BioControl **49:** 701–714, 2004.

Evaluation of winter wheat as a potential relay crop for enhancing biological control of cotton aphids in seedling cotton

Xing Y. MEN[1], Feng GE[1]*, Erdal N. YARDIM[2] and Megha N. PARAJULEE[3]
[1]*Key Laboratory of Integrated Management of Pest Insects and Rodents, Institute of Zoology, Chinese Academy of Sciences, Beijing 100080, PR China;* [2]*Department of Entomology, Faculty of Agriculture, Yuzuncu Yil University, Turkey;* [3]*Texas Agricultural Experiment Station, Rt. 3, Box 219, Lubbock, TX 79403, USA*
**Author for correspondence; e-mail: gef@panda.ioz. ac.cn*

Received 4 April 2003; accepted in revised form 23 March 2004

Abstract. A 2-year study was conducted to evaluate the role of winter wheat, *Triticum aestivum* L., as a potential relay crop to conserve arthropod natural enemies and suppress cotton aphids, *Aphis gossypii* Glover, in seedling cotton. The results suggested that the natural enemies that moved from the adjacent wheat fields to cotton fields with the maturity and harvest of wheat could keep the cotton aphid population at the edges (0–4 m) of cotton fields under the action threshold of 100 aphids/m^2. Data also suggested that the wheat strip served as a reservoir to conserve arthropod predators and "relayed" its predators to cotton when wheat matured and senesced.

Key words: *Aphis gossypii*, arthropod predators, cotton, wheat

Introduction

The cotton aphid, *Aphis gossypii* Glover (Homoptera: Aphididae) is a serious worldwide pest of cotton (Paddock, 1919; Isley, 1946) and the primary pest of seedling cotton in China (Zhu and Zhang, 1950; Fan et al., 1991). Because of extensive dependence on insecticides for its control, cotton aphids have developed resistance to many chemical insecticides (Herron et al., 2001). As a result, chemical control of cotton aphids in cotton has become inconsistent and cost prohibitive in many agroecosystems (Hardee, 1993). With the introduction and adoption of transgenic Bollgard cotton in China, the cotton aphid, instead of the cotton bollworm, *Helicoverpa armigera* (Hübner), has become one of the most important pests in cotton agroecosystems. Alternative approaches are necessary to develop ecologically intensive and economically viable cotton aphid management strategy for seedling cotton.

Host plant species diversity is a key characteristic of an agroecosystem (Altieri and Letourneau, 1982) and can be utilized as an approach to conserve and enhance populations of natural enemies, and consequently to reduce the chemical dependency in agroecosystems. Root (1973) stated that greater numbers of natural enemy species may exist in a diverse habitat than in a monoculture setting owing to the availability of alternative food sources from alternative insect prey or host. Various crop species can increase the populations of natural enemies in cotton agroecosystems when they are planted in cotton fields. For instance, populations of green lacewings, *Chrysoperla* spp. (Neuroptera: Chrysopidae), have been shown to increase in cotton strip-cropped with sorghum, corn or alfalfa (Smith and Reynolds, 1972; Massey and Young, 1975). It has also been reported that strip-cropping has a potential role in increasing predator numbers and reducing the abundance of cotton aphids in Texas cotton (Parajulee et al., 1997; Parajulee and Slosser, 1999; Slosser et al., 2000).

Wheat, *Triticum aestivum* L., is one of the most important grain crops in the Cotton Belt in China. It is planted in the winter and harvested in the summer; many natural enemies overwinter within wheat fields and reproduce in the spring. In Hebei Province of China, approximately 50 generalist natural enemy species occur in wheat cropping systems, primarily feeding on cereal aphids, *Schizaphis graminum* Rondani and *Macrosiphum avenae* F. (Homoptera: Aphididae). Most of these arthropod predators in wheat are also natural enemies of cotton aphids (Zhao, 1995). Compared with monoculture cotton, populations of natural enemies can be increased significantly and cotton aphid populations can be significantly reduced in cotton inter-cropped (Wang, 1993; Xia, 1997) or strip-cropped with wheat (Parajulee and Slosser, 1999).

An understanding of temporal and spatial movement of natural enemies from wheat to cotton fields is a necessary first step toward developing a management plan to maximize the effectiveness of the relay cropping system. The objectives of this study were to: (1) determine the influence of wheat planted adjacent to cotton on wheat aphids, cotton aphids and their natural enemies, (2) determine the spatial distribution of wheat aphids, cotton aphids and their natural enemies in the fields, and (3) investigate the time of migration of primary natural enemy species from wheat to cotton fields.

Materials and methods

This study was conducted in Raoyang County, Hebei Province of China (38° 15′ N, 115° 40′ E) in 2001 and 2002. Wheat was planted on 9

October at the rate of 690 seeds/m^2 and harvested on 7 June of the following year in both years. Transgenic *Bt* cotton (Deltapine NuCOTN 33B) containing the Bollgard gene expressing Cry1 A(c) (Monsanto, St. Louis, MO), was planted at the rate of 5 plants/m^2 on 25 April and harvested before 5 October each year. Cotton fields were fertilized with 150–50–25 kg/ha (N–P–K) each year and furrow irrigated four and five times in 2001 and 2002, respectively. No pesticides were used during the study.

Experimental units were 40 m × 100 m cotton plots, planted adjacent to 40 m × 100 m wheat plots, with 10 and 9 replications in 2001 and 2002, respectively. Cotton plots and wheat plots were randomly assigned along the longer side of the plots and a 0.3 m strip of bare soil separated the plots. Five, 1-m^2 sites were marked along the width of the experimental plots at 0 m (border), 2, 4, 8 and 16 m outward from the wheat–cotton border in both wheat and cotton plots. Each 1-m^2 site included two rows of cotton or six rows of wheat; therefore, 2-row cotton × 1 m and 6-row wheat × 1 m served as sample units.

Arthropod species sampled included two groups of predator species and aphid species. The predator species were selected based on their abundance in wheat and cotton, their potential to control wheat and cotton aphids, and their movement potential between wheat and cotton fields (Zhao, 1995). Predator species included lady beetles, *Propylaea japonica* Thunberg (Coleoptera: Coccinellidae) and *Coccinella septempunctata* L. (Coleoptera: Coccinellidae), and spiders, *Eringonidium graminicola* Sundevall (Araneida: Linyphidae), and *Misumjenops tricuspidatus* F. (Araneida: Thomisidae). Aphid species sampled included wheat aphids, *S. graminum* and *M. avenae*, and cotton aphids. Arthropod species were counted visually on all plants within each sample unit in cotton. Predatory arthropods in wheat were counted on all plants within each sample unit, but only 10 wheat plants were sampled for wheat aphids. Arthropods were sampled at 5-day intervals between 18 May and 2 June in 2001 and between 13 May and 2 June in 2002 in wheat plots, and between 13 May and 17 June in 2001 and between 18 May and 17 June in 2002 in cotton plots.

Arthropod abundance as affected by distance from the wheat–cotton border was analyzed using one-way ANOVA, and means were separated by least significant difference. In the cases of significant differences in arthropod abundance between distances, regression analyses were performed to examine the relationships of arthropod numbers and the distances from the wheat–cotton border. An estimation curve method based on the significance of all model effects was used to evaluate the relationship between arthropod abundance and distance from the border. If there were more than one significant model effects, the model with the highest r^2 was selected.

Results

Abundance of wheat aphids, lady beetles and spiders in wheat fields

The distance from the wheat–cotton border affected arthropod abundance in wheat. On 18 May 2001, abundance of wheat aphids varied significantly between distances. The numbers at 16 m were 1.5 times higher compared to the numbers at 0 m ($F = 5.09$; df = 1, 18; $p = 0.037$) (Table 1). Aphid numbers were lowest at the edges and their numbers increased as the distance increased from the border of field; regression analysis showed a linear relationship between aphid abundance and the distance from the field edge (Table 3). On 28 May 2001 (1 week before the harvest of wheat), there were significant differences between wheat aphids at different distances from the border ($F = 3.038$; df = 4, 45; $p = 0.027$), and density of wheat aphids at 0 m was twice that of at 8 and 16 m. In 2002, the only significant differences with respect to wheat aphid numbers occurred on 2 June when aphids were significantly more abundant at 0 m compared to that at 2, 4 and 16 m from the field border ($F = 2.745$; df = 4, 40; $p = 0.042$) (Table 1).

The abundance of lady beetles in wheat was affected by distance from the wheat–cotton border. Before wheat senesced, the abundance of lady beetles tended to increase as the distance from the wheat–cotton border increased (Table 1). This relationship was significant on 18 May 2001 ($F = 10.38$; df = 4, 45; $p < 0.001$), 23 May 2001 ($F = 3.81$; df = 4, 45; $p = 0.009$), and 18 May 2002 ($F = 2.74$, df = 4, 40; $p = 0.042$) (Tables 1 and 3). However, when wheat matured and was 1 week away from harvest (2 June 2001), lady beetles were more abundant near the border and were 2.7 times more abundant at 4 m compared to that at 16 m ($F = 4.60$; df = 1, 16; $p = 0.046$). The same trend was observed on 2 June 2002, with 2.3-fold higher abundance of lady beetles at 4 m compared to that at 16 m ($F = 5.52$; df = 1, 16; $p = 0.032$). This relationship was best described with quadratic models (Table 3).

Abundance of spiders decreased with an increase in distance from the border on 18 May 2001 and 13 May 2002 (Tables 1 and 3). Spiders at 0 m were 4.3 times and 2.5 times more abundant than those at 16 m on 18 May 2001 ($F = 7.42$; df = 1, 18; $p = 0.014$) and 13 May 2002 ($F = 6.02$; df = 1, 16; $p = 0.026$), respectively. These data indicate that lady beetles and spiders spatially partitioned their resource habitat in wheat field.

Table 1. Mean (± SEM) abundance of wheat aphids (numbers/10 plants), ladybeetles (numbers/m^2) and spiders (numbers/m^2) at 0, 2, 4, 8 and 16 m from the border in wheat fields in 2001 and 2002 (within a column, values indicated by different letters are significantly different at $p < 0.05$)

Sampling dates	Distances (m)	2001			2002		
		Wheat aphids	Lady beetles	Spiders	Wheat aphids	Lady beetles	Spiders
13 May	0				154.98 ± 74.46 a	0.18 ± 0.23 a	0.78 ± 0.49 a
	2				174.58 ± 110.22 a	0.22 ± 0.25 a	0.56 ± 0.43 ab
	4				170.69 ± 113.51 a	0.29 ± 0.32 a	0.49 ± 0.32 ab
	8				176.27 ± 101.00 a	0.36 ± 0.49 a	0.40 ± 0.33 ab
	16				206.49 ± 111.16 a	0.50 ± 0.25 a	0.31 ± 0.28 b
18 May	0	191.94 ± 58.62 b	0.06 ± 0.10 b	0.30 ± 0.25 a	100.98 ± 60.33 a	0.27 ± 0.20 b	0.56 ± 0.47 a
	2	219.66 ± 54.05 ab	0.09 ± 0.10 b	0.14 ± 0.13 ab	70.21 ± 104.43 a	0.31 ± 0.20 b	0.31 ± 0.35 a
	4	203.11 ± 87.85 ab	0.16 ± 0.15 b	0.12 ± 0.16 ab	94.47 ± 85.38 a	0.40 ± 0.37 b	0.36 ± 0.37 a
	8	277.84 ± 111.31 ab	0.34 ± 0.25 a	0.08 ± 0.13 ab	113.93 ± 83.74 a	0.53 ± 0.46 ab	0.47 ± 0.33 a
	16	289.78 ± 123.93 a	0.50 ± 0.25 a	0.07 ± 0.08 b	106.27 ± 65.99 a	0.81 ± 0.49 a	0.50 ± 0.48 a
23 May	0	39.90 ± 15.68 a	0.02 ± 0.06 c	0.18 ± 0.23 a	8.33 ± 8.71 a	0.38 ± 0.35 a	0.56 ± 0.44 a
	2	56.58 ± 23.52 a	0.04 ± 0.08 bc	0.08 ± 0.19 a	3.53 ± 3.42 a	0.37 ± 0.33 a	0.24 ± 0.49 a
	4	48.40 ± 28.48 a	0.04 ± 0.08 bc	0.14 ± 0.18 a	6.18 ± 6.92 a	0.33 ± 0.32 a	0.50 ± 0.42 a
	8	37.20 ± 20.89 a	0.16 ± 0.21 ab	0.02 ± 0.06 a	7.96 ± 7.39 a	0.36 ± 0.42 a	0.20 ± 0.26 a
	16	51.32 ± 26.64 a	0.20 ± 0.16 a	0.00 ± 0.00 a	9.82 ± 10.24 a	0.18 ± 0.16 a	0.22 ± 0.34 a
28 May	0	46.54 ± 29.76 a	0.08 ± 0.14 a	0.06 ± 0.13 a	1.56 ± 2.12 a	0.40 ± 0.39 a	0.24 ± 0.43 a
	2	22.90 ± 17.74 b	0.14 ± 0.18 a	0.02 ± 0.06 a	0.93 ± 1.78 a	0.49 ± 0.44 a	0.29 ± 0.35 a
	4	41.58 ± 22.19 ab	0.06 ± 0.09 a	0.04 ± 0.13 a	1.38 ± 2.52 a	0.49 ± 0.47 a	0.18 ± 0.37 a
	8	22.40 ± 18.62 b	0.10 ± 0.17 a	0.02 ± 0.06 a	1.52 ± 3.25 a	0.40 ± 0.46 a	0.11 ± 0.15 a
	16	23.40 ± 26.64 b	0.08 ± 0.14 a	0.04 ± 0.08 a	1.16 ± 1.55 a	0.22 ± 0.18 a	0.11 ± 0.20 a

Table 1. (Continued)

Sampling dates	Distances (m)	2001			2002		
		Wheat aphids	Lady beetles	Spiders	Wheat aphids	Lady beetles	Spiders
2 June	0	11.24 ± 7.62 a	0.28 ± 0.19 ab	0.06 ± 0.09 a	0.47 ± 0.77 a	0.51 ± 0.28 bc	0.47 ± 0.44 a
	2	9.14 ± 7.36 a	0.34 ± 0.36 ab	0.04 ± 0.08 a	0.07 ± 0.14 b	0.56 ± 0.34 bc	0.18 ± 0.23 a
	4	13.68 ± 10.99 a	0.44 ± 0.45 a	0.00 ± 0.00 a	0.00 ± 0.00 b	1.09 ± 0.74 a	0.22 ± 0.23 a
	8	6.46 ± 7.19 a	0.20 ± 0.26 ab	0.02 ± 0.06 a	0.40 ± 0.56 ab	1.00 ± 0.69 ab	0.20 ± 0.53 a
	16	11.38 ± 8.08 a	0.12 ± 0.14 b	0.02 ± 0.06 a	0.09 ± 0.20 b	0.47 ± 0.28 c	0.16 ± 0.18 a

Table 2. Mean (±SEM) abundance (numbers/m^2) of cotton aphids, lady beetles and spiders at 0, 2, 4, 8 and 16 m from the border in cotton fields in 2001 and 2002 (within a column, values indicated by different letters are significantly different at $p < 0.05$)

Sampling dates	Distances (m)	2001			2002		
		Cotton aphids	Lady beetles	Spiders	Cotton aphids	Lady beetles	Spiders
13 May	0				2.67 ± 3.90 a	0.00 ± 0.00 a	0.33 ± 0.28 a
	2				0.51 ± 0.70 b	0.00 ± 0.00 a	0.27 ± 0.24 a
	4				0.47 ± 0.58 b	0.00 ± 0.00 a	0.29 ± 0.25 a
	8				0.51 ± 0.57 b	0.00 ± 0.00 a	0.22 ± 0.27 a
	16				1.02 ± 1.25 ab	0.00 ± 0.00 a	0.18 ± 0.23 a
18 May	0	1.83 ± 1.60 b	0.02 ± 0.06 a	0.32 ± 0.32 a	7.22 ± 5.37 a	0.00 ± 0.00 a	0.31 ± 0.28 a
	2	2.14 ± 1.76 b	0.00 ± 0.00 a	0.26 ± 0.31 a	3.44 ± 3.80 a	0.00 ± 0.00 a	0.38 ± 0.31 a
	4	3.14 ± 2.76 ab	0.00 ± 0.00 a	0.16 ± 0.16 a	3.93 ± 1.83 a	0.00 ± 0.00 a	0.33 ± 0.24 a
	8	4.08 ± 3.02 ab	0.00 ± 0.00 a	0.28 ± 0.23 a	4.53 ± 6.30 a	0.00 ± 0.00 a	0.38 ± 0.31 a
	16	4.78 ± 2.51 a	0.00 ± 0.00 a	0.32 ± 0.30 a	3.56 ± 1.25 a	0.00 ± 0.00 a	0.49 ± 0.39 a
23 May	0	19.70 ± 11.53 a	0.00 ± 0.00 a	0.14 ± 0.16 a	10.16 ± 10.32 ab	0.00±0.00 a	0.60 ± 0.58 a
	2	13.87 ± 7.58 a	0.00 ± 0.00 a	0.22 ± 0.19 a	8.53 ± 10.16 ab	0.02 ± 0.07 a	0.28 ± 0.38 a
	4	23.34 ± 17.57 a	0.00 ± 0.00 a	0.20 ± 0.21 a	6.51 ± 6.35 b	0.00 ± 0.00 a	0.51 ± 0.45 a
	8	22.44 ± 19.48 a	0.00 ± 0.00 a	0.14 ± 0.23 a	17.76 ± 15.02 a	0.00 ± 0.00 a	0.42 ± 0.25 a
	16	19.44 ± 9.86 a	0.00 ± 0.00 a	0.08 ± 0.17 a	5.00 ± 3.86 b	0.00 ± 0.00 a	0.47 ± 0.37 a
28 May	0	9.18 ± 7.17 c	0.02 ± 0.06 a	0.40 ± 0.35 a	31.27 ± 25.41 a	0.00 ± 0.00 a	0.51 ± 0.36 a
	2	33.62 ± 16.41 bc	0.00 ± 0.00 a	0.12 ± 0.17 b	37.73 ± 19.35 a	0.00 ± 0.00 a	0.40 ± 0.41 a
	4	21.25 ± 13.53 c	0.00 ± 0.00 a	0.10 ± 0.11 b	59.53 ± 78.67 a	0.02 ± 0.07 a	0.40 ± 0.42 a
	8	60.76 ± 20.47 b	0.00 ± 0.00 a	0.08 ± 0.19 b	57.00 ± 45.87 a	0.00 ± 0.00 a	0.22 ± 0.23 a
	16	107.68 ± 77.92 a	0.00 ± 0.00 a	0.16 ± 0.21 b	70.44 ± 61.84 a	0.00 ± 0.00 a	0.22 ± 0.27 a
2 June	0	6.58 ± 6.53 c	0.04 ± 0.08 b	0.16 ± 0.23 a	28.33 ± 19.36 b	0.02 ± 0.07 a	0.38 ± 0.32 a
	2	23.28 ± 10.80 c	0.04 ± 0.08 b	0.24 ± 0.21 a	49.16 ± 48.24 ab	0.00 ± 0.00 a	0.24 ± 0.33 a
	4	37.62 ± 17.66 c	0.08 ± 0.14 ab	0.20 ± 0.21 a	46.96 ± 42.59 ab	0.04 ± 0.09 a	0.18 ± 0.25 a

Table 2. (Continued)

Sampling dates	Distances (m)	2001			2002		
		Cotton aphids	Lady beetles	Spiders	Cotton aphids	Lady beetles	Spiders
	8	125.08 ± 58.17 b	0.22 ± 0.22 ab	0.14 ± 0.13 a	72.40 ± 66.12 ab	0.00 ± 0.00 a	0.20 ± 0.22 a
	16	233.80 ± 125.84 a	0.24 ± 0.31 a	0.10 ± 0.11 a	90.91 ± 82.28 a	0.00 ± 0.00 a	0.22 ± 0.25 a
7 June	0	19.12 ± 12.04 c	0.92 ± 0.56 ab	0.54 ± 0.30 a	24.33 ± 25.69 b	0.11 ± 0.15 b	0.71 ± 0.41 a
	2	41.32 ± 21.16 bc	1.30 ± 0.98 a	0.31 ± 0.33 ab	47.02 ± 39.55 b	0.13 ± 0.14 b	0.62 ± 0.34 a
	4	32.22 ± 19.73 bc	0.88 ± 0.51 ab	0.10 ± 0.11 b	84.47 ± 74.74 ab	0.36 ± 0.33 a	0.44 ± 0.36 a
	8	77.42 ± 60.22 ab	0.64 ± 0.71 b	0.18 ± 0.18 b	82.36 ± 71.32 ab	0.31 ± 0.23 ab	0.42 ± 0.31 a
	16	99.02 ± 86.13 a	0.44 ± 0.36 b	0.26 ± 0.25 b	128.96 ± 86.33 a	0.18 ± 0.16 ab	0.44 ± 0.22 a
12 June	0	2.82 ± 3.66 c	0.64 ± 0.31 a	0.22 ± 0.24 a	14.18 ± 13.09 b	0.44 ± 0.37 b	0.47 ± 0.57 a
	2	3.50 ± 3.73 c	0.84 ± 0.54 a	0.20 ± 0.21 a	38.78 ± 34.09 ab	0.49 ± 0.81 b	0.27 ± 0.28 a
	4	1.96 ± 2.82 c	0.84 ± 0.64 a	0.12 ± 0.14 a	42.24 ± 42.86 ab	1.18 ± 0.64 a	0.53 ± 0.40 a
	8	27.04 ± 23.92 b	0.92 ± 0.68 a	0.22 ± 0.20 a	32.82 ± 39.94 ab	0.47 ± 0.48 b	0.24 ± 0.26 a
	16	49.46 ± 30.34 a	0.97 ± 0.74 a	0.18 ± 0.15 a	67.72 ± 41.72 a	0.38 ± 0.34 b	0.31 ± 0.28 a
17 June	0	0.84 ± 0.96 c	1.46 ± 0.70 a	0.24 ± 0.18 ab	15.41 ± 16.16 b	0.36 ± 0.26 a	0.64 ± 0.51 a
	2	0.60 ± 1.15 c	1.68 ± 0.98 a	0.16 ± 0.21 ab	45.20 ± 34.54 ab	0.29 ± 0.20 a	0.51 ± 0.38 a
	4	1.58 ± 1.56 c	1.40 ± 0.82 a	0.30 ± 0.38 a	22.33 ± 21.34 ab	0.18 ± 0.19 a	0.36 ± 0.34 a
	8	13.10 ± 12.91 b	1.38 ± 1.22 a	0.14 ± 0.13 b	29.67 ± 31.21 ab	0.38 ± 0.16 a	0.32 ± 0.42 a
	16	27.70 ± 22.67 a	1.86 ± 1.21 a	0.22 ± 0.15 ab	49.07 ± 41.72 a	0.31 ± 0.21 a	0.56 ± 0.58 a

Table 3. Regression models to describe relationships between arthropod densities and the distance from the wheat–cotton border

Year	Species	Sampling dates	Regression model	R^2	*F*-value	df	*p*
2001							
	Wheat aphids	18 May	$y = 198.326 + 6.358x$	0.142	7.933	48	0.007
	Lady beetles in wheat field	18 May	$y = 0.053 + 0.029x$	0.462	41.28	48	<0.001
		23 May	$y = 0.019 + 0.012x$	0.227	14.11	48	<0.001
	Spiders in wheat fields	18 May	$y = 0.207 - 0.011x$	0.126	6.92	48	0.011
	cotton aphids	18 May	$y = 2.064 + 0.188x$	0.171	9.93	48	0.003
		28 May	$y = 10.246 + 6.039x$	0.464	41.52	48	<0.001
		2 June	$y = -3.990 + 14.897x$	0.660	93.08	48	<0.001
		7 June	$y = 23.798 + 4.004x$	0.263	17.10	48	0.004
		12 June	$y = -1.904 + 3.060x$	0.342	5.04	48	<0.001
		17 June	$y = -2.209 + 1.892x$	0.455	40.13	48	<0.001
	Lady beetles in cotton fields	2 June	$y = 0.039 + 0.014x$	0.163	9.36	48	0.004
		7 June	$y = 1.091 - 0.043x$	0.122	6.66	48	0.013
2002							
	Lady beetles in wheat field	18 May	$y = 0.251 + 0.035x$	0.214	11.72	43	0.001
		2 June	$y = 0.449 + 0.152x - 0.010x^2$	0.189	4.88	42	0.012
	Spiders in wheat fields	13 May	$y = 0.656 - 0.025x$	0.125	6.12	43	0.017
	cotton aphids	2 June	$y = 35.2994 + 3.7086x$	0.130	6.43	43	0.015
		7 June	$y = 37.9550 + 5.9438x$	0.231	12.92	43	0.001
		12 June	$y = 23.4604 + 2.6138x$	0.149	7.55	43	0.009
	Lady beetles in cotton fields	7 June	$y = 0.0988 + 0.0566x - 0.0032x^2$	0.143	3.52	42	0.039

Note: y = density (numbers/m^2) of arthopods except wheat aphids (numbers/10 plants), x = distance at 0, 2, 4, 8 and 16 m from the wheat–cotton border.

Abundance of cotton aphids, lady beetles and spiders in cotton fields

In general, cotton aphid abundance increased as the distance from wheat–cotton border increased (Table 2), with significant relationships observed in six out of eight sample dates ($F = 4.45$; df = 4, 45; $p = 0.057$ on 18 May; $F = 10.536$; df = 4, 45; $p < 0.001$ on 28 May; $F = 22.847$; df = 4, 45; $p < 0.001$ on 2 June; $F = 4.529$; df = 4, 45; $p = 0.004$ on 7 June; $F = 14.431$; df = 4, 45; $p < 0.001$ on 12 June; $F = 10.188$; df = 4, 45; $p < 0.001$ on 17 June). Abundances of cotton aphids at 0, 2 and 4 m were less than the action threshold of 100 aphids per plant (Zhang and Yuan, 1982) on all sampling dates (Figure 1). However, at 8 and 16 m, populations of cotton aphids increased to levels above the action threshold on 2 June; they were reduced on later dates (Figure 1). Similar results were observed in 2002, with significant relationships on sample dates between 2 June and 17 June ($F = 1.529$; df = 4, 40; $p = 0.186$ on 2 June; $F = 3.534$; df = 4, 40; $p = 0.015$ on 7 June; $F = 2.554$; df = 4, 40; $p = 0.054$ on 12 June; $F = 2.117$; df = 4, 40; $p = 0.094$ on 17 June) (Tables 2 and 3). It is noteworthy that the significant relationships were observed after the wheat crop was terminated. Also, abundances of cotton aphids at all sampled distances (0, 2, 4, 8 and 16 m) were lower than the action threshold on all sampling dates except at 16 m on 7 June in 2002 (Figure 1).

Populations of lady beetles were relatively low in the cotton field prior to 7 June (before wheat harvest) in both years. Considerable increases in lady beetle numbers were observed on 7 June in both years (Figure 2), coinciding with wheat harvest. In general, abundance of lady beetles increased as the distance from the wheat–cotton border increased (Table 2). In 2001, lady beetles were more abundant at distances near the wheat–cotton border just after wheat harvest (7 June)

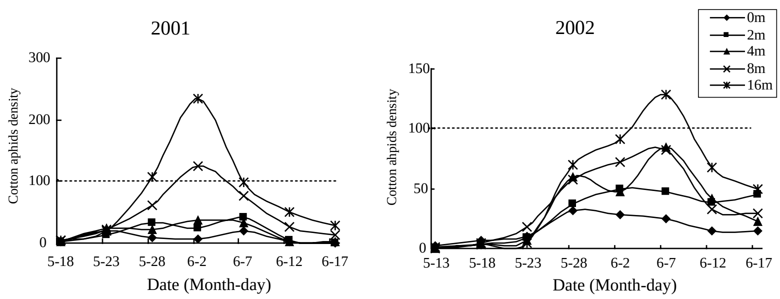

Figure 1. Average abundance of cotton aphids (numbers/m^2) at different distances from the border in cotton fields.

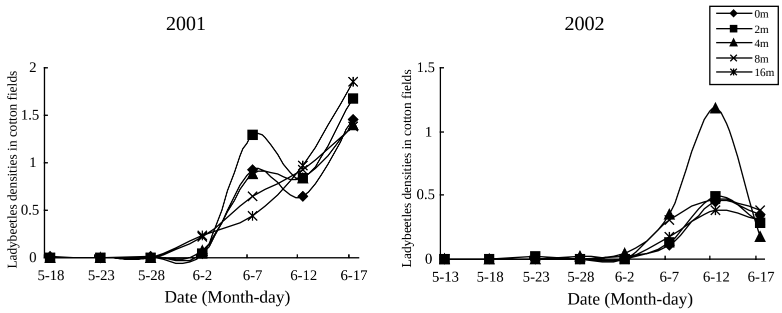

Figure 2. Average abundance of lady beetles (numbers/m^2) at different distances from the border in cotton fields.

($F = 6.76$; df = 1, 18; $p = 0.018$) (Tables 2 and 3). In 2002, the highest numbers of lady beetles were observed closer to the wheat–cotton border right after wheat harvest as in 2001, but the effect continued for 2 weeks in 2002 (Table 2). This relationship was best described with quadratic models (Table 3).

Abundance of spiders at wheat–cotton border was significantly higher than those at other distances on 28 May 2001 ($F = 4.23$; df = 4, 45; $p = 0.005$) and 7 June ($F = 6.33$; df = 18; $p = 0.022$) (Table 2). Following wheat harvest, spider abundance was greatest in the plot interior and the numbers did not significantly vary across different distances. No significant differences were observed in numbers of spiders at any distances in 2002 (Table 2).

Discussion

Although some cropping patterns such as intercropping are practiced to protect highly erodable land from soil erosion, fertilizer management, or weed control (Vandermeer, 1989; Theunissen, 1994), they can also enhance insect predator populations through their contribution to habitat diversification (Alderweireldt, 1994; Theunissen, 1994; Mineau and Mclaughlin, 1996; Obrycki and Kring, 1998; Mensah, 1999; Parajulee and Slosser, 1999; Prasifka et al., 1999). Relay intercropping is a pattern that allows planting of one inter-crop species before another so that their life cycles partially overlap (Kass, 1978) and provide a predator reservoir before the arrival of key pests of the primary crop (Gold et al., 1990; Lys and Nentwig, 1992). The success and efficiency of natural enemies in the control of pest populations in relay intercropping largely depends on the crops chosen, the time of maturity of the crops and the behavior of pests and beneficial arthropods (Parajulee et al., 1997).

The results of the present study indicated that numbers of lady beetles and their prey, wheat aphids, were lower at the wheat–cotton border than they were at central parts of wheat fields prior to wheat maturity in both years. However, after wheat senesced, abundance of wheat aphids decreased within the wheat field while the abundance of lady beetles and spiders increased near the wheat–cotton border. Although number of cotton aphids in cotton fields were higher than wheat aphids in wheat fields right before wheat was harvested, relatively few lady beetles were found in cotton fields prior to wheat harvest. However, immediately following wheat harvest, significant numbers of lady beetles were found in cotton fields adjacent to wheat, indicating that the wheat strip served as a reservoir to conserve arthropod predators. This event also coincided with increased cotton aphid activity in cotton. In a cotton-lucerne relay system in Australia, Mensah (1999) reported that the populations of predatory arthropods recorded on cotton declined with increasing distance from the lucerne strip.

In general, the number of seedling cotton aphids between 0 and 4 m distances were less than 100 individuals/m^2, far below the action threshold. At 8 and 16 m, natural enemies in cotton fields apparently kept the populations of cotton aphids under the threshold for up to 2 weeks following wheat harvest. Our results suggest that the natural enemies from the adjacent wheat fields could suppress seedling cotton aphids at least up to 4 m from the wheat–cotton border. This distance is well within the most common cotton–wheat intercrop system (three rows of wheat with two rows of cotton) in northern China (Xia, 1997). However, further studies are warranted to quantify the intensity and direction of predator movement from wheat to cotton. Nevertheless, these results indicate that a strip planting of wheat can conserve natural enemies of cotton arthropods and act as a relay crop to transfer natural enemies into adjacent cotton plots, with a significant potential to suppress cotton aphids.

Acknowledgements

This project was supported by the Program of the State Key Basic Research "973" Program (Grant No. G2000016209), Chinese Academy of Sciences (Grant No. KSCX2-1-02 and KSCX2-sw-103), Innovation Program by CAS (KSCX3-IOZ-04) and the Chinese National Science Fund (Grant No. 39970137).

References

Alderweireldt, M., 1994. Habitat manipulations increasing spider densities in agroecosystems: possibilities for biological control? *J. App. Entomol.* 118: 10–16.

Altieri, M.A. and D.K. Letourneau, 1982. Vegetation management and biological control in agroecosystems. *Crop Prot.* 1: 405–430.

Fan, G.H., J.Y. Mu, B.X. Liu and L.S. Liu, 1991. Studies on the population dynamics of natural enemies of cotton aphid and aphid control. *Acta Phytophylacica Sinica* 18: 211–214.

Gold, C.S., M.A. Altieri and A.C. Bellotti, 1990. Effects of intercropping and variety mixtures on the cassava hornworm, *Erinnyis ello* L. (Lepidoptera: Sphingidae), and the stemborer, *Chilomima clarkei* (Amsel) (Lepidoptera: Pyralidae). *Exp. Appl. Entomol. Netherlands Entomol. Soc.* 3: 191–196.

Hardee, D.D., 1993. Resistance in aphids and whiteflies: principles and keys to management, In: *Proceedings, Beltwide Cotton Production and Research Conferences*. National Cotton Council of America, Memphis, TN, pp. 20–23.

Herron, G.A., K. Powis and J. Rophail, 2001. Insecticide resistance in *Aphis gossypii* Glover (Hemiptera : aphididae), aserious threat to Australian cotton. *Aust. J. Entomol.* 40: 85–89.

Isley, D., 1946. The cotton aphid. *Ark. Agric. Exp. Stn. Bull.* No. 462.

Kass, D.C.L., 1978. *Polyculture cropping systems: review and analysis*. Cornell International Agriculture Bulletin 32, Cornell University, Ithaca, NY.

Lys, J.A. and W. Nentwig, 1992. Augmentation of beneficial arthropods by strip management, 4. Surface activity, movements and activity density of abundant carabid beetles in a cereal field. *Oecologia* 92: 373–382.

Massey, W.B. Jr. and J.H. Young, 1975. Linear and directional effects in predator populations, insect damage, and yield, associated with cotton interplanted with corn and sorghum. *Environ. Entomol.* 4: 637–641.

Mensah, R.K., 1999. Habitat diversity: implications for the conservation and use of predatory insects of *Helicoverpa* spp. in cotton systems in Australia. *Int. J. Pest Manage.* 45: 91–100.

Mineau, P. and A. Mclaughlin, 1996. Conservation of biodiversity with in Canadian agricultural landscapes: integrating habitat for wildlife. *J. Agric. Environ. Ethics* 9: 93–113.

Obrycki, J.J. and T.J. Kring, 1998. Predaceous Coccinellidae in biological control. *Annu. Rev. Entomol.* 43: 295–321.

Paddock, F. B., 1919. The cotton or melon louse. *Tex. Agric. Exp. Sta. Bull.* 257.

Parajulee, M.N. and J.E. Slosser, 1999. Evaluation of potential relay strip crops for predator enhancement in Texas cotton. *Int. J. Pest Manage.* 45: 275–286.

Parajulee, M.N., R. Montandon and J.E. Slosser, 1997. Relay intercropping to enhance abundance of insect predators of cotton aphid (*Aphids gossypii* Glover) in Texas cotton. *Int. J. Pest Manage.* 43: 227–232.

Prasifka, J.R., P.C. Krauter, K.M. Heinz, C.G. Sansone and R.R. Minzenmayer, 1999. Predator conservation in cotton: using grain sorghum as a source for insect predators. *Biol. Control* 16: 223–229.

Root, R.B., 1973. Organization of a plant-arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleracea*). *Ecol. Monogr.* 43: 95–124.

Smith, R.F. and H.T. Reynolds, 1972. Effects of manipulation of cotton agro-ecosystems on insect pest populations, In: M.T. Farvar and J.P. Milton (eds), *The Careless*

Technology: *Ecology and International Development*. Natural History, New York, pp. 373–406.

Slosser, J.E., M.N. Parajulee and D.G. Bordovsky, 2000. Evaluation of food sprays and relay strip crops for enhancing biological control of bollworms and cotton aphids. *Int. J. Pest Manage*. 46: 267–275.

Theunissen, J., 1994. Effect of intercropping on pest populations in vegetable crops. *IOBC/WPRS Bulletin*. 17: 153–158.

Vandermeer, J., 1989. *The Ecology of Intercropping*. (Cambridge University Press, Cambridge), p. 237.

Wang, H., 1993. The ecology effects of cotton interplanted in wheat field on cotton pests. *Acta Phytophylacica Sinica* 20: 163–167.

Xia, J., 1997. *Biological control of cotton aphid* (*Aphis gossypii* Glover) *in cotton* (*inter*) *cropping systems in China*; *a simulation study*. Thesis Landbouwuniversiteit Wageningen, The Netherlands.

Zhang, Y.Q. and Q.C. Yuan, 1982. Studies on the criteria for control of cotton aphids *Aphis gossypii* Glover in the seedling stage of cotton. *Acta Phytophylacica Sinica* 9: 223–228.

Zhao, J.Z., 1995. *Natural Enemies of Cotton Pest in China*. Wu Han Publishing House Press. p. 1559.

Zhu, H.F. and G.X. Zhang, 1950. Damage of cotton aphids to cotton growth and yield. *Sci. China* 1: 201–242.