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THE EVOLUTION OF COTTON PEST MANAGEMENT PRACTICES IN CHINA

K.M. Wu and Y.Y. Guo
Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing 100094, P. R. China; email: wkm@caascose.net.cn; yuyuanguo@hotmail.com

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■ **Abstract** The development of cotton pest management practices in China has followed a pattern seen for many crops that rely heavily on insecticides. *Helicoverpa armigera* resistance to chemical pesticides resulted in the unprecedented pest densities of the early 1990s. Transgenic cotton that expresses a gene derived from the bacterium *Bacillus thuringiensis* (Bt) has been deployed for combating *H. armigera* since 1997. The pest management tactics associated with Bt cotton have resulted in a drastic reduction in insecticide use, which usually results in a significant increase in populations of beneficial insects and thus contributes to the improvement of the natural control of some pests. Risk assessment analyses show that the natural refuges derived from the mixed-planting system of cotton, corn, soybean, and peanut on small-scale, single-family-owned farms play an important function in delaying evolution of cotton bollworm resistance, and that no trend toward Bt cotton resistance has been apparent despite intensive planting of Bt cotton over the past several years.

INTRODUCTION

Cotton production plays an important role in the economic development of many countries, and any crises that decrease the production of this commodity can adversely affect these countries. In almost all cotton-producing countries of the world, insect pests and crop diseases are considered the major factors that contribute to a decrease in cotton production (51). The key to maintaining a "modern" agricultural system capable of meeting the cotton production needs of a country without unduly damaging the agricultural resource base is a better understanding of the ecological consequences of any crop production technique (31).

The integrated pest management (IPM) concept has gradually gained acceptance and has been adopted over the past three decades as an eco-friendly pest management approach suitable for sustained production of a commodity. IPM practices in agriculture can be defined as an optimum combination of pest management methods implemented in farmers' fields that minimizes economic yield loss of a crop caused by insect pests without resulting in toxic effects to other organisms (31).

IPM practices in cotton have been developed in various ways in many countries of the world, but these practices vary with the socioeconomic and environmental characteristics of each country. Research on insect management of cotton has resulted in the development of viable IPM technologies for the production of cotton, especially in the United States, Australia, Brazil, and Russia (51). The development and implementation of IPM strategies specifically for China have increased substantially over the past 30 years. Since 1984, China has become one of the largest producers of cotton in the world. An area of 4 to 6 million ha under cotton cultivation in China meets 20% of the annual worldwide demand for cotton (7, 8, 63). Because cotton farming in China occurs over a wide range of agroecological zones, distinct cotton production systems have been developed to meet specific environmental and socioeconomic needs. This review presents a general perspective of cotton pest problems and the evolution of management practices of cotton insect pests in China, with emphasis on the impact of *Bacillus thuringiensis* (Bt) cotton deployment in recent years.

GEOGRAPHIC PRODUCTION REGIONS AND PRODUCTION SYSTEMS

China began to grow cotton (*Gossypium arboretum*) two thousand years ago. In ancient times, the cotton-growing region was located in the southern part of China. The primary growing area shifted northward to the Changjiang River Region in the thirteenth century and then expanded to the Yellow River Region in the sixteenth century. Upland cotton (*G. hirsutum*) varieties were introduced to China in the late nineteenth century and became the predominant species of cotton produced by the early twentieth century (63).

Since the middle of the twentieth century, cotton growing has been extended to 24 of China's 29 provinces and autonomous regions. On an agroecological basis, these cotton-growing areas can be grouped into three major regions: the Changjiang River Region (CRR), the Yellow River Region (YRR), and the Northwestern Region (NR) (Figure 1). The climate in these different regions varies greatly in terms of rainfall, temperature, and length of the growing season (26, 63).

The CRR is located between 25°N and 33°N, where annual rainfall is between 800 and 1500 mm. This region has slightly acidic, alluvial soil. Typically, two crops are grown per year, cotton and wheat, with a small amount of oilseed rape. Because of the long growing period for cotton in this southern area, cotton is grown at a density of less than 35,000 plants per hectare, and the plants attain a height of about 160 mm by midseason.

The YRR is located between 33°N and 41°N. Influenced by the highland dry monsoon, the annual average rainfall of 500 to 700 mm is concentrated in June, July, and August. Soil is moderately fertile and salty or alkaline in some areas.

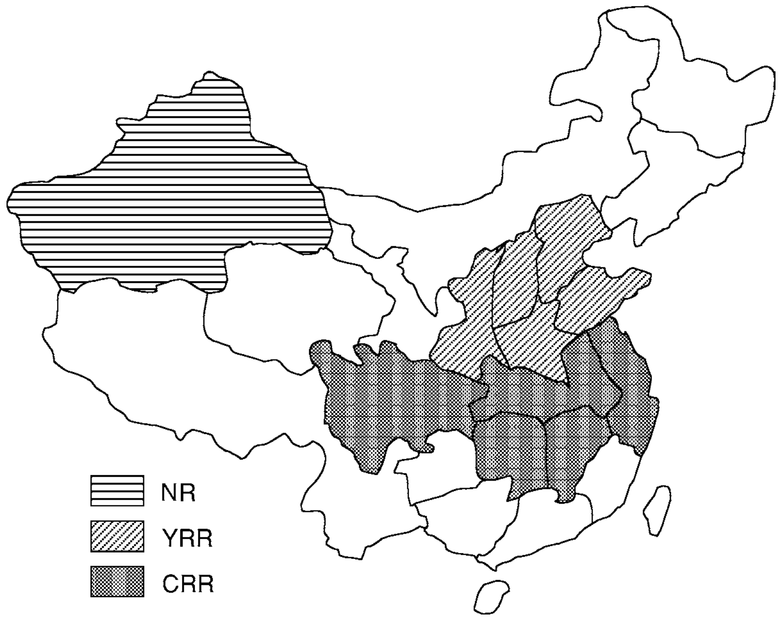

Figure 1 Geographic regions of cotton production in China. CRR, Changjiang River Region; YRR, Yellow River Region; NR, Northwestern Region (31, 63).

Cotton is often the only crop planted within a year, or in some areas and cases cotton is seeded after the harvest of wheat or as an intercrop with wheat.

The NR has become a main cotton-producing region since 1990. In recent years it has constituted 20% of the total area harvested and contributed about 30% of the national production. The winter climate in this region is very cold, with temperatures frequently dropping below −20°C. Most cotton-producing areas are concentrated in the western desert basins, where irrigation is essential. Because of the short season for crop growth, one crop of cotton is produced annually, with no winter cover crop. In contrast to CRR and YRR, where cotton is planted by single families with small farms of less than one hectare, cotton in NR is managed at a large scale similar to that in the western United States.

ARTHROPOD PESTS

The major pest complexes infesting the Chinese cotton crop at various growth stages include the cotton bollworm (*Helicoverpa armigera*), aphids (*Aphis gossypii*, *A. atrata*, *A. medicaginis*, and *Acyrthosiphon gossypii*), the pink bollworm (*Pectinophora gossypiella*), spider mites (*Tetranychus cinnabarinus*, *T. truncates*, *T. turkestani*, and *T. dunhuangensis*), a complex of thrips (*Frankliniella intonsa, Thrips tabaci*, and *T. flavus*), mirids (*Adelphocoris suturalis*, *A. lineolatus*, *A. fasciaticollis*, *Lygus lucorum*, and *L. pratensis*), whiteflies (*Bemisia argentifolii* and *B. tabaci*), the corn borer (*Ostrinia furnacalis*), the beet armyworm (*Spodoptera exigua*), the spiny bollworms (*Earias cupreoviridis*, *E. fabil*, and *E. insulana*), the cotton looper (*Anomis flava*), and leafhoppers (*Empoasca biguttula* and *E. flavescens*) (9). Temporal changes in the arthropod complex are common within all regions, but the above are the most common pest species (63).

The arthropod fauna varies from region to region. For example, the pink bollworm is found mainly in CRR (39), and aphids (*A. atrata, A. medicaginis*, and *Acyrthosiphon gossypii*) are problematic only in NR (9). Irrigation schemes create new habitats that can promote altered migratory routes for some insect species, resulting in pest populations that develop in areas that were previously beyond their geographic range. Large-scale changes in the planting and cultivation of cotton and other preferred plant hosts of *H. armigera* can further aggravate the pest situation because of population shifts of the pest from one host to another (30). Changes in the pest complex are usually related to evolution in management practices or cropping systems, and introduction of new pests. The silverleaf whitefly, *B. argentifolii*, was reported to first appear in China in the late 1990s and now has become more prevalent in YRR (44). Commercialization of Bt cotton is a major factor that has influenced the evolutionary status of cotton insect pests in recent years (48). In order of economic importance (Table 1), the key pests in China include cotton bollworm, spider mites, cotton aphids, pink bollworm, and mirids. In general, the

TABLE 1 Major arthropod pests of China cotton and their impact on estimated crop loss before and after Bt cotton commercialization[a]

	Estimated % crop loss[c], 1994[d]				**Estimated % crop loss, 2001**			
Pest complex[b]	**CRR[e]**	**YRR**	**NR**	**Total**	**CRR**	**YRR**	**NR**	**Total**
Cotton bollworm	5.97	10.13	0.32	6.60	3.91	2.92	0.32	2.47
Cotton aphids	0.44	1.46	1.27	1.03	0.33	0.84	0.25	0.52
Pink bollworm	2.02	0.14	0.00	0.85	0.90	0.01	0.00	0.27
Spider mites	0.58	0.61	0.76	0.63	1.22	0.39	0.22	0.59
Mirids	0.26	0.32	0.09	0.15	0.54	0.23	0.08	0.28
Other pests	0.34	0.30	0.18	0.29	0.23	0.23	0.28	0.24
Total	9.60	12.96	2.62	9.65	7.13	4.62	1.15	4.38

[a]Calculated from data supplied by China Agriculture Yearbook (7, 8).

[b]Pest complexes include several species described in the text.

[c]Crop loss estimates reflect loss in the presence of insect control.

[d]Crop losses in 1994 and 2001 represent the situation before and after Bt cotton commercialization, respectively.

[e]CRR, YRR, and NR represent the Changjiang River Region, the Yellow River Region, and the Northwestern Region, respectively.

cotton bollworm is the most important pest of cotton in China, inflicting substantial crop loss in CRR and YRR (94).

BENEFICIAL ARTHROPODS

Several reviews on beneficial arthropods and their relationship to pest control in cotton are available (9, 31, 38, 63). The major predatory groups include predatory beetles (*Cicindela*, *Coccinella*, *Leis*, *Propylaea*, and *Scymnus* spp.), lacewings (*Chrysopa* and *Hemerobius* spp.), predatory bugs (*Nabis*, *Orius*, and *Pirates* spp.), hover flies (*Epistrophe* and *Sphaerophoria* spp.), and spiders (*Erigonidium*, *Misumenopos*, *Neoscona*, *Oedothorax*, and *Pardosa* spp.). The main parasites include egg parasites of lepidopteran pests (*Trichogramma* spp.), larval parasites of lepidopteran pests (*Apanteles*, *Campoletis*, *Dibrachys*, *Elasmus*, *Eurytoma*, *Goniozus*, *Habrobracon*, *Litomastix*, *Macrocentrus*, *Meteorus*, and *Sympiesis* spp.), parasites of aphids (*Lysiphlebus* and *Trioxys* spp.), and the parasite of whiteflies (*Encarsia* sp.). Only the natural enemies of cotton bollworm and cotton aphid have been well documented (13–15, 17–19, 25, 49, 52, 54, 55, 65, 67, 104, 114). The egg parasites *Trichogramma* spp. and the larval parasites *Campoletis chlorideae* and *Microplitis mediator* play a major role in natural control of *H. armigera*. In addition, lacewings (*Chrysopa* spp.), minute flower bugs (*Orius* spp.), lady beetles (*Propylaea* spp.), and various species of spiders are all important predators of cotton bollworm (13, 58).

PHENOLOGY AND ABUNDANCE OF INSECT PESTS

Cotton Bollworm

H. armigera completes 3 to 4 generations in YRR and NR and 4 to 6 generations in CRR annually (26, 92, 100). Rainfall during cotton growth is an important climatic factor that influences the regional population dynamics of the pest during a season. Especially in CRR, high levels of rainfall early in the season drastically inhibit *H. armigera* population development, which usually reaches outbreak status in later generations that occur during the drought season (91, 101–103). The pest status of cotton bollworm comprises a suite of four physiological, behavioral, and ecological characteristics that enable the insect to survive in unstable habitats and in turn to colonize and exploit agricultural systems successfully: polyphagy, high mobility, high fecundity, and facultative diapause (1, 2, 20). Here we emphasize its potential to adapt to different climate zones of China in association with regional migration behavior and diapause characteristics.

Photoperiod and temperature are the main environmental factors that regulate diapause of the cotton bollworm (76). Temperature, but not photoperiod or intensity of diapause, affects termination of diapause. Exposure of diapausing pupae to low temperatures (under 10°C) can significantly reduce the number of degree-days (above 20°C) needed to complete metamorphosis. There is great heterogeneity among pupae within a population in their diapause-termination requirements (79). This heterogeneity among pupae and variation in winter temperatures determine the pattern of adult emergence in any given year. There are significant differences in diapause response among populations at different latitudes, and the critical photoperiod (light:dark) for diapause induction increases as latitude increases (76). The diapause duration of populations from YRR and NR can be significantly shortened by low-temperature vernalization, but such low temperatures have only minor effects on populations from CRR (79).

The supercooling point of diapausing pupae, an important indicator of insect cold hardiness, drops significantly as the latitude increases. The supercooling points of diapausing pupae from NR are significantly lower than those of the populations from both CRR and YRR. In general, the cold hardiness of the geographical populations is in the following order: NR > YRR > CRR > SR (Southern Region) (78). The inheritance of cold hardiness in cotton bollworm is not sex linked and is controlled by more than two incomplete recessive genes. There is no significant difference in fecundity, hatching rate of eggs, or reproductive duration among *H. armigera* sampled from different regions. Fitness investigations using field populations in Beijing indicate that there is a significant difference in the diapause dynamics of CRR and YRR populations. As a result, most individuals in CRR failed to produce diapausing pupae in late autumn, whereas the YRR population did produce diapausing pupae (77).

The populations of *H. armigera* in all of China can be divided into four regional groups: the tropical, subtropical, temperate, and Xinjiang geotypes. Their adaptive zones are respectively in southern China; the middle and lower CRR, which includes the Sichun Province, Hunan Province, Hubei Province, and Zhejiang Province; YRR, which includes the Henan Province, Hebei Province, and Shandong Province; and the Xinjiang Uygur Autonomous Region and Gansu Province (Figure 2).

Long-distance migratory movement of *H. armigera* in China was first recognized because of unexplained appearances of moths (*a*) in areas where pupae cannot overwinter, (*b*) in densities that could not have been locally produced, and (*c*) before the predicted local emergence from diapause (86). Further evidence of long-distance migration was later obtained by trapping insects flying at high altitudes and analyzing the pollen attached to the moths (97). Xu et al. (98) identified pollen attached to the proboscises of *H. armigera* trapped in Liaoning Province, Beijing, Henan Province, and over the Bohai Sea, and documented the long-distance migration from northern China into northeastern China (especially Liaoning Province) across the Bohai Sea. These observations led to the hypothesis that *H. armigera* moths trapped in late June in northeastern China were emigrating from the Shandong, Hebei, and Henan Provinces further south. Insecticide-resistance monitoring and RFLP (restriction fragment length polymorphism) analysis of the genetics of populations collected from different geographical regions of China show that there are frequent gene exchanges between populations in different ecological regions in China (80, 99). The northeastward migration in late June was

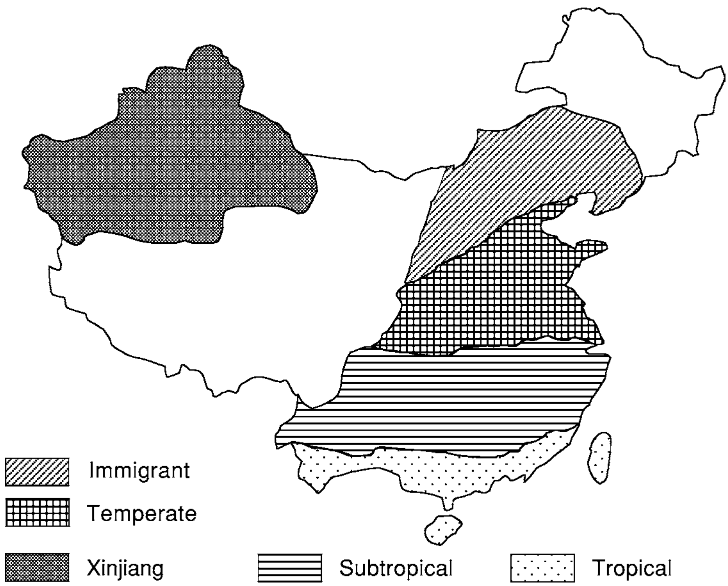

Figure 2 Ecological zones of different geotypes and immigrant zone of temperate genotypes of cotton bollworm in China (76, 86, 90).

also confirmed by observations of the ovarian development of the migrants and by direct capture of *H. armigera* over the Bohai Sea (86, 90). Entomological radars have also provided details of the flight behavior exhibited by *H. armigera* during its long-distance, wind-borne nocturnal migrations (6).

On the basis of the analysis of *H. armigera* population dynamics and climatic conditions, the Beijing area is probably the northernmost boundary for the temperate zone geotype of the cotton bollworm. Damage to cotton by larvae of the temperate zone geotype can extend into areas of northeastern China such as Liaoning and Jilin Provinces by long-distance, facultative migration during the summer East Asia monsoon (Figure 2).

Cotton Aphids

Historically, the period during which cotton aphids caused yield loss was restricted to the seedling stage of cotton plants. Before the 1970s, aphids could easily be controlled by treating seeds with insecticide. In the mid-1970s, aphids became an important insect pest of cotton owing to an insecticide-induced resurgence in mid- and late season (9, 81). Since the 1980s, aphid damage to cotton has become more serious and frequent because insecticide sprays against *H. armigera* kill most natural enemies of the aphid, such as ladybeetles and lacewings. Reduction in predation coupled with a high resistance to insecticides has resulted in major yield losses (21, 96).

Mirids

Mirids, such as *Adelphocoris fasciaticollis*, *A. lineolatus*, and *L. lucorum*, overwinter as eggs in scars of tree trunks. Hatching begins in early May. Nymphs then leave the trees and typically move to weeds in adjacent areas, but can sometimes move directly to cotton fields (22). Once mature, these mirids generally lay eggs in the tissues of cotton, alfalfa, and weeds. Overlapping generations frequently occur, since the adult stage of the mirids may last more than one month. Mirids prefer shady and moist environments, and the level of rainfall and quality of host plants are key factors that regulate the seasonal population dynamics of mirids. The mixed-species population dynamics of cotton mirids may be influenced by the amount and temporal distribution of rainfall from June to August (87).

Other Insect Pests

There are several reviews on the biology and ecology of spider mites and pink bollworm (9, 63, 71). Infestation of spider mites is most severe during the drought season and in fields where cotton is planted as an intercrop. There are three generations of pink bollworm per year in CRR, and the generations in mid- and late season inflict heavy losses to cotton (68, 70).

STRATEGIES FOR INTEGRATED INSECT PEST MANAGEMENT

In the middle part of the twentieth century, protection from insect pests of cotton consisted solely of chemical insecticides (63). These chemicals were used intensively and often on fixed schedules. Little attention was given to the dynamics of pests or the role of predators, parasites, and other biological control organisms. Insecticide usage increased from zero or a few applications per season in the early 1950s to 10–15 applications by the end of the 1970s. Insecticide usage increased even more rapidly during the 1980s, and in the early 1990s many fields received in excess of 30 applications of chemical insecticides per year (93). Some cotton insect pest populations in China increased rapidly after insecticide treatments. Insect pest populations gradually became resistant to many insecticides and thus control became difficult or impossible in some areas. By the mid-1990s, the combination of insecticide resistance and resurgence of cotton bollworm, cotton aphid, and other pests had become a major threat to cotton production in China. Facing many serious problems caused by insect pests of cotton, Chinese entomologists have conducted a substantial body of research on pest control in the past two to three decades (94, 105, 107).

Population Monitoring

Population monitoring of insect pests is a main task for each plant protection station in every county where cotton is grown. The general sampling scheme includes (*a*) visual examination of cotton plants every 3 to 5 days during the cotton-growing season to obtain information on population dynamics of all pests and natural enemies, and to estimate damage to the cotton plants. (*b*) Adult densities of cotton bollworm and pink bollworm are monitored daily by means of light traps and pheromone traps (27, 46, 60). (*c*) Overwintering population surveys are conducted usually in early winter and early spring. Some prediction models on population dynamics of main pests are available (16, 58, 62, 68, 72, 73). To take advantage of the survey information, the national pest forecasting and monitoring system of cotton was established in the 1980s. Forecasting of pest occurrences in cotton have been standardized across all growing regions and are used to provide timely information on pest dynamics to farmers.

Economic Threshold

An economic threshold (ET) is defined as the pest population density that can be tolerated without significant yield loss. The ETs for the key insect pests in each cotton-growing region are available (3, 23, 24, 32, 45, 47, 71, 95, 108, 113). When the pest density reaches or exceeds an ET, a management decision is made on the basis of the population dynamics of the pest and its natural enemies. For conventional cotton, egg density historically was used to indicate control thresholds for *H. armigera*. However, because the Bt toxin in transgenic cotton is active only against larvae, egg density is not an accurate indicator. Field trials in Hebei Province have established a new ET for the pest in midseason defined as 13 larvae per one hundred plants (38).

Biological Control

There are two approaches to the utilization of natural enemies of insect pests in an agricultural system: preservation and augmentation of existing predators and parasites, and mass rearing of natural enemies for release to regulate the population density of the target insect pest. Preservation and augmentation of existing predators and parasites in cotton by means of rational application of insecticides and crop habitat manipulation can effectively decrease population density of aphids and cotton bollworms (96). In many areas of northern China, intercropping cotton with wheat is recommended for enhancing naturally occurring biological control of cotton aphids during the early stages of cotton growth (69). Another practice to increase the impact of natural enemies is to use selective pesticides instead of broad-spectrum insecticides.

Mass production of natural enemies has been practiced since 1990. The techniques of quality control in mass production and field release have greatly improved. The use of automation, standardized procedures, and improvements in artificial eggs has revolutionized the availability and utilization of parasitic wasps (19). Industrial technology for commercial production of microbial agents is being gradually adopted and offers substantial improvements over the small-scale procedures previously employed. Augmentations of natural enemies by means of release of *Trichogramma* spp. and *Microplitis mediator* for suppression of cotton bollworm eggs and caterpillars, respectively, are recommended when the pest population density exceeds the ET (37). Biopesticides such as Bt, nuclear polyhedrosis virus, and *Beauveria bassiana* are also suitable in these situations (96, 106). After testing biological control of pests, more researchers understand that it is very difficult to effectively control pests solely with natural enemies and biocontrol agents, especially during the season when cotton bollworm poses a serious threat. Instead, biological control should be one of the important components of IPM.

Chemical Control

Chemical control is the primary suppression technique used when pest densities exceed the ET. Different groups of pesticides, mainly synthetic pyrethroids and organophosphate insecticides, are used for pest control in cotton (88, 89). Insecticide-treated seed has been used in main cotton-growing areas for control of spider mites, cotton aphids, thrips, and other sucking insects during the seedling stage. Because many experiments show that spraying chemicals during the early-growth period of cotton can induce resurgence of cotton aphids and other pests late in the season, it has been recommended that insecticide use be delayed as long as possible. Pest density during critical periods of cotton development, ET, and natural enemy population density must be considered before insecticides are applied. Appropriate rotational application of chemicals includes careful selection of pesticides, preparations, and spray methods (33). In general, because pyrethroid pesticides are highly toxic to natural enemies, it is usually suggested that they be used late in the cotton-growing season. Few acaricides that have a narrow spectrum activity are used for the control of spider mites. Chemical sprays are recommended to target at the egg or early-instar stage of cotton bollworm to avoid the reduced toxicity observed after larvae reach the third instar (38). Table 2 presents an overview of pesticide applications in China and indicates that the number of chemical applications has dropped drastically following the recent deployment of Bt cotton.

Insecticide Resistance Management

Cotton bollworm and cotton aphid resistance to the major insecticides used on cotton in YRR and CRR have been widely reported (40, 50, 56, 59, 88). The efficacies of these insecticides have declined quickly owing to the evolution of insect resistance. Compared with that of the cotton bollworm and cotton aphid, the levels of resistance for mirids, spider mites, and pink bollworm are still low. In response to cotton bollworm resistance to pyrethroids in the early 1990s, a resistance management strategy based on alternation of chemical groups, biopesticides, pheromone trapping, light trapping, and other methods was implemented (46, 93, 94, 112). Of particular importance was the introduction of Bt cotton in the late 1990s, which proved to be a valuable tool for managing insect resistance.

A continuous monitoring program assessing *H. armigera* resistance to commonly used insecticides was established for determining the impact of Bt cotton

TABLE 2 Major arthropod pests of China cotton and their impact on insecticide use[a]

	Number of applications, 1994[c]				Number of applications, 2001[c]			
Pest complex[b]	**CRR**[d]	**YRR**	**NR**	**Total**	**CRR**	**YRR**	**NR**	**Total**
Cotton bollworm	7.0	12.0	0.2	8.5	7.0	3.4	0.4	3.7
Cotton aphids	1.4	2.8	0.6	1.9	1.6	1.9	0.3	1.4
Pink bollworm	1.6	0.2	0.0	0.7	1.4	0.0	0.0	0.4
Spider mites	1.7	0.8	0.2	1.1	2.5	1.0	0.3	0.8
Mirids	0.5	0.2	0.0	0.3	0.7	0.3	0.0	0.3
Other pests	0.3	0.4	0.3	0.4	0.5	0.4	0.3	0.4
Total	12.3	16.4	1.4	12.8	13.6	7.1	1.3	7.6

[a]Calculated from data supplied by China Agriculture Yearbook (7, 8).

[b]Pest complexes include several species described in the text.

[c]Number of insecticide applications in 1994 and 2001 represent the situation before and after Bt cotton commercialization, respectively.

[d]CRR, YRR, and NR represent the Changjiang River Region, the Yellow River Region, and the Northwestern Region, respectively.

planting on the evolution of insecticide resistance in China. The average resistance levels per year in field populations of *H. armigera* to lambda-cyhalothrin, phoxim, and endosulfan are decreasing quickly. This significant increase in insect susceptibility to insecticides is expected to result in a reduction in insecticide application for *H. armigera* control in Bt cotton (89).

Many investigations have been conducted to gain an evolutionary understanding of the patterns of *H. armigera* resistance to insecticides in the field (61, 80, 89). The development of insecticide resistance in the insect is a complex phenomenon, and it seems to be influenced by a number of interacting factors. Genetic factors include initial resistant gene frequencies, additive genetic variance, dominance, mode of inheritance, drift, mutation rate, and insect biological behavior such as migration and diapause. Environmental factors include, among others, natural enemies and natural refuges; and management factors include planting schedules, crop rotation, structured refuges, and pesticide control.

The frequency of resistant phenotypes increases in a saw-toothed seasonal cycle owing to intensive sprays of pesticides during the cotton growth period (61). There are two main hypotheses in relation to this pattern of *H. armigera* resistance evolution. The first hypothesis is that unsprayed refugia for susceptible insects exist, and these result in decreased resistance frequencies owing to immigration and subsequent breeding of insects from the refugia with insect populations in heavily insecticide-treated crops. The second hypothesis involves a biological cost of resistance or "fitness deficit," which confers some disadvantage to resistant insects in the absence of selection pressure. Current studies show that migrations of the bollworm moths, which occur frequently in northern China, can affect regional resistance patterns of the pest. Large-scale Bt cotton deployment is expected to drastically increase the refugia area for individuals susceptible to pyrethroids and other pesticides (89). In addition, Wu & Guo (80) reported that insecticide resistance in *H. armigera* field populations is unstable. These may be the major factors that enhance the increase in susceptibility of *H. armigera* field populations to insecticides after Bt cotton was used in 1997.

Cultural Control

H. armigera overwinters as diapausing pupa in the soil of cotton and corn fields. Irrigation in winter and early spring can kill most pupae in the field, which is thought to be an effective method to decrease population density for the next season (78). In contrast to the migratory ability of cotton aphids and cotton bollworms, both spider mites and mirids disperse only short distances in adjacent fields during their life cycle. Weeds near cotton fields are their major host plants before moving to cotton plants, and any action to destroy the weed decreases the chance that the pests move to and damage cotton (22). In addition, an alfalfa/cotton mixed-planting system can result in major outbreaks of mirids in cotton fields. It is important to avoid planting Bt cotton in fields adjacent to alfalfa and other host plants that mirids prefer (42).

Implementation of IPM

In face of serious situations in cotton pest control experienced during the late 1980s and early 1990s, more researchers understand the importance and urgent need for cotton IPM (94). During this period a large number of research projects focused on IPM were conducted. Through effective collaboration among research institutes, universities, and extension agencies, adaptive IPM technologies have been developed and extended to most cotton-growing areas following field demonstrations (105). Insecticide use has been reduced in areas where IPM is practiced, with the average number of pesticide applications per season declining from about 20–25 to 10–15 treatments. Although extension of IPM programs is meeting the many challenges faced by more than ten million cotton farmers, it has recently achieved progress through the development of new programs for farmer training (31).

THE INTRODUCTION OF Bt COTTON

General Situation

Field trials of *H. armigera*–resistant transgenic cotton were conducted in the early 1990s in China. During this period, several *Cry1A* cotton lines were commercialized on the black market on a small scale in YRR (31). *Cry1A* cotton and *Cry1A* + *CpTI* cotton were approved formally for planting by the Chinese government in 1997 and 1999, respectively. By 2003, five *Cry1A* cotton varieties and four *Cry1A* + *CpTI* cotton varieties from the Biotechnology Research Institute, Chinese

Academy of Agricultural Sciences, and four *Cry1Ac* cotton varieties from the Monsanto Company (St. Louis, Missouri) were planted commercially (43, 110). Planting of insect-resistant transgenic cotton was limited to YRR before 1999, and then extended to NR and CRR in 1999. By 2003, Bt cotton had been planted in Hebei Province, Shandong Province, Henan Province, and Shanxi Province in YRR; Anhui Province, Jiangsu Province, and Hubei Province in CRR; and Xinjiang in NR. Plantings of Bt cotton totaled less than 0.1 million ha in 1997, but expanded rapidly to 1.1 million ha in 2000 and 2.8 million ha in 2003. This represented 58% of the total cotton acreage of 4.8 million ha in 2003 (36). Bt cotton has been exclusively planted in most cotton-growing areas of YRR since 2000 (57, 110).

Target Insect Pests

A series of field experiments on resistance efficiencies of Bt cotton to several lepidopteran species have been conducted in YRR, NR, and CRR in recent years. In general, the main target insect pests of Bt cotton deployment are defined as cotton bollworm in YRR and NR, and cotton bollworm and pink bollworm in CRR.

On the basis of field evaluations, Bt cotton resistance efficiency appears promising. However, under severe egg densities, potentially damaging bollworm densities may develop in transgenic cotton (34, 85). A possible explanation for increased survival, especially in later bollworm generations, may be associated with reduced levels of available toxin in plant tissues as they age or plant-toxin interactions (109). There is no difference in cotton bollworm resistance efficiency between *Cry1A* cotton and *Cry1A* + *CpTI* cotton. Because of the extreme bollworm egg densities that may occur in northern China and the decrease in efficacy associated with plant aging, insecticide application is still an essential alternative for late-season bollworm control in Bt cotton fields (43).

Bt cotton planted in CRR also possesses a high potential for control of pink bollworm and thus may be beneficial for the management of this pest, though its efficacy is significantly lower than that observed in Arizona. In particular, few larvae can develop normally in the Bt cotton lines in September and October. Further, the high efficacy seen during early season can effectively decrease the risk of a pest outbreak in late season. Considering that cotton is the sole host plant of this pest, area-wide planting of Bt cotton can severely limit the numbers of immigrant pink bollworm producing late-season infestations (66).

Nontarget Insect Pests

There are numerous insect pests in cotton fields. Although the Bt protein is directly toxic to only a narrow spectrum of lepidopteran species, the dynamics of these species may be indirectly affected (110). Effects on nontarget pest species may be positive owing to the removal of disruptive pesticides or negative owing to the increase in density of natural enemies resulting from a decrease in chemical use.

Field experiments on population dynamics of cotton aphid in Bt cotton fields indicate that planting Bt cotton efficiently prevents a resurgence of cotton aphids caused by insecticide use for control of cotton bollworm (81). On the other hand, an investigation of the seasonal dynamics of mixed populations of mirids in different cotton fields shows that mirid density is significantly higher on nonsprayed Bt cotton than on sprayed non-Bt cotton owing to a reduction in the number of insecticide applications against *H. armigera*. This suggests that the mirids have become key insect pests in Bt cotton fields, and their damage to cotton could increase further with the expansion of Bt cotton–growing areas if no additional control measures are adopted (87).

Natural Enemies

Transgenic Bt cotton may affect natural enemies indirectly through the removal of eggs, larvae, and pupae of lepidopterans that serve as food sources for parasitic and predatory arthropods (48, 49). Considerable reduction in the number of insecticide applications is another important factor that regulates population dynamics of natural enemies. Field trials show that by midseason the population density of predators, such as lady beetles (*Coccinella septempunctata*, *Leis axyridis*, and *Propylaea japonica*), lacewings (*Chrysopa sinica*, *C. septempunctata*, *C. shansiensis*, and *C. formosa*), spiders (*Erigonidium graminicolum* and *Misumenops tricuspidata*), and *Orius similis*, in Bt cotton are significantly higher than those in conventional cotton fields treated with insecticides for control of *H. armigera* (38). However, the population densities of parasitic wasps (*Singa hamata, Trichogramma confusum, Microplitis mediator*, *Campoletis chlorideae*, and *Litomastix* sp.) decrease significantly owing to poor quality and lower density of *H. armigera* in Bt cotton fields (10).

Diversity of Arthropods

A number of studies on the influence of Bt cotton on community structure and diversity of arthropods have been carried out in recent years to assess the ecological consequences in cotton ecosystems (11, 12, 43, 53). There are differences among several Bt cotton lines on which experiments have been conducted in different environmental conditions. Men et al. (53) published a three-year investigation in Henan Province demonstrating that Bt cotton can increase the diversity of arthropod communities and pest subcommunities, but that the diversity of natural enemy subcommunities is decreased. Similar results were obtained by Liu et al. (47), who pointed out that the nonpest arthropods and secondary pests in Bt cotton fields were key factors that kept arthropod communities more stable than those in conventional cotton fields by regulating the pest–natural enemy food chain. We therefore conclude that planting Bt cotton can increase the stability of arthropod diversity in cotton ecosystems, which may be beneficial for management of cotton insect pests (48).

Resistance Management of Target Insects

The greatest threat to the continued efficacy of Bt cotton against *H. armigera* is evolution of resistance (4, 82). Continuous monoculture of varieties that express Bt toxins is likely to select the insect intensively for resistance, particularly when Bt toxin decreases as the plants age (84). Field studies of *H. armigera* in China demonstrate that about 5% to 20% of naturally occurring larvae can survive on Bt cotton toward the end of the growing season. This indicates that Bt cotton does not maintain a high dose relative to the tolerance of *H. armigera*. Simulation studies and some experimental data have shown that, without refuge populations, pest resistance to Bt could evolve rapidly with widespread use of Bt cotton. The need to implement resistance management strategies to delay the development of pest resistance to Bt toxins in Bt crops is widely recognized (28).

The most promising strategy entails the use of plants with a high dose of toxin in combination with the maintenance of refuge crops that produce Bt-susceptible insects within the pest population. In the United States, the Environmental Protection Agency requires that each farm set aside some land for non-Bt-producing cotton. In Australia the government and farmer groups have decided to restrict Bt cotton to 30% of the land, leaving a large refuge for susceptible bollworms (29). Although this strategy seems reasonable, it is difficult to implement in YRR and CRR because of the challenges associated with educating and monitoring more than ten million farmers in China.

In YRR and CRR the cropping system is quite different from the large-scale farming in the United States and Australia. Mixed plantings of cotton, corn, soybean, and peanut are common. In general, wheat is the main host of first-generation *H. armigera* larvae, and cotton, corn, peanut, and soybean are the major host plants of subsequent generations (82). In YRR, it has been reported that the host crops of *H. armigera* are planted on approximately 14 million ha in the proportions of 5, 55, 15, 15, and 10% for cotton, corn, peanut, soybean, and other crops annually, respectively (8).

Field trials indicate that both soybean and peanut can supply refuges for the second and third generations of cotton bollworm. As the most abundant crop, corn is planted widely but has a long sowing date, from April to June in YRR (74, 75). The varied planting time for corn in YRR increases the overlap between the moth oviposition period and the occurrence of corn in the silk stage, which could serve as the refuge for the third and fourth generations of *H. armigera*. A planting system consisting of wheat, soybean (peanut), corn, and Bt cotton can supply refuges for cotton bollworm all season long. This strategy has been recommended for areas where farmers exclusively grow cotton without natural refugia from other crops (75, 82).

In addition, it is also important to consider the prudent use of insecticides, especially late in the season, to reduce overall larval densities in transgenic fields. If late-season survivors in Bt fields are selectively reduced by insecticide use, the total number of resistance alleles in a region can be reduced.

Resistance/susceptibility monitoring is an integral tool for managing resistance (64, 111). Wu et al. established baseline Cry1Ac susceptibility data for *H. armigera* before the commercialization of Bt cotton by measuring the geographic variability in the response of *H. armigera* to Cry1Ac (83). Resistance monitoring has subsequently been conducted annually (84). The monitoring results indicate that the field populations sampled are still susceptible to Cry1Ac protein and that a shift toward resistance among *H. armigera* populations is not apparent.

Currently, an F_1/F_2 resistance monitoring system that estimates the frequency of nonrecessive or recessive homozygous Cry1Ac resistance genes in *H. armigera* is already in place in Xiajin of Shandong Province, where Bt cotton has been exclusively planted for several years. The resistance gene frequency is 0.00059 in Xiajin populations, suggesting that *H. armigera* resistance genes are still rare (41). The existing refugia in corn, soybean, peanut, and other crops may be a major factor that contributes to the maintenance of *H. armigera* susceptibility to Bt cotton after several years of large-scale commercialization. In addition, gene flow derived from migration of cotton bollworms over a large area also may be an important factor that delays the evolution of Bt resistance. It is possible that immigrant individuals from non-Bt-cotton-growing areas account for a large proportion of the population during some years owing to the decrease of moths from the Bt cotton in the local area (75, 86).

In contrast to cotton bollworm, cotton is the sole host plant in the region for pink bollworm, and monocultures of lines that express Bt toxins continuously are likely to select intensely for resistance. Resistance management strategies to delay pink bollworm resistance to Bt cotton have been developed for the southwestern United States, including analyses of refuge design and resistance monitoring (5, 64). The lower efficacy of Bt cotton against pink bollworm in China compared with that in Arizona indicates that further studies of Bt cotton deployment and resistance management strategies in CRR are necessary.

FUTURE CHANGES AND CHALLENGES IN PEST MANAGEMENT

Great progress has been made in IPM of Bt cotton in recent years, although additional data on the potential of natural enemies, microbial insecticides, and cultural practices are still needed (38). However, insect pests will continue to challenge cotton production of China. The potential resistance of cotton bollworm to Bt cotton may change current practices of cotton pest control. Bt corn commercialization in China is an important issue related to pest management of cotton. Although Bt corn is not grown in China, its commercialization is currently under consideration by the Chinese government. If the Chinese government decides to commercialize Bt corn, a key refuge for cotton bollworm will be lost and resistance to Bt cotton may evolve more rapidly (29, 75).

Although no changes in the resistance of cotton bollworm to Bt cotton can be found at present, some scientists in China feel that the bollworm may evolve resistance to Bt toxin in the near future. Their concerns are based on the fact that Chinese bollworm populations quickly evolved resistance to organophosphate and pyrethroid insecticides, even though farmers rarely sprayed corn, soybean, and other host crops of cotton bollworm with these insecticides.

Second-generation Bt cotton (Monsanto Company, St. Louis, Missouri), which expresses two Bt endotoxins (*Cry1Ac* and *Cry2Ab*), is available in the United States. The increased level of control gained by the two cotton genes can be valuable in delaying Bt cotton resistance evolution in cotton bollworm (35). Undoubtedly, the major change in future pest management practices will rely heavily on the introduction of transgenic cottons that express insecticidal genes other than *Cry1Ac* and *CpTI*.

The reduction in chemical pesticide use associated with Bt cotton production is increasing the abundance of some beneficial insects and improving the natural control of specific pests such as cotton aphids. However, chemical control, especially the use of more specific, less disruptive compounds, remains important for controlling nonlepidopteran pests such as mirids and spider mites. An increase in susceptibility of *H. armigera* because of decreased insecticide applications associated with large-scale planting of Bt cotton will help preserve the usefulness and effective lifespan of conventional insecticides.

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LITERATURE CITED

1. Bai L, Sun H, Sun Y, Cao C. 1998. Studies on the source-sink relationship among host plants of cotton bollworm and control pressure on cotton. *Acta Phytophylacica Sin.* 25:198–203
2. Bai L, Sun H, Sun Y, Shu C. 1997. Studies on the host plant species and their fitness to cotton bollworm. *Acta Phytophylacica Sin.* 24:1–6
3. Bai S, Ha G, Guo W, He J. 2000. A research on the economic damage and control threshold of second generation cotton bollworm in northern Xinjiang. *J. Xinj. Agric. Univ.* 23:18–21
4. Burd AD, Gould F, Bradley JR, Vanduyn JW, Moar WJ. 2003. Estimated frequency of non-recessive Bt resistance genes in bollworm, *Helicoverpa zea* (Bolddie) (Lepidoptera: Noctuidae) in eastern North Carolina. *J. Econ. Entomol.* 96:137–42
5. Carriere Y, Ellers KC, Sisterson M, Antilla L, Whitlow M, et al. 2003. Long-term regional suppression of pink bollworm by *Bacillus thuringiensis* cotton. *Proc. Natl. Acad. Sci. USA* 100:1519–23
6. Cheng D, Wu K, Tian Z, Wen L, Shen Z. 2002. Acquisition and analysis of migration data from the digitised display of a scanning entomological radar. *Comput. Electron. Agric.* 35:63–75
7. *China Agricultural Yearbook.* 1995. Beijing: Agricultural Press

8. *China Agricultural Yearbook*. 2003. Beijing: Agricultural Press
9. *Cotton Insect Pests and Their Natural Enemies*. 1980. Wuhan, China: Hubei People's Press
10. Cui J, Xia J. 1999. Effects of transgenic Bt cotton on the population dynamic of natural enemies. *Acta Gossypii Sin.* 11:84–91
11. Cui J, Xia J. 2000. Effects of transgenic Bt cotton R93-6 on the insect community. *Acta Entomol. Sin.* 43:43–51
12. Cui J, Xia J. 2000. Studies on the components of diversity of the community in transgenic Bt cotton. *Acta Ecol. Sin.* 20:824–29
13. Cui S. 1996. Studies on biological characteristics of *Propylea japonica* and its predation function to *Helicoverpa armigera*. *Acta Gossypii Sin.* 8:269–75
14. Dai X. 1990. Biology of C*ampoletis chlorideae* and its field control effect on cotton bollworm. *Chin. J. Biol. Control* 6:153–56
15. Dai X, Li SY, Guo YY. 1991. Studies on the life table of cotton bollworm. *Acta Phytophylacica Sin.* 18:199–206
16. Ding S, Li Z. 1997. Technique of discriminatory analysis for forecasting occurrence amount of the second generation of the pink bollworm larvae. *Acta Gossypii Sinica* 9:52–54
17. Fan G, Mu J, Liu B, Liu L. 1991. Studies on the population dynamics of natural enemies of cotton aphid. *Acta Phytophylacica Sin.* 18:211–14
18. Feng H, Wang L, Xiong R. 2000. A study on the population dynamics and predacious function of *Hippodamia* (*Adonia*) *variegata* (Goeze). *Entomol. Knowl.* 37:223–26
19. Feng J, Tao X, Zhang A, Zhang Q. 1997. Study on using artificial eggs of *Trichogramma chilonis* to control *Helicoverpa armigera*. *Chin. J. Biol. Control* 13: 6–9
20. Fitt GP. 1989. The ecology of *Heliothis* species in relation to agroecosystems. *Annu. Rev. Entomol.* 34:17–52
21. Gao X, Zheng B. 1990. Biochemical methods for detecting and monitoring insecticides resistance in melon-cotton on aphid. *Acta Phytophylacica Sin.* 17:373–77
22. Gao Z, Li Q, Qiu F, Wu Y, Jiang D. 1992. Studies on the Rb-marked cotton plant bugs and dispersal from weeds to cotton fields. *Sci. Agric. Sin.* 25:15–21
23. Gao Z, Luo Y, Guo L. 1989. Economic threshold for cotton aphids (*Aphis gossypii*) on different development stages of cotton in Henan provice. *Acta Agric. Boreal Sin.* 4:60–66
24. Gao Z, Zhao H, Jiang Y. 1992. Studies on economic threshold for pink bollworm on cotton in Henan Province. *Acta Phytophylacica Sin.* 19:159–64
25. Ge F, Ding Y. 1995. The foraging behavior of lady beetle *Propylaea japonica* towards cotton aphids, *Aphis gossypii*. *Acta Entomol. Sin.* 38:436–41
26. Ge F, Liu X, Ding Y, Wang X, Zhao Y. 2003. Life-table of *Helicoverpa armigera* in northern China and characters of population development in southern and northern China. *Chin. J. Appl. Ecol.* 14:241–45
27. Ge S, Li D, Xie B. 1997. Effect of sex pheromone on behaviors of adult *Heliothis armigera* and its field control. *Chin. J. Appl. Ecol.* 8:291–94
28. Gould F. 1998. Sustainability of transgenic insecticidal cultivars: integrating pest genetics and ecology. *Annu. Rev. Entomol.* 43:701–26
29. Gould F, Blair N, Reid M, Rennie TL, Lopez J, Micinski S. 2002. *Bacillus thuringiensis* toxin resistance management: stable isotope assessment of alternate host use by *Helicoverpa zea*. *Proc. Natl. Acad. Sci. USA* 99:16581–86
30. Guo Y. 1997. Progress in the researches on migration regularity of cotton bollworm and relationships between the pest and its host plants. *Acta Entomol. Sin.* 40(Suppl.):1–6
31. Guo Y. 1998. *Research Progress in Cotton Bollworm*. Beijing: Agricultural Press

32. Guo Y, Wang W, Wang H. 1985. On the damage and economic threshold of cotton bollworm to cotton. *Acta Phytophylacica Sin.* 12:261–68
33. Hao X, Hu F, Fang C. 1992. The effects of granular insecticides on cotton insect pests and their natural enemies at seedling stage. *Acta Gossypii Sin.* 4:69–74
34. Huang M, Wan P, Wu K, Wu J, Fan X, et al. 2002. Resistance evaluation of Bt transgenic cotton to cotton bollworm, *Helicoverpa armigera,* in mid-Changjiang River Valley. *Cotton Sci.* 14:283–86
35. Jackson RE, Bradley JR, Duyn JW. 2003. Field performance of transgenic cottons expressing one or two *Bacillus thuringiensis* endotoxins against bollworm, *Helicoverpa zea* (Boddie). *J. Cotton Sci.* 7:57–64
36. James C. 2003. International service for the acquisition of agri-biotech applications (ISAAA). *Brief No. 30*
37. Ji W, Huo S, Gu X, Wei C, Dang G, et al. 1994. The ecological effect of controlling cotton bollworm by releasing *Trichogramma chilosis*. *Acta Agric. Boreal Sin.* 3:87–89
38. Jia S, Guo S, An D. 2002. *Transgenic Cotton.* Beijing: Science Press
39. Kuang X, Huang H, Zhang G. 1993. The demography of pink bollworm natural population. *Acta Entomol. Sin.* 36:308–14
40. Li F, Han Z, Wu Z, Wang Y. 2001. Insecticide resistance of *Aphis gossypii* in cotton in China. *Cotton Sci.* 13:121–24
41. Li G, Wu K, Gould F, Feng H, He Y, Guo Y. 2004. Frequency of Bt resistance genes in *Helicoverpa armigera* populations from the Yellow River cotton-farming region of China. *Entomol. Exp. Appl.* 103:135–43
42. Li Q, Liu Q, Deng W. 1994. The effect of different host plants on the population dynamics of alfalfa plant bug. *Acta Phytophylacica Sin.* 21:351–55
43. Li W, Wu K, Chen X, Feng H, Xu G, Guo Y. 2003. Effects of transgenic cottons carrying *Cry1A + CpTI* and *Cry1Ac* genes on the diversity of arthropod community in cotton fields in northern China. *Chin. J. Agric. Biotechnol.* 11:383–87
44. Lin K, Wu K, Wei H, Guo Y. 2002. Population dynamics of *Bemisia tabaci* on different host plants and its chemical control. *Entomol. Knowl.* 39:284–88
45. Liu L, Chen J, Gu G, Yang G, Wang T, et al. 1994. Observation on the occurrence and injury of *Ostrinia furnacalis* in the cotton field. *Entomol. Knowl.* 31:15–21
46. Liu L, Chen X, Chen J, Chen H, Gu G, et al. 1999. Effects of double-wave trapping light on the forecast and control of *Heliothis armigera*. *Entomol. Knowl.* 36:7–10
47. Liu L, Gu G, Chen J, Yang G, Shao X. 1996. Studies on the damage caused by the corn borer *Ostrinia furnacalis* (Guenee) in the cotton field. *Acta Entomol. Sin.* 39:109–11
48. Liu W, Wan F, Guo J. 2002. Structure and seasonal dynamics of arthropods in transgenic Bt cotton field. *Acta Ecol. Sin.* 22:729–35
49. Liu W, Wan F, Zhang F, Meng Z, Wang F. 2000. Evaluation on role of predators in *Helicoverpa armigera* control. *Chin. J. Biol. Control* 16:97–101
50. Luo W, Ling B, Yue L, Liu F. 1990. Research on the insecticide resistance of cotton aphids in Xinjiang. *Acta Phytophylacica Sin.* 17:283–88
51. Luttrell RG, Fitt GP, Ramalho FS, Sugonyaev ES. 1994. Cotton pest management: part 1. A worldwide perspective. *Annu. Rev. Entomol.* 39:517–26
52. Ma D, Guo H, Liu F, Kang F, Xun J, et al. 2000. Use *Trichogramma pintoi* to control cotton bollworm in Xinjiang. *Chin. J. Biol. Control* 16:143
53. Men X, Ge F, Liu X, Yardim EN. 2003. Diversity of arthropod communities in transgenic Bt cotton and non-transgenic cotton agroecosystems. *Environ. Entomol.* 32: 270–75
54. Meng X, Ge S, Ding Y, Xie B. 1994.

Studies on bionomics of *Litomastia heliothis*. *Entomol. Knowl.* 31:234–237
55. Mu J, Chen T, Mou S. 1997. Studies on ecological niche of primary insect pests and natural enemies in the fields of cotton interplanting with wheat. *Entomol. Knowl.* 34:325–29
56. Mu L, Wang K, Liu F, Yi M, Mu W, et al. 1995. A survey on the resistance of cotton bollworm to insecticides. *Pesticides* 34:6–9
57. Pray C, Huang J, Ma D, Qiao F. 2001. Impact of Bt cotton in China. *World Dev.* 29:813–25
58. Qin H, Ye Z, Ding J, Huang S, Luo R. 2002. Studies on predation and simulation models of two spider enemies on *Spodoptera littoralis* Fabricius. *Cotton Sci.* 14:126–29
59. Rui C, Meng X, Fan X, Liang G, Li Y. 1999. Resistance to insecticides in *Helicoverpa armigera* in Hebei, Henan, Shandong and Xinjiang. *Acta Phytophylacica Sin.* 26:260–64
60. Sheng C, Su J, Wang H, Fan W, Xuan W. 2002. An efficiency comparison of cone and water tray traps baited with pheromone for capturing male moths of *Heliothis armigera*. *Acta Entomol. Sin.* 45:271–74
61. Souza KD, Holt J, Colvin J. 1995. Diapause, migration and pyrethroid-resistance dynamics in the cotton bollworm, *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Ecol. Entomol.* 20:333–42
62. Su Z, Zhang X, Zhai B. 2002. Simulation and prediction of population dynamics of the fifth generation of *Helicoverpa armigera* (Hübner) in Jiangsu province. *Acta Entomol.* 45:465–70
63. Sun J, Chen B. 1999. *Cotton.* Beijing: Agricultural Press
64. Tabashnik BE, Patin AL, Dennehy TJ, Liu Y, Carriere Y, et al. 2000. Frequency of resistance to *Bacillus thuringiensis* in field populations of pink bollworm. *Proc. Natl. Acad. Sci. USA* 97:12980–84
65. Wan F, Liu W, Guo J. 2002. Comparison analyses of the functional groups of natural enemy in transgenic Bt-cotton field and non-transgenic cotton fields with IPM, and chemical control. *Acta Ecol. Sin.* 22:935–42
66. Wan P, Wu K, Huang M, Wu J. 2004. Seasonal pattern of infestation by pink bollworm *Pectinophora gossypiella* (Saunders) in field plots of Bt transgenic cotton in the Yangtze River Valley of China. *Crop Prot.* 23:463–67
67. Wang C. 2001. Effects of host size on oviposition and development of the endoparasitoid, C *ampoletis chlorideae*. *Chin. J. Biol. Control* 17:107–11
68. Wang D, Ye Z, Wan M. 1994. A study of catastrophe prediction of third generation of pink bollworm *Pectinophora gossypiella* (Saunders) by means of grey prediction model. *Acta Entomol. Sin.* 31:77–81
69. Wang H, Zhao H, Su J, Zhang D, Gao Z. 1993. The ecological effects of cotton interplanted in wheat field on cotton pests. *Acta Phytophylacica Sin.* 20:163–67
70. Wang R, Huang M, Fan X, Wan P, Qi L, et al. 1998. A study on the population dynamics of the second generation of pink bollworm in cotton field in Jianghan plain. *Acta Gossypii Sin.* 10:312–15
71. Wang R, Zhang S, Fan X, Xiong Y. 1994. Studies on the complex damages by *Pectinophora gossypiella* (Saunders) and *Tetranychus cinnabarrinus* (Boisduval) and their dynamic economic threshold. *Acta Gossypii Sin.* 6:53–56
72. Wang W, Guo Y, Dai X. 1995. Two prediction methods for the occurrence degree of the second generation cotton bollworm on cotton in North China. *Plant Prot.* 21:26–28
73. Wang X, Yang B, Xiang Y, Yu L. 2001. An integrated meteorological method for forecasting the cotton bollworms population in Hebei province. *Acta Phytophylacica Sin.* 21:948–53
74. Wang Z, He K, Wen P, Zhang G, Zheng L. 2001. Spatial-temporal distributions of cotton bollworm eggs on summer corn

seeded at different times in north China. *Sci. Agric. Sin.* 34:153–56
75. Wu K, Feng H, Guo Y. 2004. Evaluation of maize as a refuge for management of resistance to Bt cotton by *Helicoverpa armigera* in the Yellow River cotton farming region of China. *Crop Prot.* 23:523–30
76. Wu K, Guo Y. 1997. Diapause response of different geographical populations of cotton bollworm *Helicoverpa armigera*. *Sci. Agric. Sin.* 30:1–6
77. Wu K, Guo Y. 1997. Investigation on population fitness of cotton bollworm, *Helicoverpa armigera* (Hübner). *Acta Entomol. Sin.* 40(Suppl.):7–12
78. Wu K, Guo Y. 1997. On the cold hardiness of cotton bollworm, *Helicoverpa armigera*. *Acta Ecol. Sin.* 17:298–302
79. Wu K, Guo Y. 1997. The characteristics of diapause termination of different geographical populations in cotton bollworm, *Helicoverpa armigera* (Hübner) in China. *Acta Entomol. Sin.* 40(Suppl.):25–29
80. Wu K, Guo Y. 2000. The coordinated development and analysis of contributing factors of cotton bollworm resistance to insecticides in Round-Bohai Bay region. *Acta Phytophylacica Sin.* 27:173–78
81. Wu K, Guo Y. 2003. Influences of Bt cotton planting on population dynamics of the cotton aphid, *Aphis gossypii* Glover, in northern China. *Environ. Entomol.* 32:312–18
82. Wu K, Guo Y, Gao S. 2002. Evaluation of the natural refuge function for *Helicoverpa armigera* (Lepidoptera: Noctuidae) within *Bacillus thuringiensis* transgenic cotton growing areas in northern China. *J. Econ. Entomol.* 95:832–37
83. Wu K, Guo Y, Lv N. 1999. Geographic variation in susceptibility of *Bacillus thuringiensis* insecticidal protein in China. *J. Econ. Entomol.* 92:273–78
84. Wu K, Guo Y, Lv N, Greenplate JT, Deaton R. 2002. Resistance monitoring of *Helicoverpa armigera* to Bt insecticidal protein in China. *J. Econ. Entomol.* 95:826–31
85. Wu K, Guo Y, Lv N, Greenplate JT, Deaton R. 2003. Efficacy of transgenic cotton containing a *cry1Ac* gene from *Bacillus thuringiensis* against *Helicoverpa armigera* (Lepidoptera: Noctuidae) in northern China. *J. Econ. Entomol.* 96:1322–28
86. Wu K, Guo Y, Wu Y. 2002. Ovarian development of adult females of cotton bollworm and its relation to migratory behavior around Bohai Bay of China. *Acta Ecol. Sin.* 22:1075–78
87. Wu K, Li W, Feng H, Guo Y. 2002. Seasonal abundance of the mirids, *Lygus lucorum* and *Adelphocoris* spp. (Hemiptera: Miridae), on Bt cotton in northern China. *Crop Prot.* 21:997–1002
88. Wu K, Liang G, Guo Y. 1997. Phoxim resistance in *Helicoverpa armigera* (Lepidoptera: Noctuidae) in China. *J. Econ. Entomol.* 90:868–72
89. Wu K, Mu W, Liang G, Guo Y. 2004. Regional reversion of insecticide resistance in *Helicoverpa armigera* (Lepidoptera: Noctuidae) is associated with the use of Bt cotton in northern China. *Pest Manage. Sci.* In press
90. Wu K, Xu G, Guo Y. 1998. Observations on migratory activity of cotton bollworm moths across the Bohai gulf in China. *Acta Phytophylacica Sin.* 25:337–40
91. Wu Z, Xue Z, Zhang Z. 1993. A study on the nature population life table of cotton bollworm and its application. *Acta Ecol. Sin.* 13:185–93
92. Xia J, Wang C, Cui S. 2000. Comparative studies on life tables of cotton bollworm in the different cotton cropping sysems. *Acta Gossypii Sin.* 12:281–87
93. Xia J. 1993. Status and management of insecticide resistance of cotton bollworm *Heliothis armigera*. *Acta Gossypii Sin.* 5:1–6
94. Xia J. 1994. Strategy of area wide pest management for outbreak of cotton bollworm. *Acta Gossypii Sin.* 6:1–8
95. Xiao J, Fang C. 1990. Studies on the optimum developmental threshold of cotton

bollworm for insecticide spraying against pink bollworm. *Acta Phytophylacica Sin.* 17:219–22

96. Xing J, Feng S, Fan X, Li B, Feng S. 1991. The application of *Bt* emulsion against cotton bollworm and its preserving effect for natural enemies to suppress summer cotton aphid. *Acta Phytophylacica Sin.* 18:207–10
97. Xu G, Guo Y, Wu K, Jiang J. 2000. On the mark-release techniques of *Helicoverpa armigera* (Hübner). *Acta Gossypii Sin.* 12:247–50
98. Xu G, Guo Y, Wu K. 1999. Analyses of pollens adhering to cotton bollworm moths (Lepidoptera: Noctuidae). *Sci. Agric. Sin.* 32:63–68
99. Xu G, Guo Y, Wu K. 2000. Allozyme variations within and among five geographic populations of *Helicoverpa armigera* (Hübner). *Acta Entomol. Sin.* 43(Suppl.):63–69
100. Yang Y, Pang X, Liang G. 2000. Lifetable of cotton bollworm under different control conditions. *Chin. J. Appl. Ecol.* 11:856–60
101. Yang Y, Wang D, Zhu M. 2001. Damage and economic threshold of the third generation of cotton bollworm in the Yangtze River cotton region of Jiangsu province. *Chin. J. Appl. Ecol.* 12:86–90
102. Yang Y, Wang D, Zhu M. 2001. Effects of soil characteristics on the occurrence of *Helicoverpa armigera* (Hübner) and its region division. *Acta Ecol. Sin.* 21:959–63
103. Yang Y, Wang D, Zhu M, Yi H. 1998. Studies on the relationship between soil moisture and the occurrence of cotton bollworm. *Acta Gossypii Sin.* 10:210–15
104. You L, Lei R, Jiang J, Bo L, Xiao Z. 2002. Bionomics of *Campoletis chlorideae* as a parasitoid of the cotton bollworm *Helicoverpa armigera*. *Entomol. Sin.* 9:29–37
105. Zhang G, Liu D, Zhao J, Zhu S, Li B, et al. 1990. On the development of self-controlled cotton ecosystem in early-maturing cotton region in northeast China. *Acta Phytophylacica Sin.* 17:1–4
106. Zhang G, Zhang Z, Sun X, Jiang Q, Zhang C. 1996. Evaluation of applicable effectiveness of new formulation of *Helicoverpa* NPV insecticide-emulsifiable suspension. *Chin. J. Biol. Control* 12:24–28
107. Zhang R, Ren L, Zhang G. 2000. On the management strategy of cotton aphid in Xianjiang cotton fields. *Chin. J. Biol. Control* 16:183–85
108. Zhang Y, Cao Y, Bai L, Cao C. 1986. Plant bug damage on cotton in different growing stages and the threshold for control. *Acta Phytophylacica Sin.* 13:73–78
109. Zhang Y, Wu K, Guo Y. 2001. On the spatio-temporal expression of the contents of Bt insecticidal protein and the resistance of Bt transgenic cotton to cotton bollworm. *Acta Phytophylacica Sin.* 28:1–6
110. Zhang Y, Wu K, Peng Y, Guo Y. 2002. Progress in ecological safety of insect-resistant transgenic plants. *Entomol. Knowl.* 39:321–26
111. Zhao J, Rui C, Lu M, Fan X, Ru L, et al. 2000. Monitoring and management of *Helicoverpa armigera* resistance to transgenic Bt cotton in Northern China. *Res. Pest Manage. Newsl.* 11:28–31
112. Zhao W, He J, Zhang G, Li J, Liu Q. 1999. A study on techniques to trap and kill the cotton bollworm adults with high-voltage mercuric lamps. *Acta Agric. Univ. Henan* 33:151–55
113. Zhu J, Mao A, Zhong T. 2000. Studies on the damage and economic threshold of cotton bollworm to cotton. *Acta Gossypii Sin.* 12:202–4
114. Zou Y, Bi S, Chen G, Meng Q, Geng J, et al. 1998. Influence of natural enemies on population of *Aphis gossypii*. *Chin. J. Appl. Ecol.* 9:499–502