 4 assess farmers' understanding of the ecological relationship between natural enemies and pests, while Questions 2 and 3 evaluate their ability to identify pests and natural enemies, respectively. Each question was assigned a weight based on difficulty and importance (2, 4, 2, and 1 points, respectively), with the total score serving as a composite measure of farmers' cognitive level.

3.4 Observation of Insect Population Density in Orchards

To accurately assess the ecological conditions of each study site, we conducted standardized field observations of pest and natural enemy populations in pear orchards. In each sampled village, one representative orchard was selected as the insect monitoring site.

From July to September 2020, insect population data were collected following plant protection protocols, using yellow sticky traps as the primary observation method (Krysan and Horton, 1991). In each selected orchard, a one-mu (0.067-hectare) plot was demarcated, with five monitoring points (one central and four in cardinal directions). Yellow sticky traps were placed at approximately 1.5 meters above ground on pear trees, with a density of five traps per mu, replaced biweekly. Graduate students trained in plant protection recorded the counts of natural enemies and pests on each trap. To account for potential seasonal variations in insect activity, monitoring was conducted three times over the study period, and the average of these observations was used in the subsequent econometric analysis. The primary predatory natural enemies observed included *Coccinellidae* (lady beetles), *Chrysopidae* (green lacewings), *Araneae* (spiders), *Anthocoridae* (minute pirate bugs), and *Syrphidae* (hoverflies). The major pests identified were *Aphididae* (aphids), *Cicadellidae* (leafhoppers), *Contarinia pyrivora* (pear gall midge), *Cacopsylla pyricola* (pear psylla), and *Grapholita molesta* (oriental fruit moth).

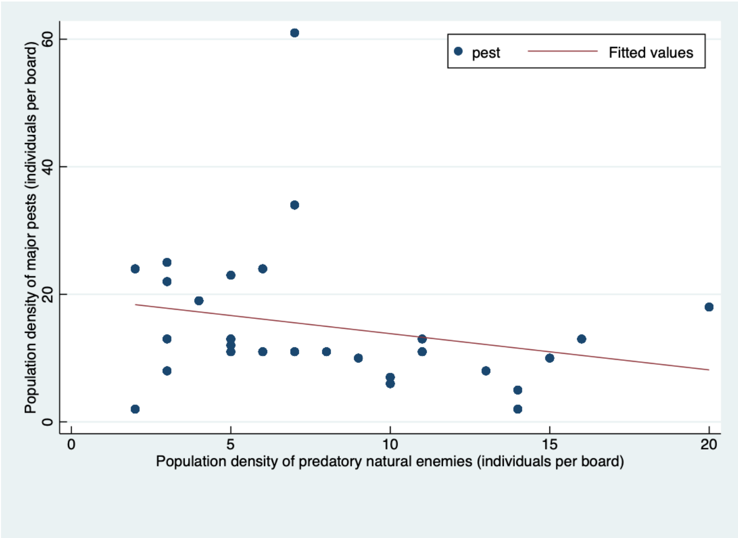

Figure 2. Relationship between predatory natural enemy and major pest population Densities

The observed relationship between predator and pest densities is depicted in Figure 2. As the density of predatory natural enemies increased, the population of major pests declined, providing empirical support for the biological control capacity of natural enemies. This pattern is consistent with established predator–prey dynamics in ecological theory and highlights the potential for natural enemies to mitigate pesticide usage and reduce production costs.

4. Data source and sample description

4.1 Data Sources

The data used in this study were collected by the Pear Industry Technology System in 2020 and consist of three major components: field observations of natural enemy populations in pear orchards, a structured household survey of pear growers, and a risk elicitation experiment. To ensure the design was grounded in production realities, a pilot investigation was conducted in Hebei Province in June 2019. The pilot helped assess key pest–enemy dynamics in orchards and gather preliminary data on farmers' input–output behavior, which informed the construction of the risk experiment.

The risk attitude of farmers was elicited through a lottery-based multiple price list experiment. The design followed Holt and Laury (2002), but was tailored to local conditions by adjusting payoff levels based on the average net returns and pesticide expenditure data collected in the 2019 pilot study. To mitigate hypothetical bias, enumerators conducted a "cheap talk" script(Cummings and Laura, 1999; List, 2001) with respondents before the experiment, encouraging them to align their choices with real-life production decisions.

The formal survey was implemented between October and December 2020 in the three major pear-producing provinces of Hebei, Shandong, and Hubei. A stratified random sampling approach was used to select 327 farm households from 32 villages (16 in Hebei, 8 in Shandong, and 8 in Hubei), with a sampling ratio of 2:1:1 to reflect Hebei's status as China's largest pear-producing province (accounting for approximately 20% of national output). Within each village, 10 households were randomly chosen for face-to-face interviews conducted with the primary decision-maker. Each interview lasted 30 to 60 minutes and was conducted at the farmer's home or local village office.

The survey instrument collected information on demographic characteristics, production practices, pest control behavior, cost and revenue patterns across production stages, and farmers' knowledge and perception of pest-natural enemy dynamics. All interviews were administered by trained graduate students with backgrounds in agricultural economics to ensure data consistency and accuracy. After completing the survey, respondents were invited to participate in the risk experiment. Of the 327 responses collected, 302 provided complete and valid information on pesticide application and were retained for empirical analysis.

4.2 Variables and Descriptive Statistics

4.2.1 Descriptive statistics

The definition and descriptive statistics for the variables used in the empirical analysis are presented in Table 1. The independent variables were selected based on a review of previous studies on the determinants of farmers' pesticide use behavior (Bell *et al.*, 2016; Chen *et al.*, 2013; Liu and Huang, 2013; Zhu and Wang, 2021).

Table 1 Variable Definitions and Descriptive Statistics

Variable	Definition	Mean	SD	Min	Max
Dependent variables					
Pesticide cost	Pesticide application cost per mu (CNY/mu)	429.867	262.72	0	1600
Pesticide frequency	Number of pesticide applications during a growing cycle	7.980	2.955	1	15
Key independent variables					
Natural enemy density	Population density of predatory natural enemies (individuals per sticky trap)	8.483	6.49	2	37
Farmers' Cognition	Farmer cognition score on pests, natural enemies, and their interactions (0–9)	3.771	2.358	0	9
Risk attitude	Coefficient of risk aversion	.734	.754	-.87	1.41
Control variables					
Age	Age of the farmer (years)	55.179	8.919	30	76
Education	Years of formal schooling	7.964	3.171	0	16
Health status	1 = Good; 2 = Fair (ill but not affecting work); 3 = Poor; 4 = Multiple chronic illnesses	1.219	.514	0	3
Poverty status	1 = Registered as poor household; 0 = Otherwise	.073	.26	0	1
Cooperative membership	1 = Member of an agricultural cooperative; 0 = Not a member	.252	.435	0	1
Agri-income share	Share of agricultural income in total household income (%)	0.606	0.352	0.001	1
Orchard size	Size of pear orchard (mu)	6.361	14.147	.68	214
Pesticide adjustment	Whether the farmer adjusts pesticide use based on field conditions (1 = Yes; 0 = No)	.606	.489	0	1
Disaster occurrence	Whether the orchard suffered from natural disasters in the current year (1 = Yes; 0 = No)	.762	.427	0	1
Pest severity	Severity of pest/disease outbreaks (1 = Very low; 5 = Very severe)	3.387	1.126	1	5
					N=302

According to Table 1, the average pesticide expenditure per mu is 429.9 CNY, with considerable variation across farmers. The maximum cost reaches as high as 1,600

CNY per mu, indicating significant heterogeneity in pesticide spending behavior. Similarly, pesticide application frequency also shows substantial dispersion: farmers spray an average of eight times during a growing season, with a range from 1 to 15 times, reflecting diverse pest control practices. The average population density of predatory natural enemies is approximately 8 individuals per sticky trap, but this figure varies widely, from as low as 2 to as high as 37 per trap. Farmers' recognition of orchard insects and their understanding of pest–natural enemy interactions appear to be limited, the average cognition score is only 3.77 out of 9. This low level of awareness may influence pesticide use behavior and increase pest control costs. Moreover, the lack of understanding regarding the ecological role of natural enemies may hinder their effectiveness in biological pest suppression.

The surveyed farmers span a wide age range from 30 to 76 years old with a mean age of 55, revealing a trend toward an aging labor force. Educational attainment is generally low among respondents, averaging only 8 years of schooling. Around 82% of farmers reported being in good health and able to participate in routine agricultural activities, whereas only 4.3% indicated that poor health significantly affected their daily life and farming work. Very few respondents were officially registered as low-income households. About 25% of farmers reported being members of agricultural cooperatives. On average, orchard size is 6.36 mu, but landholding varies greatly, ranging from 0.68 mu to as much as 214 mu. Approximately 60% of respondents reported adjusting pesticide use based on real-time field observations of pest and disease conditions. This implies that nearly 40% of farmers follow pesticide labels or rely on external advice, rather than adapting application to field-specific pest severity.

Furthermore, 76.2% of respondents indicated that their orchards experienced some degree of natural disaster in the current year. The severity of pest and disease incidence also varied across households. Regarding household income structure, agricultural income accounts for an average of 60.6% of total household income, though the proportion ranges widely from near-zero to full dependence on farming. This indicates that while agriculture remains a central income source for many households, others may rely significantly on off-farm employment, potentially influencing their production behavior and input decisions.

4.2.2 Farmers' knowledge of insect species and ecological interactions in the orchard

Survey results (**Figure 3**) indicate that 73.6% of farmers either believe natural enemies do not suppress pests or are unsure of their role, with only approximately 25% recognizing the biological control potential of natural enemies. Trichogramma spp. (parasitic wasps), a widely used natural enemy capable of parasitizing multiple pest species, including Grapholita molesta (oriental fruit moth), is commonly employed in large-scale biological control due to its mass-rearing potential. However, only 10.56% of farmers were aware of the role of Trichogramma spp. in controlling Grapholita molesta, with nearly 90% lacking knowledge of the predator–prey dynamics between natural enemies and pests. These findings suggest that farmers' awareness of the ecological relationship between natural enemies and pests is generally low, with only a small proportion recognizing their pest suppression potential.

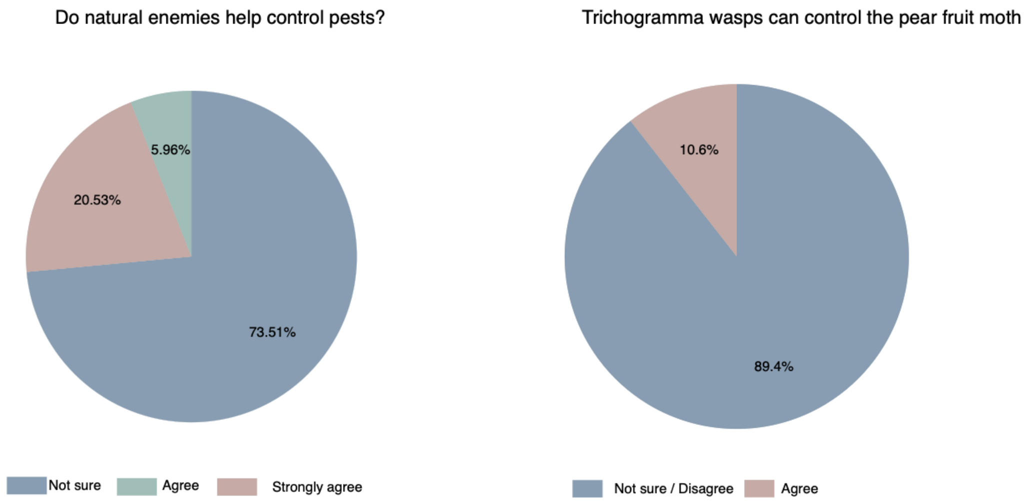

Figure 3. Farmers' Awareness of the Relationship Between Natural Enemies and Pests

Table 2 summarizes farmers' identification of common pear orchard pests and natural enemies. When presented with four common pest species, 22.44% of farmers demonstrated low identification ability, while nearly 80% could identify at least one pest, and over 50% recognized two or more pest species, indicating a moderate level of pest identification ability. In contrast, farmers' ability to identify natural enemies was significantly limited: 34% could not identify any natural enemies, only 5% correctly identified three to four out of five natural enemy species, and 60% recognized only one to two natural enemies. This disparity suggests that farmers' ability to identify natural enemies is considerably lower than their ability to identify pests. Consequently, farmers may struggle to utilize natural enemies for pest control and may mistakenly perceive natural enemies as pests, leading to increased pesticide application and overuse.

Table 2. Farmers' Identification of Pear Orchard Pests and Natural Enemies

Pest Identification (Correct Count)	Frequency	Percentage（%）	Natural Enemy Identification (Correct Count)	Frequency	Percentage（%）
0	68	22.44	0	104	34.32
1	53	17.49	1	91	30.03
2	57	18.81	2	92	30.36
3	43	14.19	3	10	3.30
4	82	27.06	4	6	1.98
Total	303	100.00		303	100.00

4.2.3 Descriptive analysis of risk preferences

As shown in Table 3, the majority of farmers in the sample exhibit risk averse behavior, accounting for 76.23% of the total. In contrast, 13.89% and 9.88% of the farmers fall into the risk loving and risk neutral categories, respectively. Specifically, 129 individuals are classified as "extremely risk averse," making it the largest group，nearly 40% of the sample，highlighting a strong aversion to risk among many farmers. The proportions of highly risk loving and risk loving farmers are relatively small, at 1.85% and 1.54%, respectively. This suggests that farmers' risk attitudes are relatively polarized, most respondents tend to be either extremely risk loving or distinctly conservative (risk neutral or risk averse), with few cases falling into ambiguous or intermediate categories. Additionally, over one third of the sample is evenly distributed across classifications between risk neutrality and extreme risk aversion, making up a significant share of the total.

Table 3. Classification of sample farmers by relative risk aversion (RRA)

Risk aversion classification	Frequency(N=324)	Percent(%)
Highly risk loving	34	10.49
Very risk loving	6	1.85
Risk loving	5	1.54
Risk neutral	32	9.88
Slightly risk averse	36	11.11
Risk averse	27	8.33
Very risk averse	27	8.33
Highly risk averse	28	8.64
Stay in bed	129	39.81

5 Empirical Results

5.1 Analysis of Pesticide Application Cost

Table 4 presents the regression results using pesticide application cost per mu as the dependent variable. Model (1) includes all core explanatory variables and control variables as a baseline specification. Given that the influence of natural enemies on farmers' pesticide behavior operates through their cognitive perception, Model (2) incorporates an interaction term between farmer cognition and natural enemy density to assess the moderating effect. Without a clear understanding of the distinction between beneficial natural enemies and pests, farmers may misidentify predators as pests and increase pesticide use. Thus, both cognition and natural enemy variables, as well as their interaction, must be included in the estimation.

Table 4. Estimation results on the effects of natural enemies on farmers' pesticide costs

Pesticide cost (per mu)	Baseline Model（1）		Interaction Model（2）	
	Coef.	Std. Err	Coef.	Coef.
Natural enemy density	2.852	2.346	-5.509	4.282
Farmers' Cognition	-4.852	6.369	-24.143**	10.426
Cognition * Enemy density			2.391**	1.028
Risk attitude	27.959	19.658	29.914	19.526
Age	-.411	1.766	-.229	1.754
Education	-6.313	4.74	-5.734	4.71
Health status	-31.264	29.457	-33.702	29.251
Poverty status	56.185	57.159	76.917	57.418
Cooperative membership	56.028	35.376	50.193	35.195
Agri-income share	-30.869	44.064	-30.78	43.727
Orchard size	-1.507	1.023	-1.351	1.017
Pesticide adjustment	80.014**	32.382	83.762***	32.176
Disaster occurrence	4.135	38.857	3.623	38.561
Pest severity	31.208**	13.459	29.126**	13.386
Hebei (ref.)	0	.	0	.
Shandong	208.378***	38.374	207.839***	38.082
Hubei	63.824	40.848	64.882	40.539
Constant	303.131**	126.564	365.175***	128.398
R-squared	0.161		0.176	
F-test	3.647		3.810	
Prob>F	0.000		0.000	
Observations	302		302	

*** *p<.01*, ** *p<.05*, * *p<.1*

Across both the baseline and the interaction models, the severity of pest and disease outbreaks in orchards has a significantly positive effect on pesticide costs. Farmers who adjust pesticide use based on field observations also tend to incur higher pesticide costs, indicating that responsive behavior to pest pressure leads to increased chemical inputs. Regional differences in pesticide expenditure are also evident: taking Hebei Province as the reference category, pear growers in Shandong have significantly higher pesticide application costs. Farmers' risk aversion is positively associated with pesticide costs—those who are more risk-averse tend to spend more on pesticide use—although this relationship is statistically insignificant.

From Model (2), farmer cognition of orchard insects has a significant negative impact on pesticide application cost, indicating that improved understanding of insect roles reduces reliance on chemical control. The interaction between predator density and farmer cognition is positively significant, confirming a moderating effect higher densities of natural enemies amplify the cost-reducing impact of farmers' better cognitive recognition.

In this model, the key explanatory variable is the overall density of predatory natural enemies, including lady beetles, lacewings, spiders, mirid bugs, and syrphid flies. Given that these predators vary in prey preferences and effectiveness, we further isolate the most commonly observed predator lady beetles to test robustness. As shown in (Appendix Table 3), the main findings remain consistent, and the interaction term between lady beetle density and cognition is significant at the 1% level. The consistency between the two models demonstrates the robustness of the empirical results.

5.2 Analysis of Pesticide Application Frequency

Due to the wide variety of pesticides used by farmers and the difficulty of accurately capturing the quantities applied, especially given the large variation in pesticide prices, application costs may not fully reflect pesticide use. In contrast, the frequency of pesticide application better represents the actual usage intensity. To ensure the robustness of our findings, we replace the dependent variable with pesticide application frequency and reestimate the model. Model (1) presents the baseline specification, while Model (2) includes the interaction term between natural enemy density and farmer cognition.

The estimation results are shown in Table 5. Farmers' risk aversion has a significant positive effect on pesticide application frequency, the more risk averse the farmer, the more frequently they apply pesticides. The interaction term between natural enemy density and farmer cognition is also significantly positive, suggesting that higher predator density significantly moderates the effect of cognition on pesticide frequency. This finding is consistent with the previous results on pesticide application costs, confirming the joint effect of cognition and ecological factors in influencing pesticide behavior. In addition, participation in farmer cooperatives is positively associated with higher pesticide application frequency. Regional differences are also notable, compared to farmers in Hebei (the reference group), those in Shandong and Hubei exhibit significantly higher application frequencies.

Table 5. Estimation results on the effects of natural enemies on pesticide application frequency

Pesticide Frequency	Baseline Model（1）		Interaction Model（2）	
	Coef.	Std. Err	Coef.	Coef.
Natural enemy density	.42*	.214	.439**	.213
Farmers' Cognition	.032	.026	-.049	.047
Cognition * Enemy density	-.048	.069	-.235**	.114
Risk attitude			.023**	.011
Age	.024	.019	.026	.019
Education	-.038	.052	-.033	.051
Health status	.331	.321	.307	.32
Poverty status	-.025	.623	.177	.627
Cooperative membership	1.206***	.386	1.15***	.385
Agri-income share	.108	.48	.109	.478
Orchard size	.003	.011	.004	.011
Pesticide adjustment	.252	.353	.289	.352
Disaster occurrence	.126	.424	.121	.421
Pest severity	.167	.147	.147	.146
Hebei (ref.)	0	.	0	.
Shandong	2.772***	.418	2.767***	.416
Hubei	1.573***	.445	1.583***	.443
Constant	3.911***	1.38	4.514***	1.403
R-squared	0.211		0.223	
F-test	5.094		5.098	
Prob>F	0.000		0.000	
Observations	302		302	

*** *p<.01*, ** *p<.05*, * *p<.1*

To further examine the role of specific natural enemies, we re-estimate the model using lady beetle density alone as the key explanatory variable. As shown in (Appendix Table 4), the results remain consistent with those of the main regression, supporting the robustness of our findings.

5.3 Marginal Effects of Natural Enemies on Pesticide Application Costs

The effect of natural enemies on farmers' pesticide application behavior is mediated by their cognitive ability to identify field insects and understand the ecological relationship between pests and beneficial predators. Only when farmers are aware of the antagonistic relationship between natural enemies and pests—and can distinguish the two—can they leverage biological control to reduce pesticide costs. When all other variables in the pesticide cost model are held at their mean values, the marginal effect of natural enemies on pesticide costs changes with farmers' cognition levels, as illustrated in Figure 4.

Figure 4. Marginal change in pesticide costs by cognition level (at Mean natural enemy density)

When the density of predatory natural enemies is fixed at the average level of 8.48 individuals per sticky trap, higher cognition scores are associated with further reductions in pesticide costs. Specifically, increasing the cognition score by one point from the current average of 3.77 can reduce pesticide costs by approximately 3.9 CNY per mu. If a farmer's cognition level reaches a high score of 9, pesticide costs could decrease by roughly 20 CNY per mu. These predictions are detailed in Table 6.

Table 6. Predicted pesticide costs at varying cognition levels (Natural enemy density held at mean)

Cognition Score	Predicted Cost	95% Confidence Interval	
3.77	433.878	405.915	461.841
4.77	430.010	399.306	460.715
9	413.650	342.497	484.803

To test the robustness of the results, we replaced the aggregate predator density with the density of lady beetles, the most commonly observed predatory natural enemy as the core explanatory variable. The results in Table 7 confirm similar marginal trends.

Table 7. Predicted pesticide costs at varying cognition levels (Lady beetle density held at mean)

Cognition Score	Predicted Cost (CNY/mu)	Std. Error
0	449.980	27.627
1	445.963	22.448
2	441.946	18.002
3	437.929	14.958
4	433.912	14.246
5	429.895	16.177
6	425.878	19.998
7	421.861	24.853
8	417.844	30.248
9	413.827	35.941

Cognitive ability plays a crucial moderating role in the marginal effect of natural enemies on pesticide costs. On average, each one-point increase in cognition score corresponds to a reduction of about 4 CNY per mu in pesticide costs. If farmers' cognitive levels improve substantially, the cost savings could be considerable.

In summary, the impact of natural enemies on pesticide use is contingent on farmers' understanding of ecological interactions. If farmers remain poorly informed, increases in natural enemy populations may even raise pesticide costs due to misidentification. Only when cognitive levels reach a certain threshold can the pest suppression function of natural enemies be activated, thereby reducing pesticide reliance. Taking lady beetles as an example, when their population density is at the mean level, farmers with high cognition scores can lower their pesticide costs by up to 20 CNY per mu. Furthermore, when the initial population density of natural enemies is low, the marginal benefit from each additional individual can be particularly substantial.

6 Conclusions and Policy Implications

6.1 Conclusions

This study introduces natural enemies as an ecological control factor into farmers' pesticide application decision models. The empirical findings demonstrate that for natural enemies to effectively reduce pest pressure and pesticide use, farmers must first possess a sufficient level of cognition regarding both the identification of natural enemies and their ecological relationship with pests. Only under such cognitive conditions can natural enemies exert their pest suppression function and contribute to lowering pesticide costs. Field survey data from major pear-producing regions in China reveal that farmers' recognition of orchard insects and their understanding of pest-natural enemy dynamics remain generally low. The negative effect of farmers' cognition on pesticide costs and application frequency is significantly moderated by the density of natural enemies, as farmers' cognition improves, higher natural enemy density corresponds to lower per-mu pesticide costs and reduced spraying frequency. At the current average natural enemy density (approximately 8 individuals per sticky board), if a farmer's cognition score improves from the average of 3.77 to 4.77, pesticide costs could decrease by around 5 CNY per mu. If cognition improves to a high level (score of 9), the cost savings could reach 26 CNY per mu.

Furthermore, we find that most pear growers in the surveyed areas are risk-averse. Risk aversion has a significant positive effect on pesticide application frequency but no statistically significant effect on per-mu pesticide costs. This aligns with theoretical expectations and the findings of Huang et al. (2008). Risk averse farmers tend to apply pesticides more frequently in order to mitigate potential pest risks. However, their total pesticide expenditure does not increase significantly, potentially due to their preference for lower-cost pesticides. Because we lack detailed data on pesticide types and prices, this hypothesis warrants further empirical testing.

Participation in farmer cooperatives is found to have a significant positive impact on pesticide application frequency. This is likely due to cooperatives' centralized procurement of agricultural inputs, which lowers pesticide prices for member farmers and may encourage increased usage. Pesticide price, therefore, appears to have a strong inverse relationship with application volume, lower prices lead to higher usage. Significant regional differences are also observed. Compared to Hebei, pear growers in Shandong have significantly higher per-mu pesticide costs. In terms of application frequency, both Shandong and Hubei farmers spray more frequently than those in Hebei, likely due to regional variations in pest and disease occurrence.

6.2 Policy Implications

As an intrinsic biological factor in agroecosystems, natural enemies play a vital role in the control of native and invasive pests. Their density significantly moderates the relationship between farmers' cognition and pesticide use. Farmers' neglect or misperception of natural enemies is a major contributor to excessive pesticide application. Given the generally low level of farmer cognition regarding natural enemies and their pest-suppressive relationships, it is imperative to enhance training and education on pest control and beneficial insects.

Incorporating natural enemies into farmers' pest management decisions requires not only ecological presence but also cognitive capacity. At the current average density of natural enemies, improving farmer cognition can effectively reduce pesticide costs. However, due to the aging trend in the farming population and limited capacity to absorb new knowledge, grassroots extension services should actively diversify information channels. Strategies may include organizing regular field-based pest management workshops and providing in-field visual aids. Moreover, the supply of production-oriented services, such as timely pest forecasting and pest control guidance, should be expanded to strengthen farmers' understanding and use of ecological control agents.

Given the prevalent risk averse behavior of farmers, risk aversion significantly contributes to over application of pesticides. When confronted with uncertainty in pest control (e.g., timing, efficacy), farmers often rely on excessive pesticide use, resulting in deviations from economically optimal input levels, increased production costs, and disruption of ecological control dynamics. To address this, more accurate and accessible field pest monitoring systems should be established, complemented by technical advisory services. Additionally, optimizing agricultural insurance schemes could enhance farmers' capacity to bear risk and reduce reliance on excessive chemical control.

Over reliance on pesticides leads to escalating costs and long-term ecological harm as pests develop resistance over time. By enhancing both cognitive and technical capabilities, farmers can better leverage the natural regulatory power of beneficial insects, reducing dependence on chemical pesticides. This transition holds potential for long-term ecological sustainability and economic efficiency.

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