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Uncovering the economic value of natural enemies and true costs of chemical insecticides to cotton farmers in China

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Supplementary material for this article is available online

Abstract

Little empirical evidence on the economic value of biological control of pests at farm level is available to improve economic decision-making by farmers and policy makers. Using insect sampling and household survey in an integrated bio-economic analysis framework, this paper studies farmers' crop management practices in cotton in the North China Plain, and estimates the marginal value of natural enemies and costs of chemical insecticides to farmers. Ladybeetles (mainly *Harmonia axyridis*, *Propylea japonica*, and *Coccinella septempunctata*), the dominant natural enemy group that controls the primary pest (aphid) in cotton in our study area, provide a significant economic benefit that is unknown to the farmers. Even at the current high levels of insecticide use, an additional ladybeetle provides an economic benefit of 0.05 CNY (almost USD 0.01) to farmers. The use of broad-spectrum insecticides by farmers is alarmingly excessive, not only undermining farmers' cotton profitability but also inducing social costs as well as disruption of the natural pest suppression system. Doubling current ladybeetle density in cotton field could gain an estimated USD 300 million for cotton farmers in China, providing a strong economic case for policies to move the pest control system towards a more ecologically-based regime, with positive consequences for farm income and environmental health. With rising use of biological control service provided by natural enemies such as ladybeetles in cotton fields, significant falls in farmers' insecticide use would be expected, which could raise the value of ladybeetles and other natural enemies even further. The results indicate that there is an urgent need to rationalize inputs and move forward to improved agro-ecosystem management in smallholder farming system. Raising knowledge and awareness on the costs and value of biological pest control versus insecticides among farmers and policy makers and having effective extension service, are priorities towards achieving a more ecologically-based approach to crop protection on smallholder farms.

1. Introduction

Crop pests negatively affect food security and farm income, while insecticide usage affects the environmental performance of agriculture and farmers' health, especially in developing countries [1–3]. Natural enemies of crop pests provide an important ecosystem service to agriculture by suppressing pests and mitigating producers' pest control costs [4–6]. This service, however, is overwhelmingly underappreciated and underutilized by farmers [7]. On the one hand, the economic value of the service to individual farmers is largely unknown and therefore not explicitly accounted for in pest management decision-making [8, 9]. On the other hand, chemical insecticides, which kill not only pests but often also natural enemies among other beneficial organisms, feed into a vicious cycle of more frequent pest outbreaks associated with pesticide resistance, breakdown of the natural regulation mechanism, and perpetuated dependency on pesticides for pest control [10–13]. As a result, the long-term costs of insecticides may be greater than what short term impacts would indicate. Therefore, uncovering the economic value of natural enemies and the 'true' costs of chemical insecticides to farmers helps correcting some of the key economic parameters in decision-making, making an economic case for private producers to adopt sustainable pest management. Public's interest in reducing risks to human health and the environment associated with insecticide use [6, 14–16] may further press for policies encouraging judicious use of chemical insecticides.

This study investigates farmers' insecticide use behavior and the economics of biological pest control services provided by natural enemies. Using Bt cotton production in the North China Plain (NCP) as a case study and applying insect sampling and household survey in conjunction with an integrated bio-economic econometric analysis framework, we address three questions: (1) How do farmers make decisions on the use of insecticides to control pests, and do they consider natural enemies in their decisions when they apply insecticides in their crop fields? (2) How do additional natural enemies of pests affect farmers' insecticides use and their crop yields in the current production practices? (3) What are the marginal economic value of natural enemies and insecticide application to farmers who make pest control decisions for their fields?

2. Methods

2.1. Data

The NCP is a densely populated agricultural area in China, covering an area of approximately 400 000 km^2 and accounting for about two-thirds of China's cotton acreage in 2011 [17]. Other major crops in the NCP are wheat, maize, vegetables and fruit. Insecticides are intensively used in crop production in China, and usage in cotton is among the highest on a per hectare basis [18], despite the extensive adoption of Bt-cotton since the late 1990s [19]. Broad-spectrum pyrethroid and organophosphate insecticides represent more than 85% of all insecticide use in cotton in the NCP, and both insecticide groups have similarly deleterious effects on natural enemies in cotton [20].

The study area is located about 100 km southeast of Beijing, and includes 10 villages from Langfang prefecture in Hebei and 10 villages from Wuqing district in Tianjin [21]. The household survey included 311 cotton-farming households, randomly selected from the 20 villages (15–16 households per village). In this area, cotton is grown in predominantly small farms, with an average farm area of 0.5 hectare per household, and Bt cotton has been nearly fully adopted by farmers since early 2000s. Detailed data on household characteristics, cotton cultivation and yield, decision making and practices with respect to insecticide use were collected for each household via face-to-face interview during the 2011 cotton growing season. To ensure the accuracy of recall production input data collected, we conducted four rounds of interviews: late June, late July, late August and mid-November 2011. For each household, we selected one focal cotton field to monitor cotton pests and natural enemies of these pests. Observations on the densities of cotton pests and natural enemies were made in each field in late June, late July and late August 2011 (details in online supplementary information, section 1, available at stacks.iop.org/ERL/13/064027/mmedia).

2.2. Economic valuation analysis

When an ecosystem service can substitute for an existing marketed input or contributes to a measurable marketed output, economic value of changes in the level of the service can be readily inferred [22, 23]. A widespread application of this factor input valuation method is fertilizer replacement value to measure the value of biological nutrient cycling, for example in cereal-legume systems [24]. Zhang and Swinton [25] used a dynamic optimal pest control model to estimate the economic value of natural pest regulation service for US soybean. Other attempts at placing economic values on pest regulation services estimated the total cost of averted pest damage due to all pest control practices and then attributed a fraction of the total to natural enemies [5, 26]. The approach adopted in our study is based on empirically estimated relationships between insect densities, insecticide quantity, labor requirement, and yield (figure 1).

2.1.1. Marginal value of ladybeetles

The value of natural enemies (ladybeetles), MV(B), is estimated at the margin and consists of three benefits: (i) reducing insecticide use due to their effect on pest density; (ii) reducing labor use for spraying insecticides due to their effect on insecticide use; and (iii) reducing cotton yield loss (or increasing cotton yield) due to their

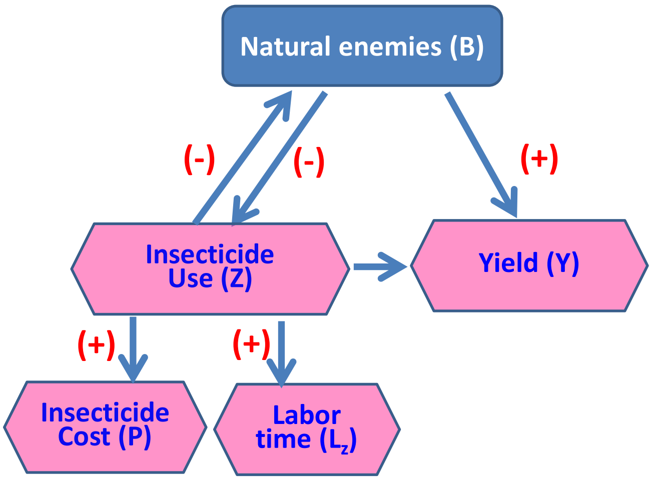

Figure 1. Bio-economic analytical framework for assessing the economic values of natural enemies and insecticide use. Note: although 'pest density' is not explicitly represented in the diagram, the economic values of natural enemies and insecticide use in the current analysis are realized through their suppression effect on 'pest density'.

effect on pest density (figure 1). The marginal value of ladybeetles implies the value of an additional unit of ladybeetle under current production environment where there is insecticide disruption and Bt cotton has been almost fully adopted by farmers, and is estimated as follows:

$$\mathrm{MV(B)} = \mathrm{MV}_1(B) + \mathrm{MV}_2(B) + \mathrm{MV}_3(B) \tag{1}$$

where $\mathrm{MV}_1(B)$, $\mathrm{MV}_2(B)$ and $\mathrm{MV}_3(B)$ are marginal value of ladybeetles from reducing insecticide use, reducing labor use, and reducing cotton yield loss, respectively.

To estimate $\mathrm{MV}(B)$, three econometric models are developed. They are farmers' per hectare insecticide use (Z, kg ha^{-1}), labor used in insecticide application (L, hour ha^{-1}), and cotton yield (Y, kg ha^{-1}) models:

$$Z = a_0 + a_1 B + a_2 P_z + a_3 S + a_4 A + a_5 E + \epsilon_z \tag{2}$$

$$L_z = d_0 + d_1 B + d_2 Z + d_3 S + d_4 A + d_5 E + \epsilon_L \tag{3}$$

$$\begin{aligned} Y = {} & \exp(b_0) F^{b_1} L^{b_2} O^{b_3} A^{b_4} E^{b_5} \\ & S^{b_6} [1-\exp(-c_1 Z - c_2 B)] + \epsilon_Y \end{aligned} \tag{4}$$

where symbols a_0 to a_5, $d_0 - d_5$, $b_0 - b_6$, and $c_1 - c_2$ denote parameters to be estimated. ε_z, ε_L and, ε_Y are random error terms with a standard distribution. Equation (2) models insecticide use as a linear function of ladybeetle density B (1000 ha^{-1}, measured as the average density in late July and late August), insecticide price or average unit value of insecticides P_z (CNY kg^{-1}) (measured as total value divided by total quantity of insecticides used), field size S (ha), age of household head A (year), and education of household head E (years). In this equation, ladybeetle density B is our key interest. We did not include pest density in this model because pest density is also a function of ladybeetle density. Using observed ladybeetle density implies that we estimate the model using a reduced form of ladybeetles. In addition, including both pest (e.g. aphid) and ladybeetle densities in the model induces multi-collinearity issue in the econometric analysis.

Equation (3) models labor use for insecticide application (L_z). Here Z becomes one of the explanatory variables. If Z is correlated with the error term in equation (3), the estimation of the effect of Z on L_z will be biased [27]. To address this potential endogeneity issue, we included P_z in equation (2) as an instrumental variable for Z and included the predicted value of Z from equation (2) in equation (3).

Equation (4) models farmers' cotton yield (kg ha^{-1}), Y, as a non-linear production function with two components. The first component is a Cobb–Douglas production function that accounts for the effects of standard inputs and household characteristics. Standard inputs include fertilizer use (F, the sum of elemental N, P and K, kg ha^{-1}), total labor use (L, hour ha^{-1}), and other input uses (O, the sum of input costs of seed, irrigation and control weed, CNY ha^{-1}). The second component is an exponentially decreasing damage control function [28, 29], which reflects diminishing returns for damage abatement inputs including insecticides and ladybeetles. We chose the exponential damage control function because it fits our field survey data better than the alternative Weibull specification. Similar to equation (3), the predicted values of Z in equation (1) are used in equation (4).

From equations (2–4), which are estimated with Ordinary Least Squares (OLS), we derive $\mathrm{MV}_1(B)$, $\mathrm{MV}_2(B)$, and $\mathrm{MV}_3(B)$, respectively. Then $\mathrm{MV}(B)$ is calculated as follows:

$$\begin{aligned} & \mathrm{MV}(B) = \mathrm{MV}_1(B) + \mathrm{MV}_2(B) + \mathrm{MV}_3(B) \\ & = [-a_1 P_Z] + [-d_1 W] + [c_2 \exp(b_0) F^{b_1} L^{b_2} O^{b_3} \\ & A^{b_4} E^{b_5} F s^{b_6} \exp(-c_1 Z - c_2 B) P_c] \end{aligned} \tag{5}$$

where P_Z is the average price of insecticides used by farmers (54.13 CNY kg^{-1}); W is the implicit wage of family farming labor. For the study area, the rate was estimated at 5 CNY $hour^{-1}$ in 2011, about two-thirds of the hourly wage of migrant labor working in the urban area during the same year (estimated at 80 CNY per day and 10 hours per day). P_c is the average price of cotton output (seed cotton, 8.33 CNY kg^{-1} in the study area in 2011). The marginal values of ladybeetles, equation (5) can be calculated for different values of B based on the mean values of all other variables, using only those estimated parameters that are statistical significant in equations (2)–(3). A summary of statistics of all variables used in regressions is presented in the online supplementary information (table S1).

2.1.2. *Marginal cost and benefit of insecticide use*

The costs and benefits of insecticide use are also evaluated at the margin and interpreted as the marginal value of an additional unit of insecticide use under current conditions. The estimation consists of three components (figure 1): (a) $MC_1(Z)$, marginal cost of insecticide product (or unit price of insecticide, P_c); (b) $MC_2(Z)$, marginal cost of labor input for insecticide application; and (c) $MB(Z)$, marginal benefit of insecticide use from reducing cotton yield loss (or increasing cotton yield). A fourth component, $MC_3(Z)$, which is the marginal cost of insecticide use due to ladybeetle mortality, is also discussed and presented in section 3 of SI but is not included in the final estimate as we opt for a conservative valuation method in light of the uncertainty about the causal directions (explained in section 3.2). The analysis also does not cover the costs to farmer's health and local environment. The marginal value of insecticide use, $MV(Z)$, is given by:

$$MV(Z) = MB(Z) - MC_1(Z) - MC_2(Z). \quad (6)$$

From equations (3) and (4), we can derive MB(Z) and $MC_2(Z)$, respectively, as follows:

$$MB(Z) = [c_1 \exp(b_0) F^{b_1} L^{b_2} O^{b_3} A^{b_4} E^{b_5} F^{b_6} \exp(-c_1 Z - c_2 B)] P_c \quad (7a)$$

$$MC_2(Z) = -d_2 W \quad (7b)$$

where variables and parameters are the same as defied above.

Then $MV(Z)$ can be estimated as:

$$MV(Z) = [c_1 \exp(b_0) F^{b_1} L^{b_2} O^{b_3} A^{b_4} E^{b_5} F^{b_6} \exp(-c_1 Z - c_2 B)] P_c - P_z - [d_2 W]. \quad (8)$$

To explore how the marginal value of insecticide use, $MV(Z)$, varies under different circumstances, we conducted simulations, using mean values of all other variables in equations (3) and (4). The parameters are estimated from equations (3) and (4), again, we used only those estimated parameters that are statistically significant.

Table 1. Cotton seed yield and inputs of fertilizer, insecticide and labor per hectare in cotton production in the study areas ($N = 311$).

	Mean ± SE
Yield of cotton (kg ha^{-1})	3146 ± 616
Inputs:	
Fertilizer use, in elemental N, P and K (kg ha^{-1})	192 ± 149
Number of insecticide applications	8.2 ± 2.7
Insecticide use (kg ha^{-1})	22.4 ± 13.7
Insecticide cost (CNY ha^{-1})	1092 ± 662
Labor use (hour ha^{-1})	2296 ± 869
Labor used in insecticide application (hour ha^{-1})	173 ± 116

3. Results

3.1. Farmers' insecticide use practices

Farmers frequently applied insecticides for the control of cotton pests. The surveyed cotton plots were treated 1–14 times over the growing season, 8.2 times on average (table 1). Our survey confirmed that most insecticides used are broad-spectrum, particular pyrethroid and organophosphate insecticides [20, 28, 30]. The average amount of formulated insecticide product applied was 22.4 kg ha^{-1}, at an average cost of 1091.7 CNY ha^{-1} (approximately USD 169)[8]. In addition, farmers put in 173.2 hours of labor per hectare, on average, to carry out the insecticide applications. For a household that planted 0.5 hectare of cotton in our study area, the estimated total cost of insecticide application was equivalent to 3.7% of household average income or 10% of the average crop income of rural households in Hebei in 2011 [17].

Cotton aphids (*Aphis gossypii*) were the only abundant cotton pest (figure 2). Whiteflies (*Bemisia tabaci*) were present in July and August, but much less abundant than aphids. Densities of spider mites (*Tetranychus cinnabarinus*; <0.2/plant), mirid bugs (mainly *Apolygus lucorum*; <0.05/plant), and bollworm (*Helicoverpa armigera*; <0.03/plant) were negligible. Ladybeetles (mainly *Harmonia axyridis*, *Propylea japonica*, and *Coccinella septempunctata*) were dominant among the natural enemies (figure 3). Their numbers were very low (1.6/100 plants) in June—none were found in 250 of the 311 focal fields and those appeared in 61 fields were predominately larvae. Ladybeetle numbers were much greater in July and August (figure 3). Most individuals observed in July and August were in the adult stage, while larvae were mostly absent, indicating that the individuals found may originate from habitats other than the focal fields. Given that aphids are the primary pest in cotton and that ladybeetles are the main natural enemy group that control cotton aphid in our study villages and the NCP [20, 21], our analysis focuses on the cotton aphid–ladybeetle relationship.

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[8] The official exchange rate was 6.46 CNY/US$ in 2011.

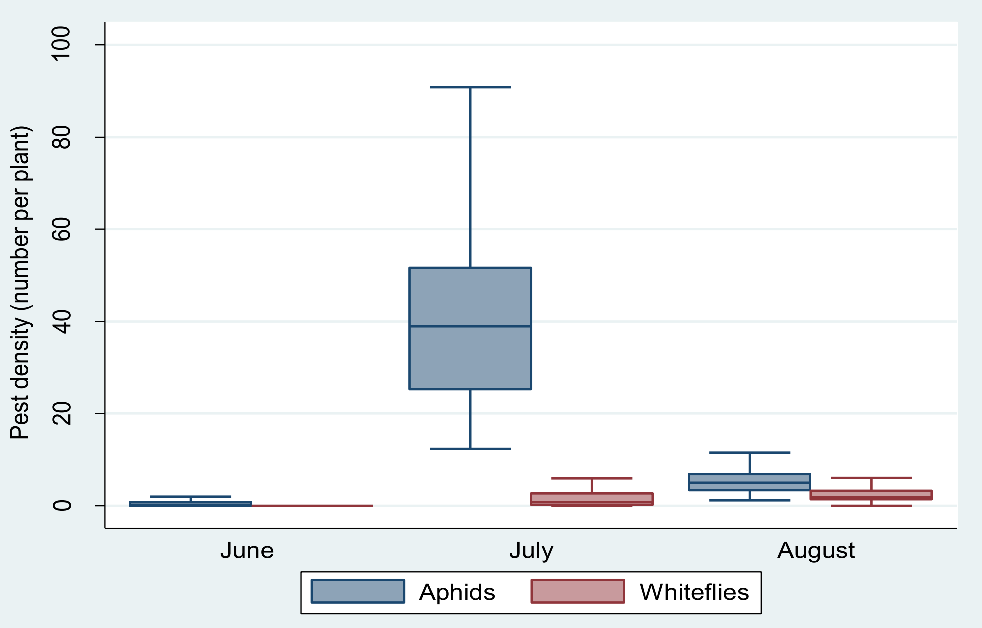

Figure 2. Density (number per cotton plant) of the two main cotton pests (aphids and whiteflies) in 311 cotton fields surveyed in June, July and August 2011. The values in the middle, the upper hinge, and the lower hinge of the box are the median, the position of the 25 percentile, the position of the 75 percentile, respectively. The whiskers indicate the highest and the lowest datum within 1.5 IQR (the difference between the 1st quartile and the 3rd quartile) of the upper quartile and the lower quartile).

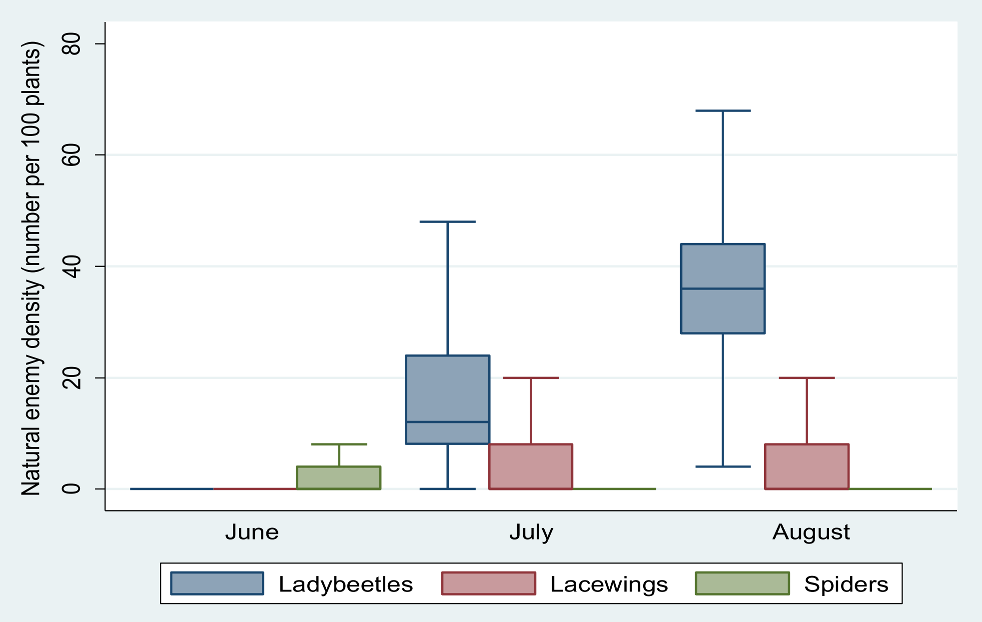

Figure 3. Number of natural enemies per 100 cotton plants in June, July and August 2011. See the legend of figure 2 for the values in the middle, the upper hinge, and the lower hinge of the box as well as the whiskers.

We interviewed farmers about their insecticide application decisions for each major pest (table 2). The vast majority based their insecticide use decisions on the presence of aphids in the cotton field (34.6% + 56.6%), while the other 9% used prophylactic (preventative) spraying to prevent cotton aphid. The practice of prophylactic treatment was more widespread for mirid bugs and cotton bollworm, at rates of 27% and 35%, respectively. Only one of the 311 interviewed farmers indicated awareness of aphid natural enemies (e.g. ladybeetles) in his cotton field but he did not take them into consideration when making insecticide treatment decisions. This finding reveals that farmers' decision-making on pest management did not factor in the potential of biological pest control by natural enemies.

On each actual insecticide application, we also asked farmers to record the primary targeted pest(s)

Table 2. Reported motivation for farmers' decision to apply insecticides to control cotton pests (percent of households). 'Others' include suggestions by other people, the number of pest natural enemies, and no clear reasons.

Pest	Preventative application	Apply when observing insects or eggs in fields		Others
		Less than 5 insects per 100 plants or some eggs	More than 5 insects per 100 plants	
Aphid	8.6	34.6	56.6	0.2
Mirid bugs	27.2	51.4	20.8	0.6
Bollworm	35.9	46.7	17.3	0.1

Table 3. Insecticide sprays by primary target pest(s) recorded by farmers.

Primary targeted pest(s) (PTPs) by each spray	Number of insecticide applications	Percentage of application that also controlled non-PTPs (%)
Aphid	2.95	4
Bollworm	0.95	18
Mirid bugs	0.38	22
Aphid + mirid bugs	0.68	17
Aphid + bollworm	1.59	11
Mirid bugs + bollworm	0.56	7
Aphid + mirid Bugs + bollworm	1.09	6
Total	8.2	9

(PTPs) that was aimed to control and non-PTPs that could also be controlled at the same time (table 3). The results show that: (1) aphids, among the singularly targeted pests, received the highest number of insecticide applications; and (2) farmers also often use insecticides to control more than one pest at a time (rows 4–7); and 3) on the average, 9% of 8.2 insecticide applications (or 0.74) also helped controlling non-PTPs.

3.2. Impact of ladybeetles on insecticide use and associated labor input

Greater ladybeetle population densities are associated with lower insecticide use (figure 4). There are multiple effects and causal pathways underlying this: (1) ladybeetles reduce pest level, which in turn reduces the volume of insecticides used; (2) a greater proportion of ladybeetles are killed in fields that receive more insecticides; (3) fields with fewer aphids will accumulate fewer ladybeetles as the residence time of ladybeetles depends on prey density [31]. Dynamically reciprocal causality in the ladybeetle-insecticide use relationship, if present, would introduce self-reinforcing feedbacks in the pest control system. This implies a potential for either a vicious cycle (i.e. the pesticide treadmill; [11]) or a virtuous cycle, when re-establishment of biocontrol services reduces the need for insecticide, further strengthening biocontrol service potential. Such dynamic relationship could in theory be modeled but this requires additional assumptions that are difficult to justify based on our survey data. Here, we identify the relationship between ladybeetle density, insecticide use, and farm economic outcomes based on econometric modelling from a farmer's behavioral point of view. The econometric model was estimated with insect density data collected in late July and late August when ladybeetle individuals were predominantly adults in our study area which are less susceptible to insecticide poisoning than larvae. Because other factors might also affect farmers' insecticide use (kg ha^{-1}) and associated labor input (hour ha^{-1}), we ran multivariate regressions to control for the confounding factors.

Table 4. Estimated parameters for insecticide use and labor used in insecticide applications in cotton production. Absolute t statistics in parentheses; * $p < .10$, ** $p < .05$, *** $p < .01$ ($N = 311$).

	Insecticide use (kg ha^{-1})[b]	Labor use in insecticide application (hour ha^{-1})
Insecticide price (CNY kg^{-1})	−0.19*** (6.71)	
Ladybeetles density (1000 ha^{-1})	−0.69*** (6.05)	−1.95* (1.85)
Insecticide use (kg ha^{-1})[a]		2.40*** (5.12)
Cotton field size (ha)	−18.81*** (3.82)	−174.65*** (4.03)
Age of household head (year)	0.04 (0.49)	1.54** (2.28)
Education of household head (year)	0.38 (1.45)	0.28 (0.12)
Constant	40.95*** (6.84)	97.85* (1.92)
Adjusted R^2	0.25	0.20

[a] Regression coefficient when using predicted value of insecticide use Z, to predict labor time.

[b] To check the robustness of our results to alternative specifications for insecticide use, we also tried using the number of insecticide applications in the regression (see section 4 in the online supplementary information).

Ladybeetle density is significantly and negatively associated with per hectare insecticide use (table 4). An increase of 1000 ladybeetles per hectare, equivalent to nearly 2 ladybeetles per 100 cotton plants at a density of 54 000 plants ha^{-1} in the study villages (details in SI, section 2), is associated with a reduction of insecticide use of 0.69 kg ha^{-1} ($P < 0.01$). Furthermore, an increase of 1000 ladybeetles per hectare is associated with a reduction in labor use in insecticide application of 1.95 hours ha^{-1} ($P < 0.10$). Expressed per ladybeetle individual, the corresponding savings are estimated at 0.69 g formulated insecticide and 7 seconds labor time per ladybeetle. Given the huge potential densities of ladybeetles per hectare, these are major potential benefits.

3.3. Impact on yield

The estimated coefficient for ladybeetle density in the cotton yield equation was positive and statistically significant (c_2 in table 5), indicating that an increase in

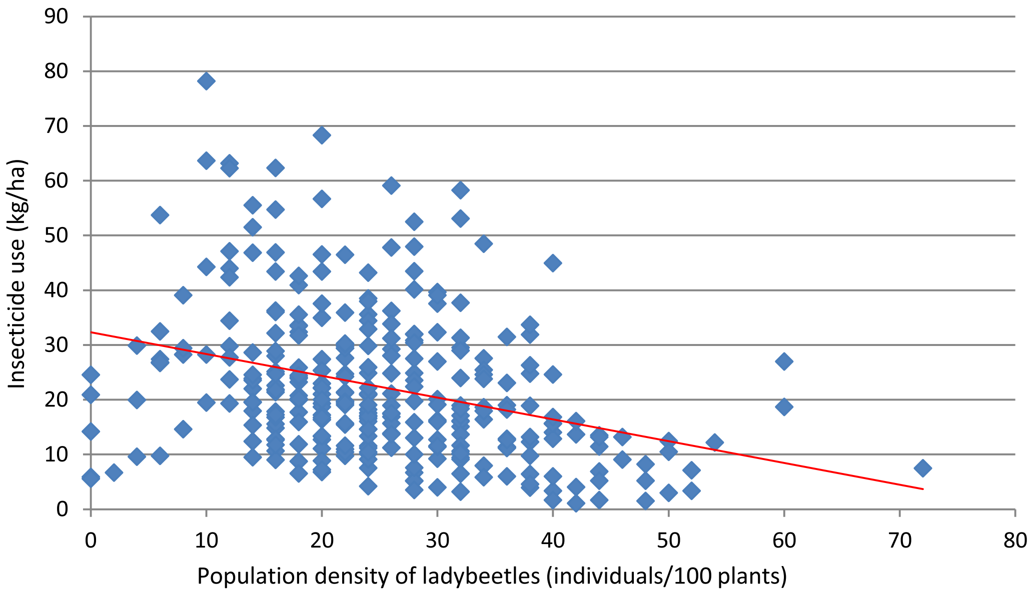

Figure 4. Population density of ladybeetles (average in July and August) and total insecticide use in cotton fields over the growing season.

ladybeetle density reduced cotton yield loss from pest attack. Based on the fitted equation, a 50% reduction of yield loss to pests is reached at a ladybeetle density of 17 000 individuals ha^{-1}, holding everything else constant at the sample mean. Likewise, the fitted model indicates a positive impact of insecticide use on cotton yield (c_1 in table 5), corresponding to a 50% reduction of yield loss to pests at an insecticide input of 2.24 kg ha^{-1}, approximately a factor 10 smaller than the actual usage of insecticides.

Other factors also contributed to cotton yield. These include total labor input, education level of household head, and size of cotton field. The latter confirms the economy of scale effect for cotton cultivation in the study area. Fertilizer use was not significantly correlated with yield, suggesting over-use of fertilizers by farmers. To ensure high yield, overuse of fertilizers in crop production has been common in China [32]. Farmers in our sample applied 192 kilograms of fertilizer per hectare. Insignificant coefficient of fertilizer use implies that marginal impact of fertilizers is about zero, which is consistent with previous findings [32, 28].

3.4. Economic value of ladybeetles

Based on estimated coefficients in tables 4 and 5, we computed the marginal value of ladybeetles to cotton farmers, accounting for (1) the reduced cost of insecticides; (2) the reduced labor cost associated with insecticide application; and (3) the yield benefit estimated from the damage control production function.

Ladybeetle density in our study fields averaged 13 500 ha^{-1} in July and August 2011. An increase of ladybeetle density by 1000 ha^{-1} (7.4% of the current density level) in the NCP is worth 47.74 CNY (equivalent to USD 7.39), given the current cotton production practices (table 6). Lower insecticide use is associated with higher densities of ladybeetles and savings of about 38 CNY ha^{-1} (or USD 5.8) on costs of insecticides and 10 CNY ha^{-1} (or USD 1.5) on costs of labor. The marginal impacts on cotton yield and income are small (0.047 kg ha^{-1} on yield and 0.39 CNY ha^{-1} on income). This is partly due to the fact that farmers in the NCP have in general applied excessive

Table 5. Estimated parameters for cotton yield using Cobb–Douglas-exponential damage control function. To avoid the endogeneity problem, the predicted values of Z based on column 1 in table 4 are used in the regression of cotton yield function. Absolute t statistics in parentheses; * $p < .10$, ** $p < .05$, *** $p < .01$ ($N = 311$).

	Ln(Y) (kg ha^{-1})
Inputs in Ln(X) form:	
Fertilizer use (kg ha^{-1})	0.02 (1.31)
Labor use (hour ha^{-1})	0.07** (2.26)
Other inputs (CNY ha^{-1})	0.003 (0.07)
Household characteristics in Ln(H) form:	
Age of household head (year)	0.08 (1.32)
Household head education (year)	0.04* (1.75)
Cotton field area (ha)	0.06*** (3.52)
Damage control function parameters	
c_1 (parameter for insecticide use, Z)[a]	0.31*** (4.43)
c_2 (parameter for ladybeetle density, B)	0.04*** (3.15)
Constant	7.10*** (16.74)
Adjusted R^2	0.11

[a] To check the robustness of our results to alternative specifications for insecticide use, we also tried using the number of insecticide applications in the regression (see section 4 in the online supplementary information).

Table 6. Marginal economic values of ladybeetles and insecticide use in cotton production in NCP in 2011. The official exchange rate was 6.46 CNY/US$ in 2011.

	Additional ladybeetles ($+1000$ ha^{-1})	Additional insecticides ($+1$ kg ha^{-1})
Insecticides:		
Quantity (kg ha^{-1})	0.69	1.00
Price (CNY kg^{-1})	54.13	54.13
Cost (CNY ha^{-1})	37.35	−54.13
Labor time:		
Quantity (hour ha^{-1})	1.95	2.40
Wage (CNY hour^{-1})	5.00	5.00
Cost (CNY ha^{-1})	9.75	−12.00
Cotton yield		
Quantity (kg ha^{-1})	0.047	0.363
Price (CNY kg^{-1})	8.33	8.33
Income (CNY ha^{-1})	0.39	+3.02
Economic value (CNY ha^{-1})	47.49	−63.14

amounts of insecticides to control pests (22.35 kg ha^{-1} on average), substantially curbing the efficiency and marginal value of both insecticides and natural pest regulation.

The marginal value of ladybeetles declines as their density rises, regardless of the level of insecticide use (figure 5). Moreover, the marginal value of ladybeetles decreases with the volume of insecticide used, especially at lower ladybeetle densities. For example, at the density of 1000 individuals ha^{-1}, the marginal value of ladybeetles is 47.74, 67.65 and 163.27 CNY ha^{-1} when evaluated at the mean, one-half of the mean, and one-fourth of the mean insecticide use volumes, respectively. This considerable driving effect of insecticide use on the marginal value of ladybeetles is mainly due to higher marginal value of ladybeetles at lower insecticide use. At the current average density of ladybeetles (13 500 individuals ha^{-1}), the marginal value of the ladybeetles would rise from 48 CNY ha^{-1} at the current insecticide use (22.35 kg ha^{-1}) to 118 CNY ha^{-1} at one fourth of the current insecticide use.

3.5. Economic value of insecticides

High insecticide use contributes negatively to farmers' income. At the current average insecticide use level, for each additional kilogram of insecticides applied in cotton fields, farmers not only pay for the purchase price of insecticides (54.13 CNY kg^{-1} on average), but also incur labor cost for spraying (12 CNY ha^{-1}) (table 6), while gaining a mere 0.36 kg ha^{-1} yield saving valued at 3.02 CNY ha^{-1}. As a result, one additional kilogram of insecticide per hectare from the current usage level would reduce farmers' income by 63.14 CNY ha^{-1}, indicating that the 'true' marginal value of insecticides is in actuality negative. Given the uncertainty about the causal directions in the system as discussed above, the actual marginal cost of insecticide use can be greater or smaller. For example, an attempt to explicitly account for the loss of biological control provided by ladybeetles (estimated at 2.71 CNY ha^{-1}) would increase the marginal cost of insecticide use to 65.18 CNY ha^{-1} (63.14 CNY ha^{-1} + 2.71 CNY ha^{-1}). Despite the uncertainties and limitations in the data and the interpretation, there is convincing evidence that ladybeetles are an important driver in the system as the estimated coefficients of ladybeetle density in both insecticide use and cotton yield equations are statistically significant at 1% level (tables 4 and 5). It is plausible that, by suppressing aphid levels, ladybeetles are likely to drive down insecticide use, offering an economic value to cotton farmers. We put the upper bracket of the marginal cost of insecticides at 63.14 CNY ha^{-1}, as opposed to 65.18 CNY ha^{-1}, as it is deemed a more conservative estimate.

Figure 6 reports the marginal value of insecticides evaluated at different levels of insecticide use, showing clearly the extent of excessive use by farmers in our study area. At the current average price of insecticides and level of ladybeetle density, the optimal level of insecticide use, at which the marginal cost of insecticides is equal to the marginal value product of insecticides, is estimated to be 10.39 kg ha^{-1}. This value places an upper bracket on the optimal insecticide use because the negative social and environmental costs associated with insecticides are not incorporated in the analysis. The actual use in our sample is more than two times the calculated upper bracket for the optimum.

4. Discussion

Even at the current high levels of insecticide use, each additional ladybeetle provides an economic benefit of 0.05 CNY (47.49/1000 or USD 0.008) to farmers. Extrapolating the results and doubling the current average density of ladybeetles ($13500\ \mathrm{ha}^{-1} \times 2 = 27000\ \mathrm{ha}^{-1}$) could potentially increase farmers' income by about 644 CNY per hectare of cotton ($47.49 \times 13500/1000$; equivalent to USD 100). If we could apply this number to two-thirds of China's cotton area ($2/3 \times 5038$ thousand hectares) in 2011, doubling the density of ladybeetles would be associated with an increase of USD 336 million ($100 \times 2/3 \times 5038\,000$) for cotton farmers, and any reduction in insecticide use would induce even higher economic value of ladybeetles. Given the commonness of ladybeetles and the high densities that may be attained when they are conserved, these values could be high enough to justify conservation investment. With rising use of biological control service provided by natural enemies such as ladybeetles in cotton fields, significant falls in farmers' insecticide use would be expected, which could raise the value of ladybeetles and other natural enemies even further.

This study expands our understanding of the actual value of insecticide use by farmers. The identified extent of insecticide overuse is alarming, to say the least, not only costing farmers farming profit but also inducing social costs as well as disruption of the natural pest suppression system. Given the current insecticide

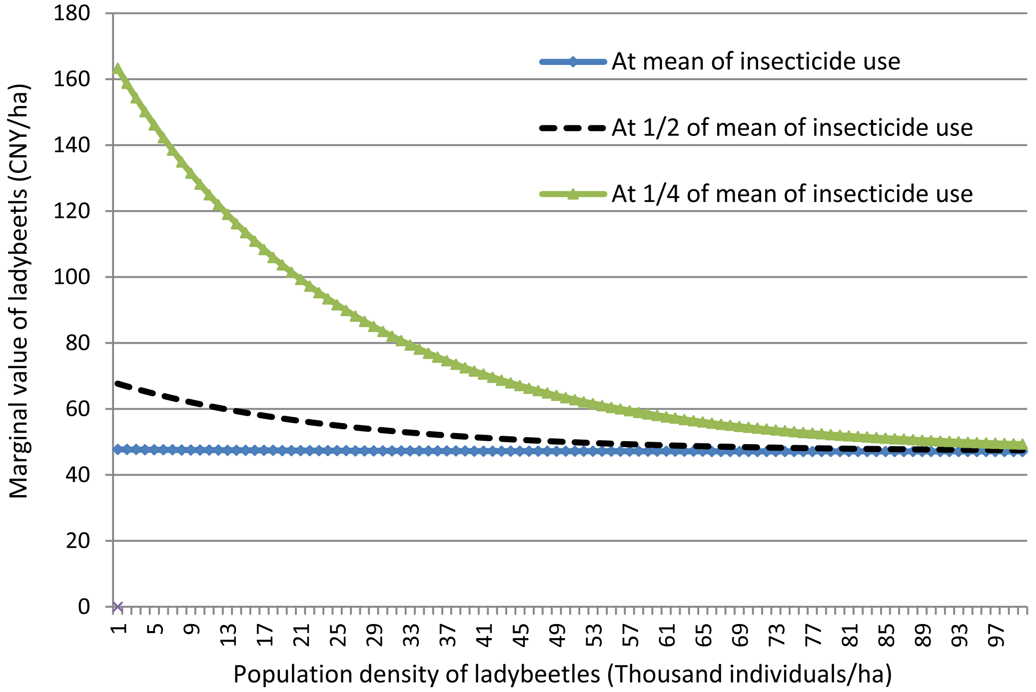

Figure 5. Marginal value of ladybeetles evaluated at different ladybeetle densities ranging from 1 k individuals ha^{-1} to 100 k individuals ha^{-1} and three levels of total insecticide use at: (*a*) mean insecticide use level (22.35 kg ha^{-1}), (*b*) 1/2 of the mean insecticide use (11.18 kg ha^{-1}), and (*c*) 1/4 of the mean insecticide use (5.59 kg ha^{-1}).

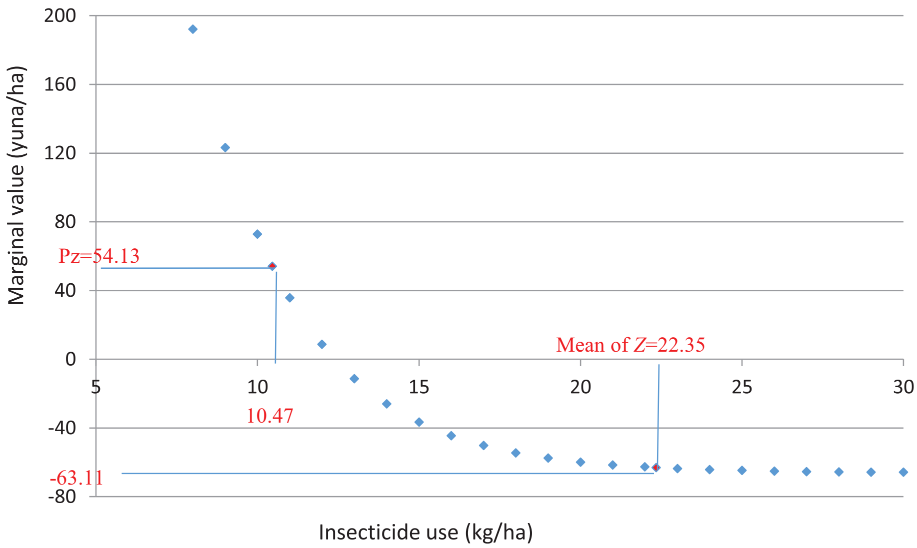

Figure 6. Marginal value of insecticide use evaluated at different levels of insecticide use. Optimal insecticide use (10.47 kg ha^{-1}) is at the point where marginal value of insecticide equals its price (P_z, 54.13 CNY kg^{-1}). Mean value of insecticide use (Z) is 22.35 kg ha^{-1}.

practices, farmers indeed can significantly increase their income by reducing the amount of insecticide used. Incorporating social and environmental benefits means additional values to the society. More research is needed to understand to what extent farmers choose input levels to maximize profit versus production, or minimize risks, so that more comprehensive policy responses can be developed to address both economic and behavioral incentives.

Based on the case of natural suppression of aphid by ladybeetles in our analysis, substituting insecticide use with biological control service is a potential win-win-win choice for farmers, though the extent of benefits can vary greatly from context to context and is influenced by many factors such as the existence of multiple pests and how each of them respond to insecticide products. Reducing reliance on insecticides and harnessing biological control service holds promise to increase farmers' income, reduce adverse health impacts [2, 33], and improve the local living and production environment. Previous studies often claim that farmers have no compelling economic incentive to reduce insecticide use [1, 6, 34]. However, our study reveals that there exists high economic incentive to reduce insecticide use and increase biological control service, but farmers (and policy makers) lack this knowledge. As a first step, it requires that the 'hidden' values of biological and insecticide pest controls are quantified and more widely disseminated. Thus, the lack of adoption of IPM and biological control is not only a problem of collaboration and risk averseness [35], but also a problem of knowledge and recognition of the private benefit from biological control service and reduction of insecticide uses to farmers. Communicating these 'hidden' values to farmers, for example, through the agricultural extension service, should be prioritized, though serious effort is required of extensions to broaden their services to include more topics about the health risks and adverse effects of agrochemicals on the environment and improve the effectiveness of their communications [36, 37]. Certainly, addressing knowledge deficit is not sufficient for farmers to change behavior and there are many other important non-economic obstacles to the adoption of biocontrol by farmers including the risk and uncertainty involved when relying on biocontrol instead of a seemingly more predictable option of insecticide-based control (at least in the short-term). Such obstacles will need to be addressed, for instance, through insurance mechanisms and intensive training such as collective and active learning in farmer field schools over multiple seasons to provide the farmers with sufficient trust to let go of insecticides.

5. Concluding remarks

This study for the first time attempted to quantitatively measure the significant 'hidden' value of ladybeetles in pest management in real farmers' fields where small plot farming is dominant and insecticides are excessively used to control pests. In the long run, effective agroecosystem management will demand more of managers than simply reducing the non-target effect of insecticides on natural enemies [25]. Habitat management designed to create a suitable ecological infrastructure within the agricultural landscape (e.g. through establishing hedgerows and woodlots) can provide needed habitat resources and functions for natural enemies [4, 38]. When arthropods providing biological control services move at the landscape level such as is the case for ladybeetles [39], and farm sizes are small as they are in the NCP [21], economic assessment at the landscape level and coordination of habitat management across neighboring farms becomes advantageous [40, 30].

The methodology developed in this study also has implications for other studies. While the estimated values are specific for cotton farming in the study area and a key pest–predator complex in the system (e.g. cotton aphid and its most important group of predator natural enemies, ladybeetles), the novel approach developed here can be applied to the valuation of a wide range of regulating and supporting ecosystem services (e.g. soil fertilization, nutrient cycling, and pollination) that, as inputs, support the production of marketed goods.

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