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Effects of land use and insecticides on natural enemies of aphids in cotton: First evidence from smallholder agriculture in the North China Plain

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ABSTRACT

Studies conducted in the USA and Europe have shown that diverse landscapes in general support greater natural enemy abundance. No quantitative evidence on the relationship between land use diversity and natural enemies has been reported from developing countries, where fields and farms are much smaller than in modernized agriculture in the west, and where insecticide use is often high and indiscriminate. This paper examines the effects of land use and farmers' insecticide application on natural enemies of aphids in cotton production, based on a unique dataset that links household and cotton field surveys to a detailed assessment of land uses in the landscapes surrounding the cotton fields in the North China Plain (NCP), a major grain and cotton production region in China. Our results show that, in the NCP where farms are small and landscape is dominated by a few crops, Shannon or Simpson land use diversity index is not a good indicator for explaining the relationship between land use and densities of aphid natural enemies. Instead, the types and proportions of cropland habitat mattered. Landscapes with more maize and grassland have higher ladybeetle populations in cotton fields. Farmers' pest management practices such as the amount and timing of insecticide use significantly affect ladybeetle densities. These results imply that there is a need to recognize the potential positive role of cropland use in pest management and call for more judicious insecticide use strategies by smallholder farmers in the North China Plain.

1. Introduction

Biological control of pests by natural enemies represents an important ecosystem service for agriculture (Naylor and Ehrlich, 1997; Losey and Vaughan, 2006). Biological control can mitigate crop yield loss and pest control costs in agricultural ecosystems (Costamagna et al., 2007; Landis et al., 2008). Increased landscape complexity is typically correlated with higher natural enemy populations and, in many cases, enhanced pest control in agricultural landscapes (Landis et al., 2000; Tscharntke et al., 2005; Bianchi et al., 2006; Gardiner et al., 2009).

Empirical evidence in support of this relationship has been collected mainly for cropping systems in North America and Europe (Marino and Landis, 1996; Thies et al., 2003; Schmidt and Tscharntke, 2005; Gardiner et al., 2009). Virtually no information is available from small-scale farming dominated systems in developing countries, where field sizes are often small, and fields with different land uses may be mixed at fine spatial scales. While people in developing countries have similar needs for safe food and environmentally sound pest control by natural enemies as people in developed countries, pest control ecosystem services have been often ignored in pest management decision making by farmers in developing countries (Wyckhuys et al., 2012). Small-scale farms highly depend on the use of broad-spectrum insecticides to control pests (Huang et al., 2002), which can damage the populations of natural enemies, reducing the cost-effectiveness of insecticide investment if unaccounted for in treatment decisions (Zhang and Swinton, 2009).

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Insecticides are intensively used in Chinese agriculture, and insecticide use in cotton is among the highest on a per area basis, despite the extensive adoption of Bt-cotton since the late 1990s (Huang et al., 2010). Besides the well-documented human health and environmental risks (Pimentel et al., 1992; Naylor and Ehrlich, 1997), the economic costs of insecticide use have been increasing since around 2005 (Huang et al., 2010), hindering the growth of farm income. Therefore, research on managing landscape and improving farmers' insecticide application practices for enhanced pest control ecosystem services, which have the potential to protect crop yield while reducing insecticide use in cotton, is meaningful and urgently needed.

The overall goal of this study is to fill the knowledge gap about the effects of land use and farmers' insecticide application on natural enemies in a developing country context characterized by small farm sizes and high use of insecticides such as China. Specifically, this paper examines the following three research questions: (1) what are the effects of land use on natural enemies of aphids in cotton production? (2) what are the effects of farmers' insecticide use on natural enemies? and (3) how to appropriately apply land use data to measure landscape impacts on natural enemies? To address these questions, we collected a unique set of data that included insect samplings in farmers' fields, household survey questionnaires on pest management practices, and detailed land use data obtained through high resolution satellite imagery and extensive ground trothing in the North China Plain (NCP).

We selected the North China Plain (NCP) because it is a major cotton production region in China. The region accounts for 27% of the agricultural land area of China but produces 40% of cotton (NSBC, 2012). Other major crops in the NCP include wheat, maize, and vegetables. Small areas of fruit trees and trees for wood production (mostly *Populus* sp.) are present in the NCP. Agricultural landscapes of the NCP consist of a mosaic of small cultivated plots crisscrossed by irrigation canals and ditches, with small patches of grassland and woodland interspersed between crop fields as the main non-crop elements. In addition, water bodies have some bordering wetland vegetation. Broad spectrum insecticides, particular pyrethroid and organophosphate insecticides, are used intensively, sometimes two times per week over extended periods of time (Lu et al., 2012; Huang et al., 2002).

2. Materials and methods

2.1. Study area

Within the NCP, we conducted surveys in 20 villages spread across three counties (Anci, Bazhou and Wuqing) of Hebei province (Fig. 1). This region is about 100 km South-East of the perimeter of the outskirts of Beijing. Ten villages were selected from Wuqing, six from Anci, and four from Bazhou, representing a gradient in land use pattern (see below). Village centers were separated by at least 3 km.

2.2. Selection of households

A random sampling approach was used to select households to avoid selection bias in econometric analysis. In each of the 20 villages, we obtained a list of all cotton farmers from the office of village committee, based on which we randomly selected 16 households. Nine households were removed from the total sample of 320 because of missing data. Thus, the sample used in the analysis included 311 households, 311 cotton fields associated with the households, and landscape data for 20 villages (see below for details).

2.3. Household survey

Detailed data on household characteristics, insecticide use decision making and actual insecticide use were collected for each household via face-to-face interview during the 2011 growing season[1]. Four rounds of interviews were carried out in: (1) late June, (2) late July, (3) late August and (4) mid-November, 2011. For each household, we selected the largest cotton field as our target field (or plot) to monitor cotton pests and their natural enemies. To obtain information on insecticide use decision making, we asked farmers whether they had considered pest numbers in their cotton fields and other factors when deciding on the application of insecticides. In this question "other factors" could include, for instance, the number of pest natural enemies (e.g. ladybeetles), the desire to prevent problems in the future (i.e. spray prophylactically), or following suggestions by other people. Data on dosage and frequency of actual insecticide use in the target fields were also collected in all four rounds. This procedure allowed us to link farmers' insecticide uses in each target cotton field to biological data on pests and natural enemies in the same cotton field obtained by field observation at the same time.

2.4. Field observations on insects

Observations on the densities of cotton pests and natural enemies were made in each of the 311 cotton plots three times in late June, late July and late August in 2011. In each plot each time, five clusters of plants were sampled, using an "X"-shaped sampling path covering the entire plot. Each cluster included 5 plants, resulting in a total sample of 25 plants per plot. The assessment of agronomically important arthropods was made for the whole plant (or all leaves in the plant). Our team of enumerators, which consisted of 15 graduate students majoring in agronomy, entomology, and agricultural economics, were trained by entomologists and IPM specialists on population sampling and assessing pests and natural enemies in cotton. On average, an enumerator spent 1 h, 2.5 h and 3 h in one field (i.e. 25 plants) to count the insect numbers in late June, late July and late August, respectively.

We collected data for five common pests: cotton aphid (*Aphis gossypii* Glover), spider mites (*Tetranychus cinnabarinus* Boisduval), mirid bugs (mainly *Apolygus lucorum* (Meyer-Dür), cotton bollworm (*Helicoverpa armigera* Hübner), and whitefly (*Bemisia tabaci*). We further collected density data for three groups of natural enemies: ladybirds (predominantly *Harmonia axyridis* Pallas, *Propylea japonica* Thunberg, *Coccinella septempunctata* L.), lacewings (predominantly *Chrysopa septempunctata* Wesmael, *Chrysoperla sinica* Tjeder and *Chrysopa formosa* Brauer) and spiders (predominantly *Erigonidium graminicolum* Sundevall, *Pardosa t-insignita* Boes. et Str. and *Misumenopos tricuspidata* Fahricius).

For pest and natural enemy survey, we adopted the entire-plant counts and counted the number of individuals at the developmental stages, when the pests fed on cotton plants and natural enemies preyed upon insect pests.

[1] Different active ingredients may have different impacts on natural enemies (e.g. ladybeetles). Ideally, the amount of insecticides used by farmers should be separated on the basis of active ingredient. In this study, the amount of insecticide use and names of insecticide products are based on farmer survey. We found that many farmers were unable to report the names of the insecticides used. It is known, however, from administrative records at county level that in northern China, where this study was conducted, pyrethroid and organophosphate insecticides represent more than 85% of all pesticide use and have similarly deleterious effects on natural enemies in cotton (Lu et al., 2012).

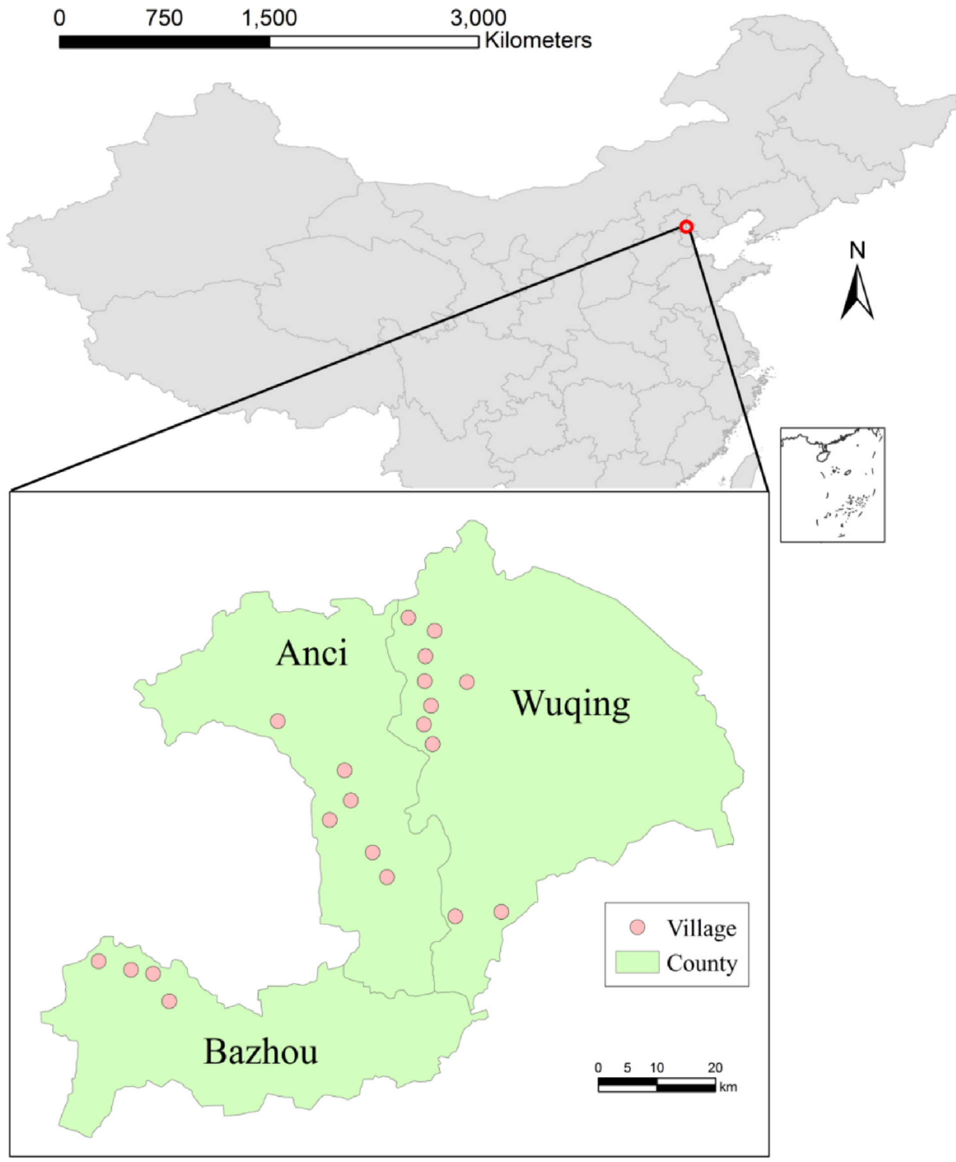

Fig. 1. Study area and the locations of the 20 villages in three counties studied.

2.5. *Land use data*

Land use data were collected for each of the 20 villages using a combination of remote sensing and ground truthing (Fig. 2). First, in each village, we used a high-resolution GPS receiver to locate the positions of the 16 target cotton fields (corresponding to 16 households). The center of gravity for these 16 positions was determined and the landscape within 1.5 km from this point was digitized using Landsat TM and Spot satellite images in ArcGIS 9.3 (ESRI, 2008). Ground truthing was conducted in late July 2011 to collect information on crop species (Table 1). Land uses were grouped into seven categories (maize, cotton, other crops, trees, grassland, water, and built-up).

While the circle of 1.5 km-radius defined the maximum range of area where detailed land use data were collected for each village, these are not the actual landscapes over which the analysis was performed for each household. This is because the target cotton field of each household would, to various degrees, deviate from the center of gravity derived from all 16 target cotton fields in the village. Therefore, for each cotton field, we assessed land uses within circles of 300 m to 1000 m with 50 m increments. Overlaying these field-specific landscapes on the 1.5 km-radius circular area in the associated village, there is for some fields an area that falls outside the village circle with 1.5 km-radius. In these cases, we retained in analysis for a given radius only the samples (or target cotton fields)

Table 1
Land use classification.

Categories	Details of land uses (and shares of land use in total land area)
Maize	Maize (41%)
Cotton	Cotton (15%)
Other crops	Vegetables, beans, sweet potato, peanuts, etc. (6%)
Trees	Poplar, apple, peach, pear, vines, pomegranate, and other trees (14%)
Grassland	Pasture and weed covered waste land, intended for construction (1%)
Water	Rivers, lakes, ponds and irrigation canals (2%)
Built-up	Buildings, roads and greenhouses (21%)

The numbers in the parentheses are the shares of each land use category averaged over the 20 villages in the study area, as determined in July 2011. Land use was evaluated over a 1500 m radius circular landscape sector around the center of gravity of 16 fields selected for insect observations in each village.

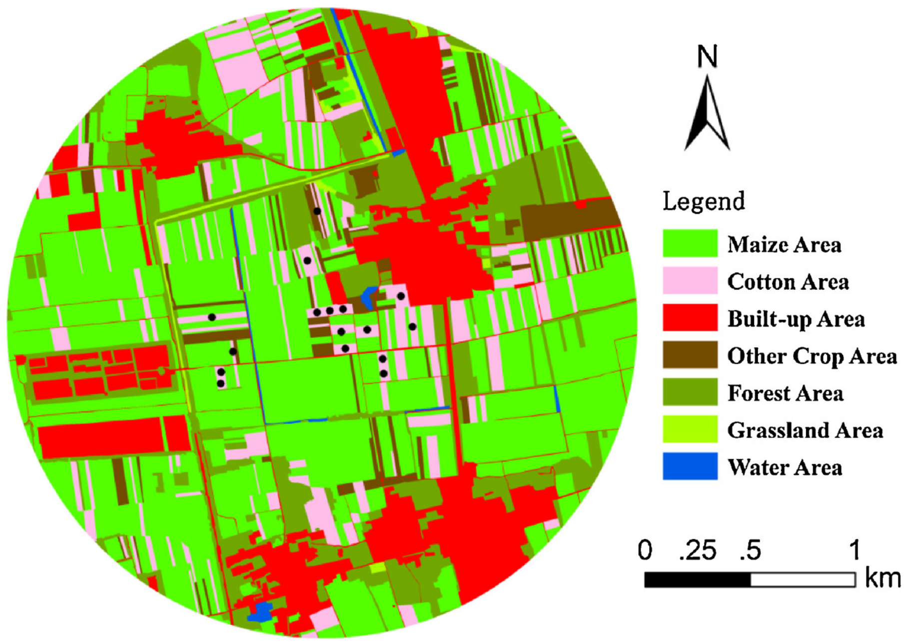

Fig. 2. Land uses in the Chenjiawu village of Anci county as observed in 2011. Black dots are farmers' fields where counts were made of pests and natural enemies in late June, late July and late August, 2011.

with the landscapes that overlap with the village's 1.5 km-radius circular area by more than 95%.

To examine the effect of land use on natural enemy abundance, we looked at two measurements of land use structure in landscapes, namely, land use composition and land use diversity, with the latter measured by the Shannon diversity index and Simpson diversity index. The Shannon diversity index (H) is expressed as (Jost, 2006):

$$H = \sum_i p_i \ln(p_i) \quad (1)$$

where p_i is the share of land use type i in total area of the landscape. The Simpson diversity index (D) is given by (Jost, 2006):

$$D = \sum_i \mathrm{p}_i^2 \quad (2)$$

Both indices were translated back to the scale of "effective number of land uses", using the following transformations (Jost, 2006):

$$E_{\mathrm{Shannon}} = \exp(H) \quad (3)$$

$$E_{\mathrm{Simpson}} = \frac{1}{D} \quad (4)$$

The back-transformed measures for the "effective number of land uses" were used throughout the analysis.

2.6. Descriptive and econometric analyses

Given that cotton aphid is a primary pest in cotton and that ladybeetle is a main natural enemy species that preys upon cotton aphid (Lu et al., 2012), our analysis focuses on the effects of land use on the abundance of ladybeetles. We first apply descriptive analysis, using various forms of tabulation and univariate linear and non-linear regression, to identify key relationships between ladybeetle density, and land use and farmers' insecticide use. To identify associations between ladybeetle density and proportions of land use for maize, cotton, other crops, trees, grassland and water, we subdivided the sampled fields in five classes according to their percentile value (0–20, 20–40, 40–60, 60–80, or 80–100) in the total sample, separately for each land use class. Then, we compared average ladybeetle density amongst those five classes to identify whether there was a difference in ladybeetle density between fields with a high percentile value for the chosen land use and fields with a low percentile value.

To quantify association direction and strength, taking into account multiple influences, we develop an econometric model that estimates the impacts of land use and farmers' insecticide use on ladybeetles based on a multiple regression approach. As, demanded by arguments of predictability and identifiability, the econometric model of ladybeetle density uses only "exogenous" variables as predictors, i.e. variables that are not influenced by the studied system, but set by the outside world. Here, we focus in the econometric analysis on landscape variables and insecticides, both of which are not affected by the dependent variable: density of natural enemies. We also studied associations between ladybeetles and density of aphid prey in cotton, but this analysis has severely endogenous problem because they impact each other.

The econometric models used in this study are:

$$\text{July}: \quad Y_i = a_1 + a_2 U_i + a_3 \ln(D_i) + a_4 Z_{1,i} + a_5 Z_{2,i} + e_i \quad (5)$$

$$\text{August}: \quad Y_i = a_1 + a_2 U_i + a_3 \ln(D_i) + a_4 Z_{1,i} + a_5 Z_{2,i} + a_6 Z_{3,i} + e_i \quad (6)$$

where Y_i represents the population density of ladybeetles measured as number of beetles per 100 cotton plants in plot i. U_i denotes measurements of land use for plot i. D_i is the time elapsed since the last insecticide spray. $Z_{1,i}$, $Z_{2,i}$ and Z_3, represent the amount of insecticides used (kg/ha) used in the period directly preceding each survey, i.e. before the first survey, between the first and the second survey, and between the second and third survey, respectively. We compared three alternative measures for land use in our regression models: (1) E_{Shannon}, (2) E_{Simpson} or (3) a set of six dummy variables indicating the area proportions of maize, cotton, other crops, trees, grassland, and water area in total land area. The share of built-up area was excluded from the third model because the seven area proportions add to 1, and one of them is therefore redundant. As

Table 2
Density of cotton pests (number per plant) in June, July and August 2011.

	June		July		August	
	Mean	SEM[1]	Mean	SEM	Mean	SEM
Cotton aphid	4.50	1.40	40.73	1.12	5.57	0.19
Spider mite	0.12	0.04	0.20	0.08	0.00	0.00
Mirid bugs	0.02	0.00	0.05	0.01	0.03	0.00
Cotton bollworm	0.02	0.01	0.03	0.01	0.01	0.00
Whitefly	0.02	0.00	3.09	0.35	2.79	0.16

[1] SEM is standard error of the mean.

the built-up category was not included in the regression model, it acted as the reference land use, against which other land uses are compared. Descriptive analysis to be presented later showed that both the amount of insecticide use (Z) and the number of days (D) between the time elapsed since the last insecticide spray have likely impacts on ladybeetles and suggested a semi-logarithmic relationship between ladybeetle densities and the number of days since the last insecticide spray. We therefore took the logarithm of D_i in models (5) and (6). The models were estimated with ordinary least squares (OLS) using STATA (version 11).

3. Results

3.1. Descriptive analysis results

3.1.1. Main characteristics of farm households

The average household had about four people and 0.87 ha of land, of which 23% of land was cultivated with cotton. The main crop in the study area was maize (Table 1). In addition, several vegetable species and other crops were cultivated (Table 1). Many household heads had off-farm employment aside their farming activity. On average, household heads spent 4.5 months per year on farming and 3.7 months on off-farm activities.

We found that there are three main crop sequences in the study area based on 311 household survey: (1) wheat–maize (wheat sown in October, harvested in June, and maize sown in June and harvested in October); (2) single season cotton (planted in April and harvested in November; no winter crop); and (3) vegetable followed by vegetable or vegetable followed by other crops such as peanut.

3.1.2. Pest and natural enemy populations in cotton fields

Cotton aphid was the most abundant cotton pest in the study area (Table 2). Its density increased from 4.5 per plant in late June to more than 40 per plant in late July and then fell to 5.57 in late August, representing a typical "boom and bust" population dynamic trend (Xia, 1997). Following large scale adoption of Bt-cotton[2], cotton bollworm was not a major pest (Table 2).

Low numbers of lacewings and spiders were present in the survey fields (ranging from 1.38 to 6.42 per 100 plants), but ladybeetles were much more common, reaching densities of 1.62 per 100 plants in late June, 16.4 per 100 plants in late July, and 33.7 per 100 plants in late August, respectively (Table 3). Three species of ladybeetle were common, including, in order of importance: *H. axyridis* Pallas, *P. japonica* Thunberg, and *C. septempunctata* L.

While we observed three natural enemies in cotton field, this study focuses only on ladybeetles, a main natural enemy species of cotton's primary pest (aphid). This is because lacewings and spiders are so small that we could not do any meaningful and viable analysis.

[2] Bt cotton was first adopted by farmers in the study villages in 1997 and its adoption rate has reached 100% since the early 2000s.

Table 3
Density of insect natural enemies in cotton (number per 100 plants) in June, July and August 2011.

	June		July		August	
	Mean	SEM[1]	Mean	SEM	Mean	SEM
Ladybeetles	1.62	0.23	16.37	0.72	33.68	0.95
Lacewings	1.93	0.26	6.42	0.58	5.62	0.51
Spiders	2.02	0.24	1.38	0.24	1.92	0.27

[1] SEM is standard error of the mean.

3.1.3. Land use and natural enemies

Agriculture was the dominant land use, covering more than 60% of the total area across villages (Table 1). Maize was the most widely planted crop, accounting for more than 41% of total land area, followed by built-up area, cotton and forest area. While water bodies and grassland covered only 1–2% of land use (Table 1). Land use varied significantly amongst villages (Fig. 3), with maize area varying from 22% to 70% and cotton area from 1% to 45%. The shares of other crops, trees and built-up areas also varied substantially among villages.

Likely relationships between land uses and ladybeetle populations were explored by comparing the average ladybeetle densities in five different percentile classes of area proportion for each of the seven land uses (Table 4). The results indicate that there is a positive association between the average population density of ladybeetles and the proportion of maize area (Table 4, row 1). For instance, in the fields that fall in the lowest 0–20 percentile of the area proportion of maize in a 500 m landscape circle, the average density of ladybeetles was 10.3 per 100 plants, as compared to 24.5 per 100 plants in the highest 80–100 percentile. There was a negative association between the density of ladybeetles and the proportion of cotton. Results are shown only for a radius of 500 m but they hold for radii ranging from 300 m to 1000 m. No relationships were found between ladybeetle density and other land uses.

Graphical analysis shows that ladybeetle densities were either not or negatively correlated with land use diversity measured as E_{Shannon} or E_{Simpson}. Since other confounding factors such as the use of insecticides could also influence ladybeetle populations as we will discuss below, we conducted a multiple linear regression analysis to single out the effect of land use diversity.

3.1.4. Insecticide use and natural enemies

Farmers frequently applied insecticides for the control of cotton pests. On average, 8.2 insecticide sprays were applied over the

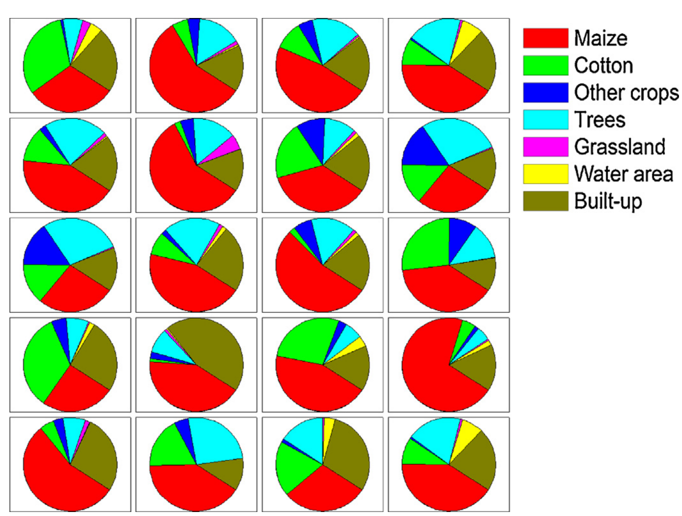

Fig. 3. Variation in land use across 20 villages.

Table 4
Average densities of ladybeetles (number per 100 plants) in landscapes with different land use, as indicated by percentile class (0–20, 20–40, 40–60, 60–80 and 80–100) of the area of maize, cotton, other crops, trees, grassland, water, and built-up area.

	Number of ladybeetles per 100 cotton plants in late July					Number of ladybeetles per 100 cotton plants in late August				
	I[a]	II	III	IV	V	I[a]	II	III	IV	V
Maize	10.3	14.1	13.6	18.5	24.5	30.4	32.8	30.6	37.5	38.9
Cotton	26.6	20.0	13.7	12.2	12.2	43.8	34.8	36.1	28.4	31.4
Other crops	16.6	23.1	14.2	17.2	12.1	35.2	34.0	33.7	32.6	35.1
Trees	18.3	17.9	17.5	13.3	13.7	30.3	37.7	34.7	37.5	30.0
Grassland	14.9	19.0	14.6	17.2	18.9	32.3	35.4	33.2	36.8	36.5
Water	18.0	13.4	13.5	17.8	15.9	36.2	36.8	32.6	31.5	33.5
Built-up	17.6	14.5	14.3	16.6	16.8	33.6	32.8	35.2	33.4	35.4

[a] For each land use category, we classified all fields (302 target fields at a radius of 500 m) in five percentile classes, based on the area proportion of the given land use (I: 0–20%, II: 30–40%, III: 40–60%, IV: 60–80% and V: 80–100%).

cotton growing season in our study area, ranging from 1 to 14 times (Table 5). The amount of formulated insecticide product applied was 22.4 kg/ha, at an average cost of 1092 yuan (or USD 173) per hectare, about 16% of the average per capita income in rural China in 2011 (NBSC, 2012). The majority of the insecticides were used before late July (Table 5).

Most of the interviewed farmers (91%) based their pesticide use decisions primarily on aphid density in their cotton field, while the other 9% sprayed insecticides prophylactically. None of the 311 interviewed farmers had considered aphid natural enemies (e.g. ladybeetles) in their cotton field when making their spray decision. This implies that farmers' insecticide use decision is exogenous to natural enemy densities, which ensures that the econometric model developed in the previous section is valid and can be estimated with OLS.

A positive correlation was found between ladybeetle densities and the time elapsed since the last insecticide application, both in July and August (Fig. 4). Although not reported in the current paper, our OLS regression analysis showed that insecticide use is significantly and negatively associated with ladybeetle densities and that the log-transformed number of days elapsed since the last insecticide application is positively correlated with ladybeetle densities.

3.2. Econometric analysis results

Adjusted R^2 in the econometric analyses varied from 0.83 to 0.89, indicating good explanatory power of the regressions (Table 7) Estimation results are very similar between late July and late August and across different spatial scales of landscape. To simplify the presentation, the current paper only reports results for two radii levels (500 m and 1000 m). Complete results are available in the on-line Appendices A and B.

3.2.1. Impacts of land use on ladybeetle densities

Both Shannon and Simpson diversity indices were negatively and significantly correlated with ladybeetle densities in late August, after controlling for the impacts of insecticide use (Table 6). This finding is consistent across models for different time periods and landscape scales considered (see Appendices A and B for details).

Across our models, the results show that cropland use plays an important role in ladybeetle densities while some models also show that grassland area can help boost ladybeetles populations (Table 7). Since the proportion of built-up area was the reference land use variable in the regression analysis, the estimated effects of other land uses on ladybeetles need to be interpreted in relative terms as compared to the built-up area.

The estimated coefficients for maize area are statistically significant and positive (Table 7), implying that the presence of maize area in the landscape enhanced ladybeetle populations in cotton. The estimated coefficients for grassland were also positive and statistically significant for the 500 m-radius model. But the estimated coefficients for cotton and "other crops" were significant and negative. There was no statistically significant effect of area of water or forest. Despite the small share of grassland area in total land area, nearby grassland appears to play a positive role in ladybeetle populations in the NCP. Finally, we found that the estimated coefficients for trees and water were not statistically significant (rows 4 and 6 in Table 7), implying that areas of water and trees may not have significant impact on ladybeetle populations in our study areas.

3.2.2. Impacts of insecticide use on ladybeetle densities

The estimated coefficients for the number of days since the last insecticide spray were highly significant in explaining ladybeetle densities in both models (Tables 6 and 7). This implies that ladybeetle densities in cotton fields increase with the time lag between the field observation date and the most recent insecticide application, holding other factors constant. The estimated coefficients presented in Table 7 (row 7) show that ladybeetle densities increased by about 12 units (number per 100 plant) (about 17) in late July (or in late August) for every one day away from the last insecticide spray.

The volume of insecticide used was found to have a significantly negative impact on ladybeetle densities. For example, Table 7 shows that, for each additional unit of insecticide used (kg/ha) between late June and late July (or between late July and late August), ladybeetle densities decreased by 0.11 units (number per 100 plant) (or 0.16) in late July (or in late August) in the model for 500 m-radius. As Table 6 shows, ladybeetle densities in late August were significantly reduced by the amount of insecticide used in the preceding month (Z_3), but not by the amount of insecticides used more than one month ago (Z_1 and Z_2). Similarly, Table 7 shows that ladybeetle densities in late July were significantly affected by insecticide use during July (Z_2) and those in late August by insecticide use during August (Z_3). Thus, the effects of insecticides

Table 5
Insecticide application during different periods across 311 cotton plots.

	Total	Before late June	From late June to late July	From late July to late August	After late August
Number of insecticide applications ± SEM	8.2 + 0.15	2.3 + 0.06	4.0 + 0.09	1.7 + 0.06	0.2 + 0.03
Amount of insecticide used (kg formulated product/ha) ± SEM	22.4 + 0.78	2.8 + 0.15	12.9 + 0.56	6.0 + 0.33	0.7 + 0.13
Costs of insecticide (Yuan/ha) ± SEM	1092 + 38	143 + 8	618 + 26	295 + 17	35 + 6

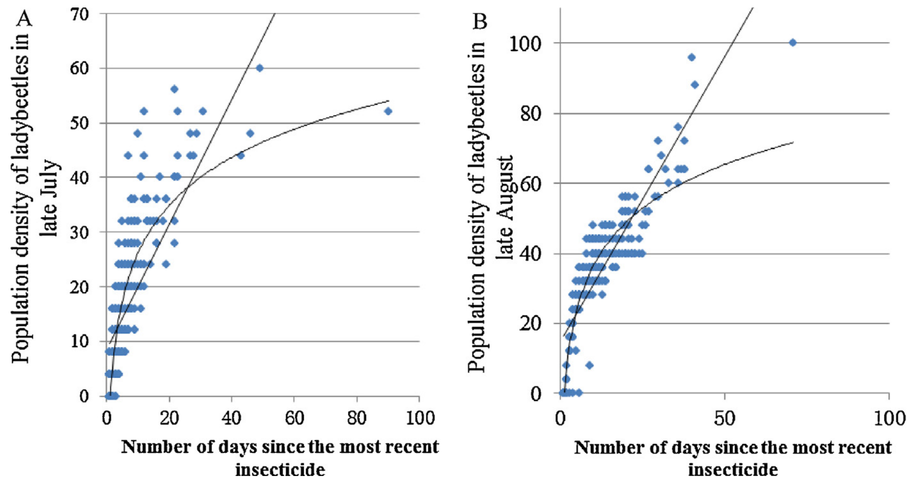

Fig. 4. Relationship between population density of ladybeetles (number per 100 plants) and the number of days since the most recent insecticide spray in (A) July, (B) August.

Table 6
Parameter estimates for independent variables in econometric multiple regression model of ladybeetle density (number per 100 cotton plants) in late August on land use diversity based on Shannon index or Simpson index and insecticide use.

	$E_{Shannon}$		$E_{Simpson}$	
	R = 500 m	R = 1000 m	R = 500 m	R = 1000 m
E	−2.99*** (5.98)[1]	−3.65*** (6.93)	−2.81*** (6.63)	−3.33*** (7.80)
Ln(D)	17.53*** (42.98)	16.67*** (38.63)	17.51*** (43.46)	16.73*** (39.67)
Z_1	0.06 (0.46)	0.07 (0.55)	0.08 (0.65)	0.09 (0.69)
Z_2	−0.02 (0.49)	−0.01 (0.33)	−0.02 (0.57)	−0.02 (0.62)
Z_3	−0.15** (2.47)	−0.17*** (2.80)	−0.15** (2.47)	−0.16*** (2.75)
Adjusted R^2	0.88	0.88	0.88	0.88
N	302	259	302	259

* p < .10.
** p < .05.
*** p < .01.
[1] Absolute t statistics are given in parentheses.

on ladybeetle densities in cotton do not identifiably persist longer than one month. These results are plausible because the lifetime of ladybeetles is about four weeks or one month (Ren et al., 2009).

4. Discussion

This paper provides to our knowledge the first empirical evidence on the effects of land use diversity, measured with remote sensing and ground truthing, on the abundance of natural enemies in smallholder field crops in a developing country context. Results indicate that high land use diversity per se as measured by Shannon or Simpson index is not associated with high density of natural enemies in cotton. Rather, the effects of land use on natural enemies were best explained by the effect of different crop and non-crop habitats that may support the insect species that provide biological control services in these landscapes.

Table 7
Parameter estimates for independent variables in econometric multiple regression model of ladybeetle density (number per 100 cotton plants) on land uses and insecticide use.

	July		August	
	R = 500 m	R = 1000 m	R = 500 m	R = 1000 m
Maize (%)	0.26*** (11.40)	0.20*** (4.89)	0.11*** (4.02)	0.12*** (2.81)
Cotton (%)	−0.07** (2.17)	−0.20*** (3.76)	−0.06* (1.66)	−0.11* (1.89)
Other crops (%)	−0.19*** (4.17)	−0.21*** (3.16)	−0.22*** (4.18)	−0.18*** (2.67)
Trees (%)	0.02 (0.52)	−0.05 (0.91)	−0.01 (0.12)	0.01 (0.10)
Grassland (%)	0.38* (1.81)	−0.32 (1.10)	0.44* (1.79)	0.11 (0.35)
Water (%)	0.15 (1.02)	−0.14 (0.85)	0.01 (0.09)	0.15 (0.90)
Ln(D)	12.04*** (36.78)	11.74*** (29.81)	17.60*** (45.60)	16.74*** (38.86)
Z_1	−0.02 (0.15)	0.01 (0.07)	0.09 (0.69)	0.09 (0.67)
Z_2	−0.11*** (3.80)	−0.09** (2.51)	−0.01 (0.29)	−0.02 (0.63)
Z_3			−0.16*** (2.67)	−0.16*** (2.72)
Adjusted R^2	0.87	0.83	0.89	0.89
N	302	259	302	259

Table presents regression coefficients. A coefficient of 0.261 for maize% means that per percentage point of maize in the regions, the number of ladybeetles per 100 plants increases by 0.261.
Absolute t statistics are given in parentheses. * p < .10, ** p < .05, *** p < .01.

In this study, we found that maize area has positive effect on densities of ladybeetles, an important group of generalist predators for cotton aphids, in cotton. This result may be explained on the one hand by the low use of insecticides in maize[3], and on the other hand by ecological functions provided by the wheat crop that is usually cultivated before maize in the double cropping system (two crops within one season) that is common in the North China Plain. The wheat crop supports high densities of natural enemies that may spill over to other crops, both in space and time. Wheat harbors several aphid species that can reach high densities, thus providing an excellent resource for aphid predators (Carter et al., 1982; Xia, 1997; Ma et al., 2006). Previous studies in the NCP showed that ladybeetles originating from wheat play an important role in controlling cotton aphids in cotton–wheat relay intercrops (Xia, 1994; Xia et al., 1996; Ma et al., 2006).

These landscape effects associated with maize area contrast with those reported previously in the USA, where maize area was negatively associated with natural enemy density and diversity in soybeans, and negatively associated with soybean aphid biological control (Gardiner et al., 2009). Thus, we show that landscape scale effects of maize on biological control services exhibit idiosyncrasy as defined by Tscharntke et al. (2005): the effects of this particular crop species on biological control services in agricultural landscapes are not universally negative or positive but require system-specific scrutiny. These landscape scale effects were also captured by simple indices like Shannon and Simpson index, but in an implicit way. The use of those indices therefore does not allow for a causal interpretation.

We found that grassland area also has positive effect on the density of ladybeetles. This finding is consistent with results from previous studies showing that grassland is an important non-crop habitat that can provide ladybeetles with shelter and alternative foods (Altieri and Whitcomb, 1979; Ferran et al., 1984; Honek, 1989; Dixon and Guo, 1993; Xia et al., 1999).

We found negative effect of cotton area on the density of ladybeetles in cotton. This is not surprising because farmers use substantially more insecticides in cotton than in any other field crops. Therefore, the overall populations of ladybeetles in the landscape would be lower when the area of cotton cultivation is higher. Furthermore, if cotton is a "sink" for ladybeetles at the landscape level, a greater proportion of this sink in the landscape is expected to lower the density of ladybeetles in the sink due to the mortality effect of broad-spectrum insecticides on ladybeetles. There was a negative association between the area of "other crops" and density of ladybeetles in cotton. In our survey area, the category of "other crops" was mainly comprised of beans, peanuts and vegetables, all requiring high use of insecticides that may suppress the ambient populations of ladybeetles. As a result, there may be fewer ladybeetles migrating to cotton fields if these crops are abundant.

Furthermore, we document the intensive use of insecticides by farmers and its detrimental consequences for natural enemies in cotton. High insecticide use by farmers is here shown to be related to decision making that does not account for biological control services provided by natural enemies. The identified lack of farmer awareness on the value of natural enemies for crop health calls for a better information transfer to farmers, in support of the health of crops, the environment, and the farmers.

Our study indicates that insecticides are used heavily in cotton production in the North China Plain (average 22.4 kg formulated product per hectare). The number of insecticide sprays in cotton in this study (8.2 per season) is slightly higher than that reported by Huang et al. (2002), who found that Bt cotton farmers in the NCP applied insecticides 6.6 times on average, while non-Bt cotton farmers applied as often as 19.8 times in 1999. The negative effect of insecticides on natural enemies needs to be addressed to take advantage of the potential benefit of landscape-scale land use management on biological control agents, (Meehan et al., 2011). Improvements in extension may be required to stimulate the adoption of integrated pest management (IPM) among farmers and address the indiscriminate use of insecticides.

Prior to this collapse, biological control was favored by more judicious use of pesticides, which was coordinated at the level of large state-owned farms that employed crop protection specialists that did consider biological control.

Findings of this study demonstrate that promotion of land use diversity has the potential to become an effective means to support cotton pest biological control services in China. However, at present, enhancing biological control services by promoting land use diversity is unlikely to be cost-effective for smallholder producers given the high return rate for insecticide use. As a public good, landscape-based ecosystem services may require coordinated habitat management at the landscape scale to avoid a tragedy of the commons (Zhang et al., 2007, 2010), and policies that encourage farmers to account for the human health and environmental costs of insecticides would help incentivize the adoption of habitat management.

Last but not least, our empirical analysis indicates that land use diversity measured by Shannon or Simpson diversity index was negatively associated with density of ladybeetles in cotton. This finding contradicts a study by Gardiner et al. (2009) in the U.S. These authors found that in their case, diversity was negatively related with maize area, while maize area was negatively associated with biological control services. Therefore, the effect of diversity could be explained by the idiosyncratic effects of maize area alone. In our study, diversity was also negatively associated with maize area, but in our case, contrary to the case of Gardiner et al. (2009), maize area was positively associated with natural enemies in cotton. Based on these findings, we suggest that analyses based on area proportions of actual land uses gave more insight in the likely underlying processes, e.g. spill-over of ladybeetle adults from wheat preceding maize to cotton, than measures of diversity that do not account for landscape functions, but merely measure diversity as such. Such a measure of diversity per se may not be sufficient to characterize functional diversity. Indeed, the literature has also indicated that landscape diversity indices have several inherent disadvantages in capturing the overall features of a landscape (NEA, 2010). Moreover, there are some fundamental issues that make the interpretation of diversity indices in terms of functional effects difficult. When comparing the two diversity indices, the Shannon index is influenced more strongly by changes in abundance of the rarest class, while Simpson's index is more strongly influenced by changes in the abundance of the most common class (Peet, 1974). Diverging responses of these indices were also observed in two Indian landscapes with the same richness, differing only in evenness (Nagendra, 2002). Nevertheless, results of regressions on the two indices in the current study were very similar, confirming each other. Thus, the main issue that we note with these indices is not so much their different sensitivities to rare or common classes (land use in this case), but the intrinsic lack of support for functional interpretation.

The role of non-crop habitats in the NCP may be only small, mostly because of very low area proportion. These landscapes may thus lack the kind of functional landscape diversity that is essential for enhancing biological pest control services. However, natural enemy–friendly crop habitats (i.e. wheat) may also provide

[3] Insecticide use in wheat and maize is considerably lower than in cotton. For instance, farmers in Hebei spent 1032 yuan/ha on insecticides in cotton, 174 yuan/ha in maize and 136 yuan/ha in wheat in 2009 (NDRC, 2010). In the late season, there is almost no insecticide use in maize in China. Therefore, maize fields may serve as a refuge for ladybeetles (Deguine et al., 2009).

valuable ecosystem services. This possibility warrants further analysis and quantification.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2013.11.008.

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