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Feng Gao [a b], Feng Ge [a], Xianghui Liu [a] & Yan Song [a]
[a] State Key Laboratory of Integrated Management of Pest Insects and Rodents, Institute of Zoology, Chinese Academy of Sciences, Beijing, P.R. China
[b] Graduate University, Chinese Academy of Sciences, Beijing, P.R. China
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Impact of insecticides on the structure and productivity of insect pest and natural enemy communities associated with intercropping in cotton agroecosystems

Feng Gao[a,b], Feng Ge[a]*, Xianghui Liu[a] and Yan Song[a]

[a]*State Key Laboratory of Integrated Management of Pest Insects and Rodents, Institute of Zoology, Chinese Academy of Sciences, Beijing, P.R. China;* [b]*Graduate University, Chinese Academy of Sciences, Beijing, P.R. China*

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Effects of insecticides on the structure and productivity of insect pest and natural enemy communities were analyzed in the four types of cotton agroecosystem associated with intercropping in Raoyang County, HeBei Province, China. The interaction of chemical control × intercropping had a significant effect on the most community structure parameters of insect pest and natural enemy communities, except for the diversity index of the predator community. The damage index for the insect pest community and control index of the natural enemy community were also affected significantly by the chemical control × intercropping interaction. Pearson correlation analyzes showed that community structure and productivity of insect pest and predator communities had a complex relationship with lower trophic productivity in these cotton agroecosystems. Few effects of chemical control on these correlations were found. Chemical methods influenced the correlations between insect pest community productivity and parasitoid community structure in most cotton agroecosystems. Our results suggest that the interaction of chemical control × intercropping significantly influenced the damage index, the control index, and the correlation between community structure and productivity of insect pest and natural enemy communities in cotton agroecosystems.

Keywords: community structure; productivity; cotton agroecosystem; insecticides; insect communities

1. Introduction

Investigations aimed at linking community structure and productivity have recently intensified. There is a growing literature based on conceptual theory, quantitative modeling, experimental tests and field observations, and debate on this topic is intensifying. The term ‘community structure’ encompasses a broad spectrum of community characteristics, from species richness and total number of individuals to the diversity of species numbers and energy flow within communities. Most research on community structure and productivity has focused on meadow (Tilman et al. 2001; Wang et al. 2006) and lake (Carcia et al. 2006) ecosystems (Tilman et al. 1997; Raffaelli 2006; Wright et al. 2006), with bacteria (Horner-Devine et al. 2003), epiphytes (Frankovich and Zieman 2005) and ‘minor species’ (Boeken and Shachak 2006) as the primary subjects of investigation. However, much remains to be known about the relationship between community structure and productivity across trophic levels in complex ecosystems such as crop-insect and pest-natural enemy communities (Ge and Ding 1996).

Maximizing the impact of natural enemies already present in the cotton agroecosystem could reduce the need for chemical inputs to manage pests (Mensah 1999). Over the past half-century, many agricultural practices that influence diversity and species richness of an insect community have been studied. Intercropping and other multiple cropping practices are becoming common in the southeastern United States, mostly as double cropping of winter wheat and summer soybean (Francis 1989). In the midwestern United States, the combination of soybean and corn in strip intercropping has been used as an economic alternative for monocultures (Reynolds 1986). Additionally, delayed uniform planting, where most cotton is planted after mid-May to delay the appearance of cotton squares until early July, has become an important and widely accepted management strategy in Texas, USA (Rummel and Carroll 1983; Slosser et al. 1994).

In northern China, there are many intercropped cotton and mono cotton agroecosystems. The use of insecticide is still a very important method to control insect pests. However, little is known about the direct and indirect effects of insecticides on the relationship between the community structure and productivity of key insect pests and natural enemies associated with intercropping. Here, we use ecological energetics as an inlet, associated with age structure, life history and mortality, to estimate the effects of chemical control on community structure of insect pests and natural enemy insects in different cotton agroecosystems of northern China. The main objectives in this study are

*Corresponding author. Email: gef@ioz.ac.cn

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to: (1) analyze the effects of chemical control on the damage index and control index, (2) determine how chemical insecticides affect the relationship between insect community structure and productivity, and (3) analyze the effects of agricultural practice, such as intercrop or monoculture, on the insect community structure associated with insecticide use.

2. Materials and methods

2.1. Study area

This study was conducted in Raoyang County, HeBei Province of northern China (25°N, 112°E). The region has a seasonal cumulative temperature of about 3500°C above 15°C and receives 500 – 600 mm rainfall annually. The soil type is a very fine sandy loam (ca. 20 – 22% clay). Soil organic matter and total N, P, and K are about 0.845, 10.5, 10.8 and 17.7%, respectively.

The experimental design was randomized complete blocks with three replications for each treatment. Each plot consisted of 10 rows of cotton, variety Shimian No. 11, and row spacing was 1 m and row length was 40 m. The four types of cotton agroecosystem for this experiment in 2004 were as follows: mono cotton planted on 27 April, mono cotton planted on 15 May, wheat – cotton intercrop planted on 27 April, and wheat – cotton intercrop on 15 May (Table 1). The wheat was planted on 1 October 2003 in the middle three rows within the 10-row cotton plots. Wheat and cotton were harvested on 10 June and 5 October in 2004, respectively. Irrigation was applied as needed to ensure sufficient moisture in the soil. The agronomic manipulations were the same in each plot.

2.2. Application of insecticides

Each cotton agroecosystem was divided into two treatments: treated with insecticide or untreated control. Therefore, there were eight treatments in our experiments; one plot of each pair received an insecticide treatment while the other plot served as a control (no-insecticide treatment). Plots were arranged with 10 m cotton separating each plot. The insecticides used are listed in Table 1. Based on the insecticide label recommendations, the insecticides Monocrotophos and Methomyl solutions (375 and 225 mL of active ingredient per hectare, respectively) were sprayed with the concentrations diluted 1500 times. Insecticides were applied by using backpack sprayers early in the morning or in the late evening. We sprayed each plot plus a 1-m buffer around each plot. At the same time, an equivalent amount of water-only was sprayed on the control plots, and we used a different sprayer on control plots to avoid possible contamination with the insecticide.

Table 1. Characteristics of the four cotton agroecosystems (cotton variety: Shimian No. 11).

Crops	Seed time	Density (plants/m^2)	Chemical control
Cotton	27 Apr. 2004	6	i + ii
Cotton	15 May 2004	6	i + ii
Cotton + wheat	Cotton: 27 Apr. 2004; Wheat: 1 Oct. 2003	5	i + ii
Cotton + wheat	Cotton: 15 May 2004; Wheat: 1 Oct. 2003	7	ii

(i) Monocrotophos was used to control aphids on seedlings on 20 June, and Methomyl to control second generation cotton bollworms (*Helicoverpa armigera*) on 2 July. (ii) Monocrotophos was used to control summer aphids on 15 July, and Methomyl to control third generation cotton bollworms on 1 August in all four treatments.

2.3. Insects sampling

Five, 1-m^2 sampling sites, each consisting of six cotton plants, were selected randomly in each plot. Numbers of sedentary insects (except cotton aphids) were counted visually on the plants at each site every 5 days from 5 June to 15 September 2004 ($n = 21$). Flying insects were sampled with five sweeps using a 38-cm diameter sweep-net near each sampling site in each plot. Insects collected by sweep-net were taken to the laboratory for species identification. The total number of insects was also counted. Five plants were randomly selected in each plot for sampling of aphids. The numbers of aphids were counted on three leaves taken from three different positions within the plant canopy as described by Hardee et al. (1993). Position 1 was the fourth fully expanded leaf below the terminal; position 2 was the first main stem green leaf about one-third the distance of plant height below the terminal, and position 3 was the first main stem green leaf above the first fruiting branch at the base of the plant.

The arthropod complex was separated into species and classified as phytophages, predators and parasitoids in each plot on each sampling date. The species and numbers of insects are listed in Appendices 1 – 2.

2.4. Individual parameters

2.4.1. Individual biomass and caloric value

The phytophages and natural enemies collected from the cotton plots were killed with ethyl acetate and dried for 48 h at 60°C. An automatic electribalance (R200D, Sartorius GmbH, Germany) was used to obtain dry weight as biomass (mg/individual) for each sample. The caloric value (J/mg) of each sample was determined with a Bomb calorimeter (PARR 1281, Parr Instrument Company, USA) from combustion of the sample. Energy content of all samples of each trophic classification was recorded separately for each of the three replications. The biomass and caloric values of insects are given in Appendices 1 – 2.

2.4.2. Individual respiratory rate

Measurements of O_2 consumption rate were made in a Gilson single valve differential respirometer (IGRP-14, Gilson Medical Electronics, Inc., France) with a water bath controlled at 25 ± 0.2°C. Ten percent KOH was used as a CO_2 absorbent in the centre well of the flasks. Readings were taken every 5 min for 15 min, and the mean value was used in calculations. Respiratory rates are given in Appendices 1 – 2.

2.5. Community parameters

2.5.1. Community biomass

Insect community biomass (W_k, mg) at (k)th investigation sampling time is the sum of the biomass ($W_{k,ij}$, mg) at each development stage (j)th of the (i)th species for all species in the community. W_k was calculated by combining the numbers and development stages of each species within each of the four cotton production systems at (k)th investigation sampling date:

$$W_k = \sum_{i=1}^{n} \sum_{j=1}^{l} W_{k,ij} \tag{1}$$

where j is the developmental stage of the (i)th arthropod species in the cotton plots; i.e. first instar, second instar, third instar, fourth instar, fifth instar, sixth instar and adult stage of the insect, respectively. l is the total number of developmental stages for each (i)th species, and n is the total number of species for each cotton production system.

2.5.2. Insect community productivity

Insect respiration depends on temperature, and $2^{(T-25)/10}$ is generally used to correct for changes in atmospheric temperature when the respiration (R', O_2 μl/mg per h) was determined in the laboratory at 25°C (Peakin 1978; Ge 1991). Respiration can be described as a function of temperature (T) as follows:

$$R(T) = R' \times 2^{(T-25)/10} \tag{2}$$

Since respiratory rate [$R(T)$] (O_2 μl/mg per h) is related to biomass (W, mg) (Albert 1983), oxygen consumption of the insect community (R, O_2 μl/h) for different biomasses approximates to:

$$R = W \times R' \times 2^{(T-25)/10} \tag{3}$$

When insect community biomass W_{k-1} (mg) and W_k (mg) were sampled in each agroecosystem at (k – 1)th and (k)th sampling time, oxygen consumption (R, O_2 ul) of insect community during (k – 1)th and (k)th time interval was calculated using the following equation:

$$R_k = \sum_{i=1}^{n} \sum_{j=1}^{l} \frac{(W_{k,ij} + W_{k-1,ij})}{2} R'_{ij}\, 2^{\frac{(T_k-25)}{10}} D_k \tag{4}$$

where j is the developmental stage of the (i)th arthropod species in the cotton plots; k and k – 1 are (k)th and (k – 1)th investigation time, respectively; $W_{k,ij}$ and $W_{k-1,ij}$ are the community biomass (mg) of each insect species at the (k)th and (k – 1)th investigation time, respectively; R'_{ij} is the respiration rate (ml/mg/day) of (j)th developmental stage of (i)th insect measured with a respirometer at 25°C (Appendices 1 – 2). D_k is the time interval (5 days) between the (k – 1)th and (k)th investigation periods; T_k is the average ambient temperature (°C) during the (k – 1)th and (k)th investigation periods. Temperature data were recorded by the weather station located near the experimental field.

Estimated respiration in the laboratory using the respirometer may underestimate actual field respiration (McEvoy 1985). The coefficient $b = 2.58$ was used to correct laboratory values for field conditions (McEvoy 1985) to minimize error in estimated field community respiration. Oxygen consumption was converted to Joule values using the oxycaloric coefficient $\alpha = 20.36$ J ml^{-1} (Barlow 1979). The energy metabolic loss (R) (J) through respiration by insect communities in the field was estimated using the following equation:

$$R = \sum_{i=1}^{n} \sum_{j=1}^{l} \left(\frac{W_{k-1,ij} + W_{k,ij}}{2}\right) R_{ij}\, ab\, 2^{\frac{T_k-T}{10}} D_k \tag{5}$$

2.5.3. Insect community productivity

Based on the net ecological efficiency (α) (Wiegert and Peterson 1983), respiration rates, and respiration capacity (R), community productivity (P) was calculated as:

$$P = \sum_{k=1}^{m} \sum_{i=1}^{n} \left(\frac{W_{k-1,ij} + W_{k,ij}}{2}\right) \times R_{ij} \left(\frac{\alpha_{ij}}{1-\alpha_{ij}}\right) ab\, 2^{\frac{T_k-T}{10}} D_k \tag{6}$$

2.6. Primary productivity in fields

Five, 1-m^2 samples of cotton or wheat and associated litter were collected randomly from each plot every 5 days in 2004 ($n = 21$) to estimate primary production. Materials were dried for 48 h at 60°C, and weight and caloric values were determined as described previously for insects.

The following equation was used to calculate gross productivity (P_0) of the primary producer (cotton plant or wheat plant) per area (J/m^2).

$$P_{0i} = \Delta B_i + R_i + L_i \tag{7}$$

where ΔB_i and L_i are the change in biomass of the primary producer (cotton plant or wheat plant) and associated litter, respectively, at each time (k)th during the experiment. R_i is the respiration loss. We used the method of Thormley and Hesketh (1973) to determine respiration loss by the plant.

2.7. *Community diversity index*

The Shannon–Weaver diversity index (HN) (Shannon and Weaver 1949) was used for analyzing community diversity:

$$HN = -\sum_{i=1}^{n} \left(\frac{N_i}{N}\right) \ln\left(\frac{N_i}{N}\right) \tag{8}$$

where N_i and N are the individual numbers of the (i)th species and total numbers of all species in each community, respectively. Similarly, a diversity index for energy flow (HE) was deduced from the Shannon–Weaver diversity index as follows:

$$H\ E = -\sum_{i=1}^{n} \left(\frac{A_i}{A}\right) \ln\left(\frac{A_i}{A}\right) \tag{9}$$

where A_i and A are the assimilation of the (i)$^{\text{th}}$ species and total assimilation of all species, respectively.

$$\text{And, } A_i = P_i + R_i\ A = \sum A_i \tag{10}$$

2.8. *Damage index and controlling index*

We used the damage index (I_1/P_0) to represent the ability of insect pests to damage the crop, and the controlling index (I_2/P_1, I_3/P_1) was used to express the ability of natural to control enemies on the pests as follows:

Damage index of the insect pest community to crop productivity $= I_1/P_0$

Controlling index of the predator community to insect pest community productivity $= I_2/P_1$

Controlling index of the parasitoid community to insect pest community productivity $= I_3/P_1$

where I_1 is the total ingestion of the insect pest community; I_2 is the total ingestion of the predator community; I_3 is the total ingestion of the parasitoid community; P_0 is the primary productivity, and P_1 is the productivity of the insect pest community, respectively.

2.9. *Data analysis*

Using SPSS for Windows, Version 12.0 (SPSS, Chicago, IL, USA) software, we analyzed productivity and assimilation of three communities using ANOVA. Twenty-one pairs of data were used to determine Pearson correlations between species richness (S), total individual numbers (N), diversity indices (HN), energy flow (HE) and productivity (P) for each community every 5 days from 5 June to 15 September 2004. Correlations were considered significant at $P < 0.05$ and at $P < 0.01$. Two-way ANOVA was used to analyze the effects of insecticide applications on the different insect communities in the four types of cotton agroecosystem. Differences between means were determined using a least significant difference (LSD) test at $P < 0.05$.

3. Results

3.1. *Effect of chemical control on community structure index of insect pest and natural enemy communities in the four cotton agroecosystems*

The chemical control × intercropping interaction significantly influenced the insect pest (S, N, HE at $P < 0.001$, and HN at $P = 0.02$, respectively), predatory (S at $P < 0.001$, and HE at $P = 0.003$, respectively) and parasitoid (S, N, HN, and HE at $P < 0.001$, respectively), except for the individual numbers and number diversity index of the predator community (Table 2). Chemical control and intercropping did not significantly influence species richness or energy diversity index of the insect pest and predator communities. Moreover, chemical control and intercropping did not significantly affect any community structure index in the parasitoid community.

3.2. *Effect of chemical control on productivity of insect pest and natural enemy communities in the four cotton agroecosystems*

3.2.1. *Insect pest community*

Productivity of the insect pest community was significantly different among the four untreated cotton plots ($P < 0.001$), but there were no differences among the treated plots in the four agroecosystems (Figure 1). Productivity in the monoculture cotton plots was significantly reduced by insecticide use ($P = 0.006$, Figure 1), but productivity in the intercropped cotton was not affected by insecticide use.

3.2.2. *Predator community*

Productivity of the predator community in the four cotton agroecosystems without chemical control ranged from 41.2 (kJ m^{-2} a^{-1}) to 50.8 (kJ m^{-2} a^{-1}) (Figure 2), but differences were not significant. After employing chemical control, productivity was higher in the intercropping agroecosystems and lower in the mono-cultural agroecosystems. The chemical control × intercropping interaction expressed a significant effect on productivity ($P = 0.025$, Table 2).

3.2.3. Parasitoid community

Productivity of the parasitoid community was lower than that of the insect pest and predator communities (Figure 3). Productivity ranged from 6.12 to 7.96 (kJ m^{-2} a^{-1}) in cotton plots without insecticides, and from 3.71 to 8.58 (kJ m^{-2} a^{-1}) in cotton plots with insecticides. The productivity in monoculture plots

Table 2. Two-way ANOVA of effects of chemical control, intercropping, and chemical control × intercropping on community structure (*S*, *N*, *HN*, *HE*) and productivity of insect pest and natural enemy communities in the four types of cotton agroecosystem.

Source of variance	Community	DF	*S*	*N*	*HN*	*HE*	*P*
	Insect pest	1	0.206	0.344	0.036*	0.259	0.169
Chemical control	Predator	1	0.252	0.011*	0.189	0.074	0.725
	Parasitoid	1	0.874	0.261	0.338	0.726	0.304
	Insect pest	3	0.489	0.401	0.013*	0.527	0.571
Intercropping	Predator	3	0.276	0.009**	0.140	0.194	0.411
	Parasitoid	3	0.236	0.500	0.196	0.061	0.300
	Insect pest	3	0.000**	0.000**	0.02*	0.000**	0.000**
Chemical control × intercropping	Predator	3	0.000**	0.082	0.172	0.003**	0.025*
	Parasitoid	3	0.000**	0.000**	0.000**	0.000**	0.000**

S is species richness, *N* is total individual numbers, *HN* is diversity index for community numbers, *HE* is diversity index for community energy flow, *P* is the productivity, * and ** indicate a significant effect at $P < 0.05$ and $P < 0.01$, respectively.

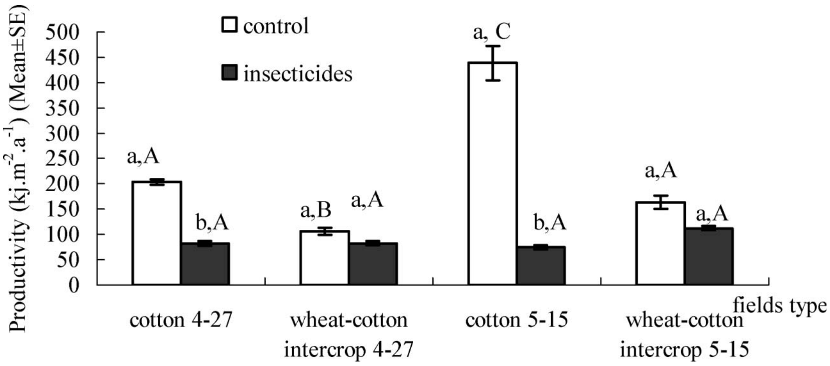

Figure 1. Productivity of the insect pest community in different cotton agroecosystems (different lower case letters show significant differences between insecticide treatments, and different upper case letters indicate significant differences among the four agroecosystems by LSD test at $P < 0.05$).

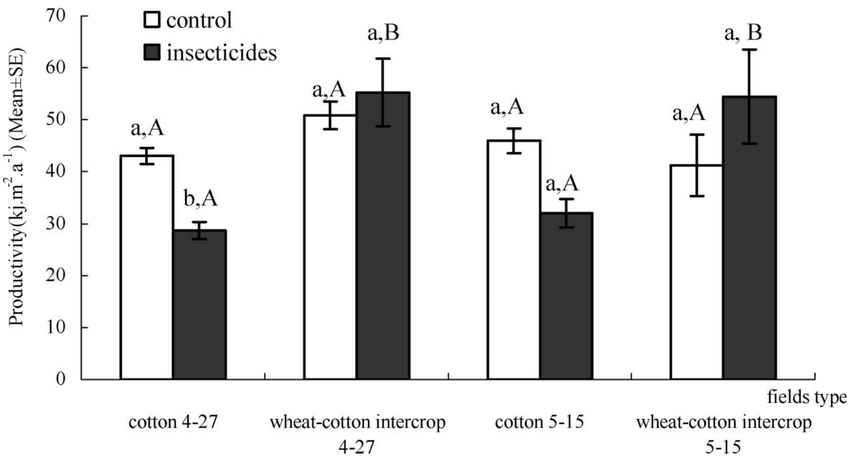

Figure 2. Productivity of the predator community in different cotton agroecosystems (different lower case letters show significant differences between insecticide treatments, and different upper case letters indicate significant differences among the four agroecosystems by LSD test at $P < 0.05$).

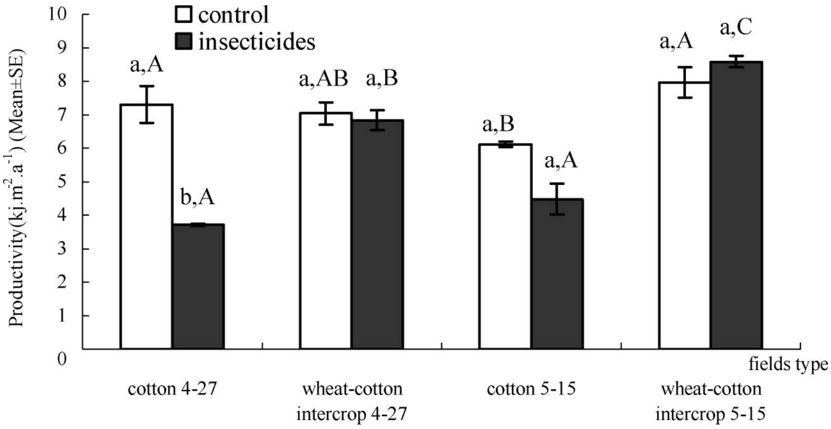

Figure 3. Productivity of the parasitoid community in different cotton agroecosystems (different lower case letters show significant differences between insecticide treatments, and different upper case letters indicate significant differences among the four agroecosystems by LSD test at $P < 0.05$).

decreased after using insecticides, indicating that monoculture plots were significantly affected by insecticides, while intercropping increased the productivity of parasitoid community. The interactive effect of chemical control × intercropping on productivity was significant ($P < 0.001$, Table 2).

3.3. Effects of chemical control on the damage index (I_1/P_0) of the insect pest community and the control index (I_2/P_1, I_3/P_1) of the natural enemy community in the four cotton agroecosystems

Chemical control × intercropping produced a significant effect on the damage index of the insect pest community (I_1/P_0) ($P < 0.001$, Table 3). Chemical control × intercropping expressed a significant effect on the control index of the predator community (I_2/P_1) ($P < 0.001$), as did the factor of intercropping ($P = 0.04$). The control index of the parasitoid community (I_3/P_1) was also affected significantly by chemical control × intercropping interaction ($P = 0.003$).

3.4. Effects of chemical control on the correlation between the community structure index and lower community productivity in the four cotton agroecosystems

3.4.1. Structure index of the insect pest community and primary productivity

The correlation between species richness of insect pests (S_1) and primary community productivity (P_0) was significant only in the insecticide monoculture plots planted on 27 April ($P = 0.006$, Table 4). The total number of insect pests (N_1) and productivity (P_1) had complex relationship with primary production (P_0) in the four cotton plots. Number diversity (HN_1) and energy flow diversity indices (HE_1) of the insect pest community did not show a significant correlation with productivity of the primary community (P_0).

Table 3. Two-way ANOVA of effects of chemical control, intercropping, and chemical control × intercropping on the damage index (I_1/P_0) of the insect pest community, the control index of the predator community (I_2/P_1), and the control index of the parasitoid community (I_3/P_1) in the four types of cotton agroecosystem.

Source of variance	DF	Damage index (I_1/P_0)	Control index (I_2/P_1)	Control index (I_3/P_1)
Chemical control	1	0.211	0.133	0.06
Intercropping	3	0.411	0.04*	0.16
Chemical control × intercropping	3	<0.001**	<0.001**	0.003**

I is the total ingestion of the community, and P is the productivity of community. Subscript 0 denotes the plant community, subscript 1 denotes the insect pest community; subscript 2 denotes the predator community; and subscript 3 denotes the parasitoid community. * and ** indicate a significant effect at $P < 0.05$ and $P < 0.01$, respectively.

3.4.2. Structure index of the predator community and productivity of the insect pest community

The effects of chemical control on the correlations between species richness of the predator community (S_2) and productivity of the insect pest community (P_1) were significant in all four cotton plots, and correlations were higher in monoculture plots and lower in inter-cropped plots (Table 5). Productivity (P_2), energy flow diversity indices (HE_2) and number diversity indices (HN_2) were not significantly correlated with productivity of the insect pest community (P_1), and chemical control did not significantly affect these correlations.

3.4.3. Structure index of the parasitoid community and productivity of the insect pest community

Correlations between species richness (S_3) of the parasitoid community and insect pest productivity (P_1) were significant only in monoculture cotton plots with no insecticides planted on 27 April (Table 6).

Table 4. Significance of correlations between the structure of the insect pest community and primary crop productivity in the four types of cotton agroecosystem (df = 20).

Seed time	Types of agroecosystem	Use of insecticides	$P_0 - S_1$	$P_0 - N_1$	$P_0 - P_1$	$P_0 - HE_1$	$P_0 - HN_1$
4 – 27	Cotton	No	0.359	0.597*	0.309	−0.060	0.056
		Yes	0.557**	0.847**	0.691**	−0.093	0.303
4 – 27	Cotton – wheat intercrop	No	0.716**	0.353	0.693**	−0.191	−0.049
		Yes	0.688**	0.486*	0.761**	−0.181	0.102
5 – 15	Cotton	No	−0.314	0.548*	0.091	−0.005	0.131
		Yes	0.156	0.433*	0.198	−0.127	−0.032
5 – 15	Cotton – wheat intercrop	No	0.336	0.536*	0.650**	−0.120	0.641*
		yes	0.136	0.366	0.346	−0.134	−0.134

P_0 is the primary crop productivity; remaining abbreviations are the same as in Tables 1 and 3.

Table 5. Significance of correlations between the structure of the predator community and productivity of the insect pest community in the four types of cotton agroecosystem (df = 20).

Seed time	Types of agroecosystem	Use of insecticides	$P_1 - S_2$	$P_1 - N_2$	$P_1 - P_2$	$P_1 - HE_2$	$P_1 - HN_2$
4 – 27	Cotton	No	0.244	0.271	−0.080	0.321	0.452*
		Yes	0.435*	0.286	0.169	−0.051	0.062
4 – 27	Cotton – wheat intercrop	No	0.594**	0.442*	0.271	−0.258	−0.284
		Yes	0.434*	0.200	0.014	−0.190	−0.248
5 – 15	Cotton	No	0.450*	0.380	0.141	−0.232	−0.308
		Yes	0.708**	0.790**	0.511*	−0.088	−0.350
5 – 15	Cotton – wheat intercrop	No	0.494*	0.351	0.088	−0.249	−0.082
		yes	0.363	0.393	0.254	−0.093	0.020

Remaining abbreviations are the same as in Tables 1 and 3.

Table 6. Significance of correlations between the structure of the parasitoid community and productivity of the insect pest community in the four types of cotton agroecosystem (df = 20).

Seed time	Types of agroecosystem	Use of insecticides	$P_1 - S_3$	$P_1 - N_3$	$P_1 - P_3$	$P_1 - HE_3$	$P_1 - HN_3$
4 – 27	Cotton	No	0.500*	0.304	0.526*	0.429	0.301
		Yes	0.299	0.513*	0.746**	0.662**	0.689**
4 – 27	Cotton – wheat intercrop	No	0.130	0.464*	0.512*	0.332	0.319
		Yes	0.322	0.719**	0.725**	0.583**	0.445*
5 – 15	Cotton	No	0.427	0.795**	0.816**	0.442*	0.245
		Yes	0.122	−0.023	0.036	−0.086	−0.033
5 – 15	Cotton – wheat intercrop	No	0.423	0.460*	0.379	0.007	0.189
		yes	0.176	0.609**	0.467*	0.048	−0.028

Remaining abbreviations are the same as in Tables 1 and 3.

Productivity (P_3), energy flow diversity (HE_3), and total individual numbers (N_3) showed significant correlations with productivity (P_1) in cotton plots treated with insecticides. Insecticides had significant effects on the correlation of number diversity indices of the parasitoid community (HN_3) and insect pest productivity (P_1) in cotton plots planted on 27 April.

4. Discussion

4.1. *Chemical control*

Many previous studies have reported on the effect of chemical control on community structure. Sigsgaard and Ersboll (1999) showed that insecticide had a negative effect upon the numbers of *Cheiracanthium inornatum* and anthicids. The results of Wang et al. (1998) indicated that species composition and individual level of spiders were influenced distinctly by insecticides, but the number of species was not affected. The diversity level increased to a certain degree after the insecticides were applied. Tan et al. (1998) showed that the number arthropod (insects and spiders) community diversity index was reduced after using chemical control in a tea plantation. In our study, chemical control showed a significant effect on the number diversity index of the insect pest community and on the total individual numbers of the predator community. Insecticides were mainly used in this experiment to control seedling and summer aphids and third generation cotton bollworms, which in turn affected the number diversity index of the insect pest community. In addition, sublethal effect of pesticides can be as important as direct toxic effects when measuring abundance of predator populations (Burn 1989). Toft (1996) found that toxic residue on prey may negate their energy and nutrient qualities. Other sublethal effects include a decreased ability to find food and an increased risk of predation of the beneficial itself (Brown 1989). The interaction of chemical control and intercropping produced significant effects on most community structure parameters of insect pest and natural enemy communities. The cotton – wheat intercropped plots probably provided many hiding locations which were beneficial to the natural enemy communities, even though insecticides were mainly applied to control aphids and cotton bollworms. Therefore, insecticides used in different types of fields can influence the community structure of insect pest and natural enemy communities.

4.2. *Intercropping*

Multiple-cropping practices influence resource concentration and, therefore, may affect density and productivity of pests and other organisms (Kareiva 1983). For primary producers, the higher species richness (e.g. intercropped cotton fields) can increase the community utilization of light energy and associated productivity. Experimental tests have been conducted mainly in agricultural ecosystems by comparing the abundance of herbivores and natural enemies in monocultures and poly cultures (Risch et al. 1983; Andow 1991; Mensah 1999; Koricheva 2000). However, reviews of the intercropping literature indicate that, relative to monocultures, herbivores in intercropping systems were less abundant in more than 50% of the studies, more abundant in 15 – 18% of the cases, and variable in about 20% (Risch et al. 1983; Andow 1991). About 9% of the studies showed no difference in herbivore density between cropping systems (Hugh and Robert 2000). Our results showed that there was lower productivity of insect pests and higher productivity of predator and parasitoid communities in the cotton intercropping fields than in the cotton monocultures. Predator and parasitoid communities were more protected from insecticides in the cotton intercropping agroecosystems.

4.3. *Diversity-productivity relationship*

Increased primary productivity generated by greater plant diversity is expected to stimulate secondary productivity. More generally, diversity changes at one trophic level may lead to a variety of potential responses for processes at higher trophic levels (Tilman 1982; Haddad et al. 2001). The existing literature, however, contains conflicting evidence on the relationship between species diversity and productivity. Theory (Rosenzweig 1971; MacArthur 1972), field studies (McNaughton 1968; Brown 1973), and field experiments (Kirchner 1977; Abramsky 1978) indicate both negative and positive correlations between productivity and species diversity (Abramsky 1984). So, the direction of the correlation between productivity and diversity appears to have a complex relationship (Loreau et al. 2001) that depends on the position of a given study on the productivity gradient (Abramsky 1984). Our studies showed diversity indices of insect pest and predator communities had no significant correlations with lower trophic community productivity in both cotton fields with insecticides and without insecticides, and these results do not match the conclusions mentioned above. But, there were significant correlations of the parasitoid community in cotton fields planted on 27 April after using insecticides, which supported the above hypotheses. Insecticides can reduce the number of individuals, but not the number of species in the insect pest community, which in turn affects the diversity of the parasitoid community, meaning that the diversity of the parasitoid community mainly depends on the productivity of the insect pest community. So we believe that the diversity index is not a good criterion to reflect the ability of natural enemies to control pests.

4.4. *Damage index and control index*

The damage index indicates the ability of a pest to damage on the crop. Wiegert and Petersen (1983) reported that the percentage of ingested energy utilized by terrestrial herbivorous insects was from 0.1 to 19%, with an average value of 3.5%. Our results showed the damage index of insect pests was 1.1 – 14.6% in untreated control fields and 0.68 – 1.95% in chemical control fields. In these four cotton agroecosystems, aphids and cotton bollworms are predominant species and play important roles in the energy flow within the cotton ecosystem. Insecticides are used to mainly control these two pests which decreased the damage ability of the insect pest community. The predator community had a greater utilization of available energy with a control index of 52.9% in untreated cotton fields and 74.5% in insecticide-treated fields, respectively. These values were lower than the value for *Sarcophaga* (89.3%) reported by Prakash and Pandian (1978). Wiegert and Petersen (1983) confirmed that prey were not always steady state productivities for a whole population, and less is usually available to the predator. We avoided this problem by recording each life-stage of some insects in detail. The control indices for the parasitoid community (5.75% in cotton plots without insecticides, and 8.92% in cotton plots with insecticides, respectively) were very close to the medium values of the two parasitoid species reported by Chlodny (1968). In our study, the interaction of insecticides and intercropping can promote higher energy use and increase the control effect by natural enemies.

Faced with difficult insect pest management problems, we require management strategies that are cost-effective and sustainable. The use of pesticides must therefore be minimized because of their high costs and the harmful effects on human health and on the environment (Giliomee 1997). Our results provided a much clearer understanding of the effects of pesticides on insect pest and natural enemy communities in different cotton agroecosystems. As pest management systems become less reliant on the use of broad-spectrum insecticides (Alghali 1992; Karungi et al. 2000), research into the enhancement of natural enemy populations through the manipulation of habitant and agricultural practices should be pursued.

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References

Abramsky Z. 1978. Small mammal community ecology: changes in species diversity in response to manipulated productivity. Oecologia. 34:113–123.

Abramsky Z, Rosenzweig ML. 1984. Tilman's predicted productivity-diversity relationship shown by desert rodents. Letters to Nature. 309:150–151.

Albert AM. 1983. Estimation of oxygen consumption of lithobird field populations from laboratory measurement. Oecologia. 56:280–291.

Alghali AM. 1992. Insecticide application schedules to reduce grain yield losses caused by insect pests of cowpea in Nigeria. Insect Science Applications. 13:725–730.

Andow DA. 1991. Vegetational diversity and arthropod population response. Annual Reviews in Entomology. 36:561–586.

Barlow CA. 1979. Energy utilization by larvae of a flower fly, *Syrphus corollae* (Diptera: Syrphidae). Canadian Entomology. 111:897–904.

Boeken B, Shachak M. 2006. Linking community and ecosystem process: the role of minor species. Ecosystems. 9:119–127.

Brown RA. 1989. Pesticides and non-target terrestrial invertebrates: an industrial approach. In: Jepson PC, editor. Pesticides and non-target invertebrates. Wimborne (UK): Intercept. p. 19–42.

Burn AJ. 1989. Long term affects of pesticides on natural enemies of cereal crop pests. In: Jepson PC, editor. Pesticides and non-target invertebrates. Wimborne (UK): Intercept. p. 177–193.

Carcia XF, Diekmann M, Bramick U, Lemcke R, Mehner T. 2006. Correlations between type-indicator fish species and lake productivity in German lowland lakes. Journal of Fish Biology. 68:1144–1157.

Chlodny J. 1968. Evaluation of some parameters of the individual energy budget of the larvae of *Pteromalus puparum* (L.) (Pteromalidae) and *Pimpla instigator* (Fabr.) (Ichneumonidae). Ekologiya Polska Seria A. 16:505–513.

Fitt GP. 1994. Cotton pest management: Part 3. An Australian perspective. Annual Reviews in Entomology. 39:543–562.

Francis CA. 1989. Biological efficiencies in multiple-cropping systems. Advances in Agronomy. 42:1–4.

Frankovich TA, Zieman JC. 2005. A temporal investigation of grazer dynamics, nutrients, seagrass leaf productivity, and epiphyte standing stock. Estuaries. 28:41–52.

Ge F. 1991. Effects on the insect respiration metabolic efficiency. Entomological Knowledge. 28:319–321 (in Chinese).

Ge F, Ding YQ. 1996. Energy dynamics of *Helicoverpa armigera* population and its damage characteristics. Chinese Journal of Applied Ecology. 7:185–190.

Giliomee JH. 1997. The future of pesticides in crop production. African Crop Science Conference Proceedings. 3:57–66.

Haddad NM, Tilman D, Haarstad J, Ritchie M, Knops JMH. 2001. Contrasting effects of plant richness and composition on insect communities: a field experiment. American Nature. 158:17–35.

Hardee DD, Smith MT, Weathersbee AA. 1993. Sampling of the cotton aphid, *Aphis gossypii* Glover, in cotton. In: Proceedings, Beltwide Cotton Production and Research 2 Conferences, Memphis (TN): National Cotton Council of America.

Hornor-Devine MC, Leibold MA, Smith VA, Bohannan BJM. 2003. Bacterial diversity patterns along a gradient of primary productivity. Ecology Letters. 6:613–622.

Hou YM, Pang XF, Liang GW, You MS. 2001. Effects of chemical insecticides on the diversity of arthropods in vegetable fields. Acta Ecology Sinica. 21:1262–1268.

Hugh AS, Robert M. 2000. Intercropping and pest management: a review of major concepts. American Entomology. 46:154–161.

Kareiva P. 1983. Influence of vegetation texture on herbivore populations: resource concentration and hervibvore movement. In: Denno RF, McClure MS, editors. Variable plants and herbivores in natural and managed systems. New York: Academic. p. 259–289.

Karungi J, Adipala E, Kyamanywa S, Ogenga-Latigo MW, Oyobo N, Jackai LEN. 2000. Pest management in cowpea. Part 2. Integrating planting time, plant density and insecticide application for management of cowpea field insect pests in eastern Uganda. Crop Proteins. 19:237–245.

Kirchner TB. 1977. The effects of resource enrichment on the diversity of plants and arthropods in a shortgrass prairie. Ecology. 58:1334–1344.

Koricheva J. 2000. Numerical responses of different trophic group of invertebrates to manipulations of plant diversity in grasslands. Oecologia. 125:271–282.

Loreau M, Naeem S, Plnchausti J, Bengtsson J. 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science. 26:804–808.

MacArthur RH, Geogr HR. 1972. Density compensation in island faunas. Ecology. 53:330–342.

McEvoy PB. 1985. Balancing insect energy budgets. Oecologia. 66:154–156.

McNaughton SJ. 1968. Structure and function in California grasslands. Ecology. 49:962–972.

Mensah RK. 1999. Habitat diversity:implications for the conservation and use of predatory insects of *Helicoverpa* spp. in cotton systems in Australia. International Journal of Pest Management. 45:91–100.

Peakin GJ. 1978. In: Brain MV, editor. Production ecology of ants and termites. Cambridge (UK): IBP Synthesis. p. 111–163.
Prakash RN, Pandian TJ. 1978. Energy flow from spider eggs through dipteran parasitoid and hymenopteran hyperparasitoid populaions. Oecologia. 33:209–219.
Raffaelli D. 2006. Biodiversity and ecosystem functioning: issues of scale and trophic complexity. Marine Ecology Progress Series. 311:285–294.
Reynolds R. 1986. 6*6 = $18/a more. The New Farm. 8:12–14.
Risch SJ, Andow D, Altieri MA. 1983. Agroecosystem diversity and pest control: data, tentative conclusions, and new research directions. Environmental Entomology. 12:625–629.
Rosenzweig ML. 1971. Paradox of enrichment: destabilization of exploitation ecosystems I ecological time. Science. 171:385–387.
Rummel DR, Carroll SC. 1983. Winter survival and effective emergence of boll weevil cohorts entering winter habitat at different times. Southwestern Entomology. 8:101–106.
Shannon C, Weaver W. 1949. The mathematical theory of communication. Urbana (IL): University of Illinois Press. p. 117–118.
Sigsgaard L, Ersboll AK. 1999. Effects of cowpea intersowing and insecticide application on *Helicoverpa armigera* Hubner (Lepidoptera: Noctuidae) and its natural ememies in pigeonpea intercropped with sorghum. International Journal of Pest Management. 45:61–67.
Slosser JE, Bordovsky DG, Bevers SJ. 1994. Damage and costs associated with insect management options in irrigated cotton. Journal of Economic Entomology. 87:436–445.
Tan JC, Deng X, Yuan ZM. 1998. Community structure of insects and spiders in different types of tea plantation. Acta Ecologia Sinica. 18:289–294 (in Chinese).
Thormley JHM, Hesketh JD. 1973. Growth and respiration in cotton bolls. Journal of Applied Ecology. 6:315–317.
Tilman D. 1982. Resource competition and community structure. Princeton (NJ): Princeton University Press.
Tilman D, Knops J, Wedin D, Reich P, Ritchie M, Siemann E. 1997. The influence of functional diversity and composition of ecosystem processes. Science. 277:1300–1302.
Tilman D, Reich PB, Knops J, Wedin D, Mielke T, Lehman C. 2001. Diversity and productivity in a long-term grassland experiment. Science. 294:843–845.
Toft S. 1996. Indicators of prey quality for arthropod predators. In: Booij K, den Nijs L, editors. Arthropod natural enemies in arable land. Survival, reproduction and enhancement. Denmark: Aarhus University Press. p. 107–116.
Wang CL, Strazanac J, Butler L. 2000. Abundance, diversity, and activity of ants (Hymenoptera: Formicidae) in oak-dominated mixed Appalachian forests treated with microbial pesticides. Environmental Entomology. 29:579–586.
Wang DL, Liao FY, Mo JC, Wang WX. 1998. Effects of chemical medicaments on the spider community structure of masson's pine stands. Journal of Central South Forest. Univ. 18:58–62 (in Chinese).
Wang WY, Wang QJ, Wang HC. 2006. The effect of land management on plant community composition, species diversity, and productivity of alpine *Kobersia* steppe meadow. Ecology Research. 21:181–187.
Wiegert RG, Ptersen CE. 1983. Energy transfer in insects. Annual Reviews in Entomology. 28:455–486.
Wright JP, Naeem S, Hector A, Lehman C, Reich PB, Schmid B, Tilman D. 2006. Conventional functional classification schemes underestimate the relationship with ecosystem functioning. Ecology Letters. 9:111–120.
Yang XG, Chen CM. 1991. Parameters of energy flow in paddy field community. Chinese Journal of Applied Ecology. 2:121–126.

Appendix 1

The species, numbers, biomass, caloric value and respiratory rate of the phytophage communities in the four types of cotton agroecosystem.

		Individual numbers						
Order	Species	Cotton planted on 27 Apr.	Cotton – wheat planted on 27 Apr.	Cotton planted on 15 May	Cotton – wheat planted on 15 May	Biomass (mg)	Caloric value (J/mg)	Respiratory rate (ulO_2/mg/h)
Acarina	*Tetranychus cinnabarinus*	34125	584	1201	1108	0.02	18.35	10.36
Coleoptera	*Aulacophora femoralis*	1	12	13	13	14.2	22.83	10.51
	Phytoscaphus gossypii	8	11	3	1	1.19	19.99	15.73
Hemiptera	*Adelphocoris suturalis*	9	37	1	13	3.39	23.14	36.44
	Halyomorpha picus	6	2	1	4	15.30	21.28*	20.24
	Aphis gossypii (apterous)	39562	61596	45641	44577	0.01	21.43	2.42
	Aphis gossypii (alate)	1566	4540	2344	3768	0.04	21.53	12.89
	Empoasca biguttula	3	54	81	24	1.31	26.42	11.21
	Empoasca flavescens	3	113	284	26	0.09	17.41	26.06
	Sogatella furcifera	6	36	7	30	0.64	22.11	9.95
Lepidoptera	*Anomis falva*	6	15	7	9	3.9	24.35	23.59
	Helicoverpa armigera (2^{nd}–3^{rd} instar larvae)	5	9	10	13	2.13	21.9	22.44
	Helicoverpa armigera (5^{th}–6^{th} instar larvae)	24	18	32	48	8.64	23.27	18.19
	Mythimna separate	7	8	10	15	22.7	24.43	6.58
Orthoptera	*Gryllus testaceus*	112	413	183	204	0.66	19.87	10.51
	Gryllotalpa unispina		2	1		20	21.47	48.95
	Locusta migratoria	12	113	27	52	66.95	21.25	213.89
Thysanoptera	*Thrips tabaci*	396	517	1029	819	0.01	19.01	47.07
Total	18	75851	68080	50875	50724			

*Data for caloric values are from Yang and Chen (1991).

Appendix 2

The species, numbers, biomass, caloric value and respiratory rate of the natural enemy communities in the four types of cotton agroecosystem.

Order	Species	Individual numbers: Cotton planted on 27 Apr.	Individual numbers: Cotton – wheat planted on 27 Apr.	Individual numbers: Cotton planted on 15 May	Individual numbers: Cotton – wheat planted on 15 May	Biomass (mg)	Caloric value (J/mg)	Respiratory rate (ulO_2/mg/h)
Acarina	*Cheyletus eruditus*	54	56	88	55	0.08	21.1	32.86
	Clubiona japonicola		181		102	1.76	22.73	17.48
	Eringonidium graminicola	80	271	36	19	0.17	19.42	19.73
	Marpissa magistar	12	45	46	20	7.7	21.33*	38.62
	Neoscona theisi	19	111	54	75	0.67	22.31	8.28
	Oedothorax insecticeps	152	523	131	58	0.5	18.77*	7.71
Araneae	*Pardosa pseudoannulata*	40	106	29	24	3.97	23.35	8.68
	Pirata subpiraticus	76	67	39	63	1.59	18.08*	12.07
	Tetragnatha maxillosa	17		12		3.28	23.82*	8.32
	Tetragnatha spp.	17			14	4.05	21.28	12.61
	Theridion octomaculatum	24	101	40	9	0.32	25.39	14.88
	Titanoecidae niteus			4		5.65	23.1	4.81
Coleoptera	*Coccinella septempunctata*	51	111	43	235	13.95	20.17	10.22
	Leis axyridis	58	35	22	12	8.70	20.17	22.89
	Paederus fuscipes	10	24	17	21	1.43	26.58	46.94
	Propylaea japonica	60	57	39	44	2.97	25.71	134.16
Diptera	*Episyrphus balteata*	16	39	18	45	3.05	20.42	33.38
Hemiptera	*Geocoris pallidipennis*	106	82	19	177	0.92	25.69	8.52
	Nabis Capsiformis	244	103	64	180	2.97	22.55	6.21
	Orius minutus	79	48	20	50	0.03	24.43	13.69
	Teisocoris pirtipennis	134	108	91	78	0.05	23.16	42.10
Hymenoptera	*Aphelinus chrysomphali*	130	140	131	156	0.54	25.15	18.45
	Aphidius gifuensis	64	20	4	1	0.36	25.54	40.53
	Brachymeria obscurata	64	18	35	47	1.2	24.57	1.53
	Charops bicolor	1	1	1		1.89	21.95*	12.14
	Temelucha biguttata	3			7	0.7	24.73*	9.12
Mantodea	*Tenodera capitata*	13			1	11.91	22.31	88.80
Neuroptera	*Chrysopa sinica*	18	18	20	7	1.53	19.67	85.26
Total	27	1542	2265	1003	1500			

*Data for caloric values are from Yang and Chen (1991).