Biological Control 68 (2014) 6–14

Contents lists available at SciVerse ScienceDirect

Biological Control

journal homepage: www.elsevier.com/locate/ybcon

Biological control of cotton pests in China

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HIGHLIGHTS

- Biological control plays an important role for control of cotton pests in China.
- More than a hundred species of major arthropod predators and parasitoids of cotton insect pests have been described.
- *Trichogramma* spp., *Bacillus thuringiensis* and HaNPV etc. have been mass reared or commercially produced and used.
- Biological control strategies have been developed for control of non-target insect pests in Bt cotton fields.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Available online 2 July 2013

Keywords:
Biological control
Cotton
Natural enemies
Habitat manipulation
Natural enemy diversity
Augmentation
Conservation

ABSTRACT

Cotton is one of the most economically important crops in China, while insect pest damage is the major restriction factor for cotton production. The strategy of integrated pest management (IPM), in which biological control plays an important role, has been widely applied. Nearly 500 species of natural enemies have been reported in cotton systems in China, but few species have been examined closely. Seventy-six species, belonging to 53 genera, of major arthropod predators and parasitoids of lepidoptera pests, and 46 species, belonging to 29 genera, of natural enemies of sucking pests have been described. In addition, microsporidia, fungi, bacteria and viruses are also important natural enemies of cotton pests. *Trichogramma* spp., *Microplitis mediator*, *Amblyseius cucumeris*, *Bacillus thuringiensis* and *Helicoverpa armigera* nuclear polyhedrosis virus (HaNPV) have been mass reared or commercially produced and used in China. IPM strategies for cotton pests comprising of cultural, biological, physical and chemical controls have been developed and implemented in the Yellow River Region (YRR), Changjiang River Region (CRR) and Northwestern Region (NR) of China over the past several decades. In recent years, Bt cotton has been widely planted for selectively combating cotton bollworm, *H. armigera*, pink bollworm, *Pectinophora gossypiella*, and other lepidopteran pest species. As a result of reduced insecticide sprays, increased abundance of natural enemies in Bt cotton fields efficiently prevents outbreaks of other pests such as cotton aphids. In contrast, populations of mirid plant bugs have increased dramatically due to a reduction in the number of foliar insecticide applications for control of the bollworms in Bt cotton, and now pose a key problem in cotton production. In response to this new pest issue in cotton production, control strategies including biological control measures are being developed in China.

1. Introduction

Cotton production plays an important role in the economic development of China. Upland cotton (*Gossypium hirsutum*) varieties were introduced to China in the late nineteenth century, then

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1049-9644/$ - see front matter
http://dx.doi.org/10.1016/j.biocontrol.2013.06.004

they rapidly replaced *Gossypium arboretum* and became the predominant cultivars (Sun and Chen, 1999). By the mid twentieth century, cotton planting had extended to 24 provinces and autonomous regions in China. In 2009, China was ranked as the largest cotton producer in the world with a total planting area of >5 million ha, and lint yields of 6377 million kg (China Agricultural Yearbook, 2010). Since the 1990's, cotton production has been mainly distributed in three major regions: the Yellow River Region (YRR), the Changjiang River Region (CRR), and the Northwestern Region (NR) (Fig. 1), Climatic conditions such as length of the rainy season differ significantly among the three regions.

In the early 1980s, cotton growing area increased rapidly in YRR, and then decreased gradually in the 1990s (Fig. 2), even though the YRR is at present still the largest cotton production region in China where cotton is often the only crop or is interspersed with wheat in each year. In southern areas of the YRR, cotton is planted following the wheat harvest. Associated with the YRR's vast population and limited farmland, cotton is planted by single families with small lands of less than one hectare (Wu and Guo, 2005).

In the 1970s, 46.0% of the cotton was planted in the CRR (Jia et al., 2004). While during the 1980s cotton production in this region was gradually reduced in association with rapid regional economic development, the planting area of cotton has been maintaining at about 1.2 million ha since 2000 (Fig. 2). In this region, two crops are typically grown per year, and cotton is often

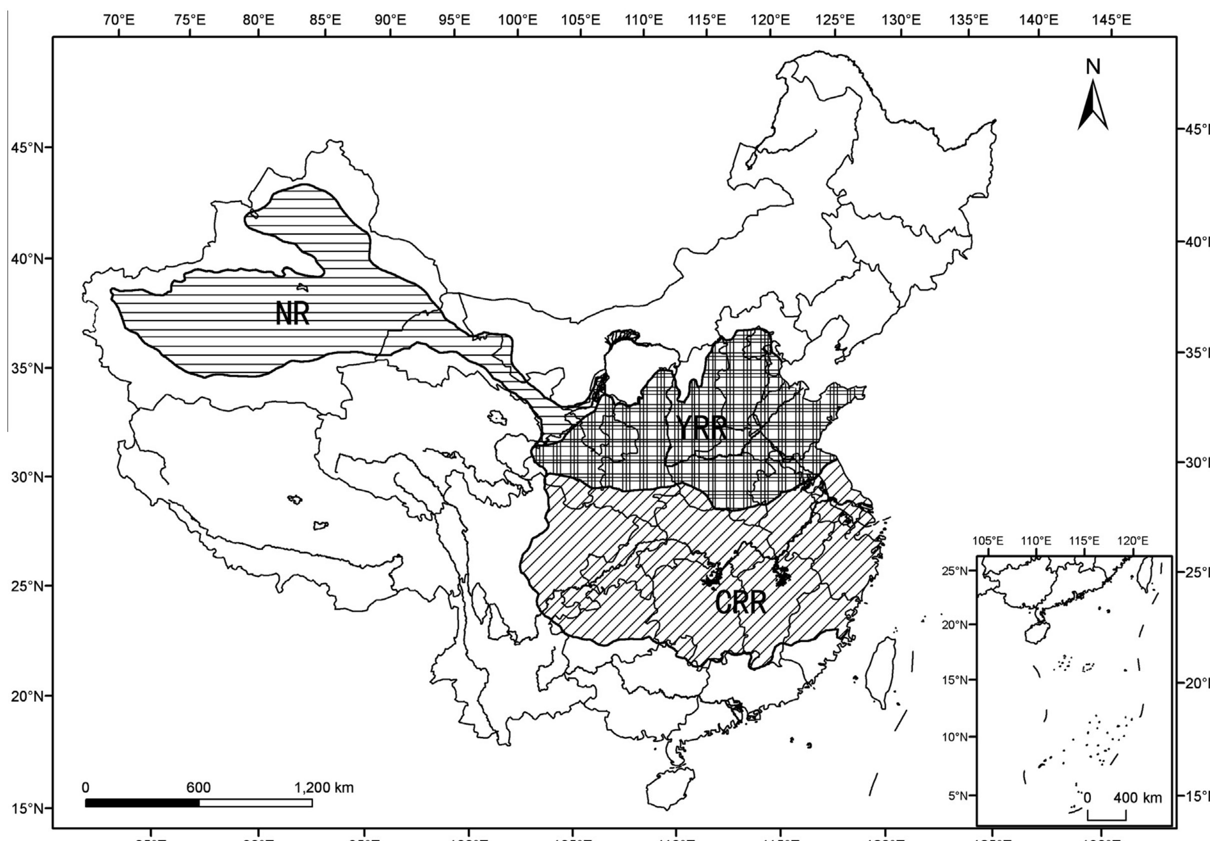

Fig. 1. Geographic regions of cotton production in China, YRR, Yellow River Region; CRR, Changjiang River Region; NR, Northwestern Region (Sun and Chen, 1999).

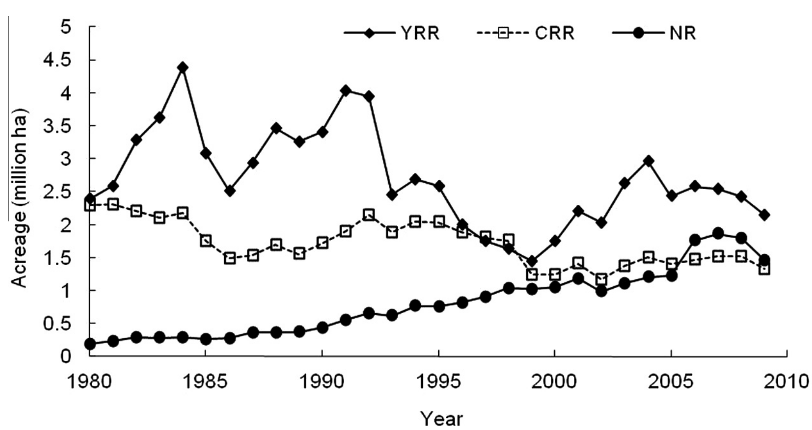

Fig. 2. The trend of the cotton production in China by region (Data source: Planting Information of China).

interspersed with cultivation of rice, corn, wheat, rape, bean, vegetables or other crops. Similar to YRR, cotton was grown on small areas managed by single families.

The cotton production area in the NR was only 0.3 million ha. during the 1980s. However it has increased rapidly over the past two decades (Fig. 2). In recent years, the NR has become the second largest cotton production region in China where cotton is the only crop per year. Cotton in the NR is managed at a large scale similar to that in the western USA (Wu and Guo, 2005).

Similar to other cotton-producing countries in the world, both insect pests and crop diseases are considered the major factors leading to decreases in cotton yields (Luttrell et al., 1994). The pest species in Chinese cotton production systems differ depend on crop growth and phenology (Zhu and Zhang, 1954), geographic distribution, environmental factors (Ding, 1963; Wu and Zhao, 1994), cotton varieties (Guo et al., 2007a), pest management strategies (Deng et al., 2003) and cropping patterns (Wen et al., 1995; Guo et al., 2007b). Pest suppression was achieved through chemical control from the 1950's to the 1970's. Organophosphate and organochlorine pesticides were widely used as seed treatments and foliar applications. In consequence, it was recognized that the misuse of chemical pesticides was seriously disrupting the ecological system, polluting the environment, and inducing pest resurgence and pest resistance at an increasing rate. Subsequently the concept of integrated pest management (IPM) started to be adopted in China in the mid-1970's. Since then, effective and environmentally safe control approaches began to be explored, and many new measures and techniques were put into use in cotton pest control as a part of IPM. Especially biological control strategies were rapidly developed and widely applied in different cotton production regions according to climatic conditions and cropping patterns.

In this article, we aim to summarize the biological control measures for cotton insect pests in China, and analyze and discuss how to improve the efficacy and implementation of biological control strategies in the future. First, we describe the major insect pests and natural enemy species occurring in Chinese cotton; second, we review the major natural enemies that have been used for biological control of major insect pests in different cotton production regions of China; third, we examine augmentation and conservation of biological control agents as components in the development and implementation of IPM in different cotton production regions of the country. Finally, we discuss approaches to improve research and adoption of biological control in Bt cotton systems. By drawing attention to past research and trends for future progress, we hope to increase the scale of research and promotion of practical biological control in Chinese cotton.

2. Major natural enemy species

The historical over-reliance on chemical insecticides and their negative impacts in China have prompted recognition of the importance of natural enemies at the national level. Accurate identification of organisms discovered during survey is often a baseline central to determining the need for classical biological pest control. The abundance and diversity of natural enemies are closely linked to herbivores, cotton varieties and production regions in China. Based on the published literature, approximately 500 species of natural enemies have been collected in Chinese cotton fields (Zhao and Zhang, 1978; HBAAS, 1980; Yuan and Chen, 1984; Xiong et al., 1988; Guo, 1998; Miao et al., 2002; Lin et al., 2003; Wang et al., 2010). Arthropod predators are a large group, with important taxa including spider families such as Micryphantidae, Theridiidae, Araneidae, Thomisidae, Lycosidae, and Tetragnathidae, predatory Phytoseiidae mites such as *Amblyseius cucumeris*, and *Amblyseius pseulongispinosus* and, predatory insects within Neuroptera, Coleoptera and Hemiptera. Among them, the predators of lepidopteran pests include 33 spider species belonging to 21 genera, and 26 predatory insect species belonging to 16 genera (Table 1). For sucking insect pests, there are 31 major species of predators belonging to 23 genera (Table 2). Important parasitoids include egg parasitoids such as *Trichogramma confusum*, *Trichogramma dendrolimi*, and *Trichogramma ostriniae* and larval parasitoids such as *Microplitis mediator*. Major parasitoids of lepidopteran pests include 21 species, belonging to 16 genera (Table 1), and of sucking pests include 13 species belonging to 6 genera (Table 2). Pathogenic microorganisms are also important. They mainly include microsporidia (e.g., *Nosema liturae*, *Vairimorpha necatrix*), fungi (e.g., Beauveria bassiana, *Neozygites fresenii*, *Conidiobolus thromboides, Paecilomyces lilacinus*), bacteria (e.g., *Bacillus thuringiensis*) and viruses (e.g., Cytoplasmic Polyhedrosis Virus, [CPV] and Nuclear Polyhedrosis Virus, [NPV]) (Sun et al., 2000, 2001; Tong et al., 2010).

3. Mass-reared and released major natural enemies of cotton pests

Mass-rearing and release of natural enemies represent one important tactics within a practical IPM strategy. With emphasis on high quality and pollution-free agricultural products, natural enemy products enjoy a high market demand in China. More than 80 kinds of bio-pesticides (including agricultural antibiotics) have been registered in China (Wu et al., 2009). Several reports of successful artificial mass-rearing system and commercial production systems of parasitoids, predators and insect pathogens in China have been compiled (Cui et al., 2007; Wu et al., 2009).

3.1. Trichogramma

Trichogramma (Hymenoptera: Trichogrammatidae) is a dominant genus of egg parasitoids and among the earliest and most widely exploited natural enemies. They can potentially attack a large number of insect pests throughout China (Zhang et al., 1984). More than 400 species of arthropods from 24 families belonging to Lepidoptera, Hymenoptera, Coleoptera, Diptera, Neuroptera and others are parasitized by *Trichogramma* spp. (Guo, 1998). Moreover, different geographic populations of *Trichogramma* spp. differ in host selectivity (Luo et al., 2001). Several *Trichogramma* spp. have been successfully mass-reared in China. Initially, mass-production used *Sitotroga cerealella* and *Corcyra cephalonica* eggs as hosts to produce *T. ostriniae* and *T. dendrolimi*. Later, innovations in mass-rearing technology replaced these hosts with eggs of the Chinese Oak tussah moth, *Antheraea pernyi*, and castor silkworm, *Philosamia cynthia ricini* (Liu et al., 1980). Much research has led to the technical standardization and regulation of commercial production processes in China (Wang et al., 2007). This has resulted in a scientific foundation for the commercial production and application of augmentative agents. Most Chinese *Trichogramma* manufacturers are located in Northeast China. Among them, several manufacturers have reached an annual production capacity of 20 billion insects. Typically, parasitoids are released via small cards containing parasitized eggs. For example, at the time of peak occurrence of cotton bollworm (*Helicoverpa armigera*) eggs, parasitoid cards are hung in the middle of the cotton canopy during morning or evening hours when *Trichogramma* adults begin to eclose. They may be released every 50–60 days at a density of 0.18–0.21 million wasps/ha per release (Lu et al., 2010a,b). At these release rates Trichogramma can parasitize 37–40% of the cotton bollworm eggs and reduce bollworm populations up to 60% (Ba et al., 2008).

Table 1
Potential biological control agents of Lepidoptera pests on cotton in China.

Major lepidopteran pests	Major natural enemies (Insecta)		Arachnida
	Parasitoids	Predators	
Helicoverpa armigera	*Campoletis chlorideae*, *Microplitis mediator*, *Charops bicolor*, *Trichogramma confusum*, *T. dendrolimi*, *Polistes okinawansis*	*Paederus fuscipes*, *Campalita chinense*, *Calosoma maximowiczi*, *Carabus coptobabrus*, *Isiocarabus fiduciaries*, *Chlaenius bioculatus*, *C. circumdatus*, *C. inops*, *Craspedonotus tibialis*, *Brachinus aeneicostis*, *Cicindela chinensis*, *C. elisae*, *C. sumatrensis*, *C. laetescripta*, *Chrysopa sinica*, *C. septempunctata*, *C. shansiensis*, *C. formosa*, *Orius similis*, *O. minutes*, *Geocoris ochropterus*, *G. pallidipennis*, *Nabis ferus*, *Hierodula saussurei*, *Euborellia pallipes*, *Apolygus lucorum*	*Erigone atra*, *E. Prominens*, *Erigonidium graminicolum*, *Gnathonarium gibberum*, *Oedothorax insecticeps*, *Enoplognatha dorsinotata*, *E. japonica*, *Theridion octomaculatum*, *Neoscona doenitzi*, *N. nautical*, *N. theisi*, *Singa hamata*, *S. pygmaea*, *Misumenopos tricuspidata*, *Synaema globosum*, *Thomisus labefactus*, *Xysticus croceus*, *X. lateralis atrimaculatus*, *Oxyopes sertatus*, *Pardosa T-insignita*, *Pirata japonicas*, *Chiracanthium japonicola*, *Clubiona japonicola*, *Marpissa magister*, *Plexippus setipes*, *Dyschiriognatha quadrimaculata*, *Tetragnatha cliens*, *T. extensa*, *T. japonica*, *T. nitens*, *T. praedonia*, *T. shikokiana*, *T. Squamata*
Pectinophora gossypiella	*T. confusum*, *Dibrachys cavus*, *Chelonus pectinophorae*, *Bracon nigrorufum*, *B. isomera*		
Ostrinia furnacalis	*T. confusum*, *T. dendrolimi*, *T. ostriniae*, *Macrocentrus linearis*, *Xanthopimpla punctata*, *P. okinawansis*, *Apanteles flavipes*, *Temelucha philippinensis*, *Trathala flavo-orbitalis*, *Lydella grisescens*		
Earias cupreoviridis, *E. fabia* and *E. insulana*	*C. bicolor*, *C. pectinophorae*, *A. eguchii*		
Spodoptera exigua	*Meteorus pulchricornis*, *Gonia bimaculata*		
Anomis flava	*C. bicolor*, *T. confusum*, *T. dendrolimi*, *M. japonicas*, *X. punctata*, *P. okinawansis*		

HBAAS (1980), Xiong et al. (1988), Guo (1998).

Table 2
Major piercing-sucking pests and their insect natural enemy on cotton in China.

Major sucking pests	Parasitoids	Predators
Cotton aphids	*Trioxys indicus*, *Lipolexis gracilis*, *L. scutellaris*, *Lysiphlebus japonicus*	*P. fuscipes*, *Propylaea japonica*, *Leis axyridis*, *Coccinella septempunctata*, *Adonia variegate*, *Coelophora saucia*, *Chilomenes quadriplagiata*, *Melanostoma scalare*, *Epistrophe balteata*, *Paragus quadrifasciatus*, *Syrphus corollae*, *C. sinica*, *C. septempunctata*, *C. shansiensis*, *C. formosa*, *Hemerobius humuli*, *H. lacunaris*, *O. similis*, *O. minutes*, *G. ochropterus*, *G. pallidipennis*, *N. ferus*, *H. saussurei*
Aphis gossypii, *A. atrata*, *A. medicaginis*, and *Acyrthosiphon gossypii*		
Mirids	*Peristenus relictus*, *P. spretus*	*O. similis*, *O. minutes*, *G. ochropterus*, *G. pallidipennis*, *N. sinoferus*, *N. stenoferus*, *H. saussurei*, *C. sinica*, *C. formosa*, *C. septempunctata*
Apolygus lucorum, *Lygus pratensis*, *Adelphocoris suturalis*, *A. lineolatus* and *A. fasciaticollis*		
Whitefly	*Encarsia sophia*, *E. japonica*, *E. formosa*, *E. smithi*, *Eretmocerus mundus*, *E. debachi*, *E. melanoscutus*	*Serangiella sababensis*, *Axinoscymnus apioides*, *P. japonica*, *L. axyridis*, *C. sinica*, *Delphastus catalinae*, *Nephaspis oculatus*
Bemisia tabaci		
Spider mites		*Scolothrips takahashii*, *Stethorus punctillum*, *P. fuscipes*, *P. japonica*, *L. axyridis*, *C. septempunctata*, *C. sinica*, *C. shansiensis*, *H. humuli*, *O. similis*, *G. ochropterus*, *G. pallidipennis*, *N. ferus*
Tetranychus cinnabarinus, *T. truncates*, *T. turkestani*, and *T. dunhuangensis*		
Thrips *Frankliniella intonsa*, *Thrips tabaci* and *T. flavus*		*O. similis*, *G. ochropterus*, *G. pallidipennis*, *N. ferus*

Zhao and Zhang (1978), HBAAS (1980), Xiong et al. (1988), Wang et al. (2010).

3.2. *M. mediator*

M. mediator (Hymenoptera: Braconidae) is an endoparasitoid that is distributed widely in the Palaearctic region. *M. mediator* can complete 7–8 generations in the YRR and 2nd–3rd instar cotton bollworm are its main hosts. Based on previous studies, *M. mediator* can be mass reared successfully on armyworm (an alternative host) in the insectary (Li et al., 2006; Luo et al., 2010). Pupal diapause of *M. mediator*, induced under conditions of low temperature and short photoperiod, allows insects to be stored for later use (Hun et al., 2005; Li et al., 2008). *M. mediator* is released for suppression of cotton bollworm larvae in cotton at a density of 4500–15000 cocoons per ha, depending on pest density, and can provide up to 60–70% control (Li et al., 2004). Field release techniques for this parasitoid have been used as a tool for promoting and demonstrating augmentative biological control.

3.3. Predatory mites

Spider mites are important cotton pests in some areas of China, especially in the NR. Thus, biological control of mite pests with predatory Phytoseiidae mites is of increasing interest (Zhang et al., 1983). A predatory mite, *A. cucumeris*, has been commercially produced and used for biological control of cotton mites in China since 2000. There are two major manufacturers of predatory mites including the Institute of Plant Protection, Chinese Academy of Agricultural Sciences and the Institute of Plant Protection, Fujian Academy of Agricultural Sciences (Yu et al., 2008; Jiang et al., 2010). About 800 billion predatory mites are commercially produced annually. It is recommended to hang three bags (1500–3000 mites/bag) of mites around the central infested plant at early stages of spider mite occurrence. When spider mite densities reach or exceed the economic threshold, 3000–5000 bags (300–600 mites/bag) should be hung per hectare and that can significantly suppress populations of this pest in cotton (Lu et al., 2010a).

3.4. Bacterial insecticides

Bacterial insecticides were the earliest developed and the most widely used microbial pesticides in China. One of the most common bacterial insecticides contains *B. thuringiensis* (Bt), which target larvae of lepidopteran pests such as cotton bollworm, pink bollworm and corn borer (*Ostrinia furnacalis*). Bt insecticides were developed in the 1960s and increasingly applied in China during the 1980s. In recent years, China has made great progress in the technology of Bt strain breeding, fermentation, product formulation and application. In the 1990s, the commencement of solid-state fermentation was a significant technological innovation, and the result is that Bt toxicity was increased to 10,000–16,000 IU/mg when the commercial Bt products were made into a wettable powder (Peng, 1992). Current research on Bt has been focused on improving the production process and product quality (Wang et al., 2000). Approximately 100 manufacturers have been registered at the national pesticide administrative department of China, and the annual output of Bt is >27,200 metric tons. When the peak of the second generation of cotton bollworm eggs appear, the Bt suspension at 2000 IU/ml can be sprayed in the cotton field (3800–7500 ml per hectare) and can significantly suppress populations of the pest.

3.5. Viral insecticides

Nuclear polyhedrosis virus (NPV) and granulosis virus (GV) are also widely applied as pest control agents in China. Among them, *H. armigera* nuclear polyhedrosis virus (HaNPV) was first successfully commercially used as a biological insecticide by the Wuhan Institute of Virology, Chinese Academy of Sciences in the 1970s (Zhang et al., 1981, 1995). It is a highly effective and specific biological control agent of cotton bollworm larvae. A spray with 1.8×10^{12}–3.6×10^{12} PIB/ha solution of HaNPV can cause 75% mortality of *H. armigera* larvae (Yin et al., 1995).

4. Biological control in the development and implementation of IPM

Since the 1990s, major emphasis has been placed on research for developing IPM systems. As a result, China has established a national and provincial network, consisting of scientific teams and special facilities at institutes and universities, for biological control (Wu and Guo, 2000). Over the past 20 years considerable effort has been expended to develop breakthroughs in IPM for insect pests in cotton applicable to the various geographic and ecological regions of China where cotton is produced. A principle for pest management of cotton pests in China can be represented by the pyramid depicted in Fig. 3. The use of insecticides depends on threshold and resistance information to optimize timing of applications, and control actions of pests rely on forecasting (sampling and mon-

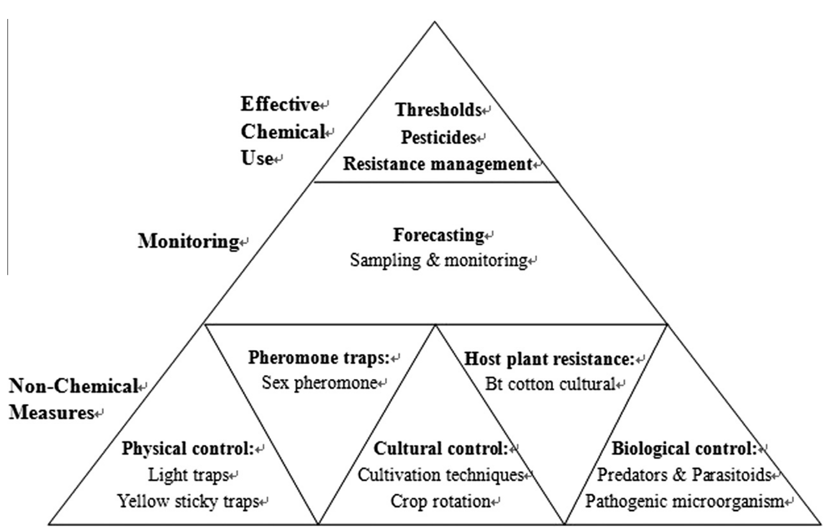

Fig. 3. Principles of integrated pest management (IPM) based on Wu et al. (2005) and Naranjo and Ellsworth (2009a).

itoring). In addition, non-chemical strategies of pests are essential components in IPM. These non-chemical measures mainly include cultural control (cultivation techniques and crop rotation), physical control (light traps and yellow sticky traps), pheromone traps (sex pheromone), host plant resistance (Bt cotton cultural) and biological control (predators, parasitoids and pathogenic microorganisms). In recent years, biological control represents a crucial strategy that plays a more dominant role for cotton pest control in the cotton production regions.

4.1. IPM and biological control in the YRR

In the YRR of China, cotton bollworm, cotton aphid (*Aphis gossypii*) and sweetpotato whitefly (*Bemisia tabaci*) are the main pests of cotton. The latter is an invasive insect pest reaching population outbreaks regularly since 2000.

Cultural measures are essential tactics for IPM that include the use of pest resistant varieties. Habitat manipulations in the form of wheat, bean, melon and garlic interspersed with small-scale cotton cultivation are also an important component of IPM, which can provide refuges for natural enemies or other beneficial arthropods that can then disperse into adjacent cotton fields (Wang et al., 1993; Ge and Ding, 1997). Such measures can reduce the dosage and frequency of insecticide sprays and further increase the control capacity of natural enemies against insect pests in cotton fields especially at the seeding stage. When insecticides are needed, the use of insecticides with low toxicity to natural enemies is recommended to further enhance biological control by the natural enemy community (Zhao et al., 1991; Wang et al., 1993; Xia et al., 1996). A similar strategy in parts of the USA has almost completely eliminated the need for insecticides in cotton production (Naranjo et al., 2004; Naranjo and Ellsworth, 2009a, 2010).

Naturally occurring biological control agents can be further conserved or supplemented through mass rearing and augmentative release. For example, in the middle of June, the 2nd generation of cotton bollworm eggs can be effectively controlled by releasing Trichogramma. Releases of *M. mediator* and application of *H. armigera* nuclear polyhedrosis virus can further supplement the control of cotton bollworm larvae at this period in the season (Yin et al., 1995; Wu and Guo, 2005; Li et al., 2004; Ba et al., 2008). For aphid pests, their populations can be effectively suppressed when the ratio of natural enemies to aphids is up to more than 1:120 in cotton fields at the seeding stage. Therefore, the number of natural enemies can be increased via conservation and artificial release in order to suppress the population of aphid pests (Lu et al., 2010a). Since *B. tabaci* can only overwinter in greenhouses in the YRR, some non-preferred hosts such as cayenne and leek can be planted in the winter that can reduce the overwinter population of the pest within greenhouses (Zhou et al., 2005). In addtion, trap crops such as *Abutilon theophrasti* can be used in the cotton field during cotton growth stage where it can significantly suppresses population of *B. tabaci* (Lin et al., 2006; Ren et al., 2011). The winter planted crops and trap crops can provide a refuge for natural enemies that can further increase abundance and diversity of natural enemy communities in the cotton field (Xia et al., 1998).

4.2. IPM and biological control in the CRR

In the CRR of China, the main pests include cotton bollworm, pink bollworm, cotton aphid, spider mite (*Tetranychus cinnabarinus*, *T. truncates*) and sweetpotato whitefly. IPM in this region is composed of cultural, biological, physical and chemical controls. In addition to protecting natural enemies by using selective insecticides, trap crops of maize and mung bean are planted around cotton fields to trap and kill certain cotton insect pests (e.g., cotton bollworm). Planting green manure crops and broad bean can offer refuges for many natural enemies in early spring, and the stalks of wheat and rape remained in the field after harvest can also provide further refuge for various natural enemies (Lu and Wu, 2008). These refuges along with weeds can enhance the biological control for the main cotton pests, and postpone the use of insecticides in cotton until the end of June (Lu et al., 2010a). Since lepidopteran adults are characteristically attracted to specific light sources, black light traps can be used for controlling these pests (Cui et al., 2007). In addition, some level of control of summer aphids and whitefly can be gained through the use of yellow sticky traps (Lu et al., 2010a).

Natural enemies have been shown to contribute significant mortality to *B. tabaci* in cotton and several other crops in China and other parts of the world (Naranjo and Ellsworth, 2005; Shen et al., 2005; Asiimwe et al., 2007; Karut and Naranjo, 2009; Naranjo et al., 2009). For control of *B. tabaci*, the parasitoid, *Encarsia formosa,* for example, can be augmentatively released at a rate of 3–5 insects/plant when *B. tabaci* reach a density of 0.5–1.0 per plant and the releases should be continued every ten days for a total of 3–4 releases during the growing season (Zhou et al., 2005). Several insect growth regulators (IGRs) have been successfully used in the USA, Israel and elsewhere for the selective control of *B. tabaci* in cotton (e.g., Gerling and Naranjo, 1998; Naranjo et al., 2004). Not only do these compounds directly kill whiteflies, but they act synergistically with conserved natural enemies to effect season-long pest control (Naranjo and Ellsworth, 2009a,b). Typically, insecticide use for cotton aphid during the bud to fruiting stage can be avoided if the ratio of natural enemies to aphids can be maintained at around 1:60–100 (Lu et al., 2010a). Use of some biological agents such as plant-derived matrine and NPVs has become more common. Augmentative releases of Trichogramma to control lepidopteran pests are also used in the CRR cotton production region.

4.3. IPM and biological control in the NR

In the NR of China, aphids (*A. gossypii*, *Acrocalymma medicaginis*, *Acyrthosiphon gossypii*, *Xerophilaphis plotnikov*, *Trifidaphis phaseoli)* and spider mites (*Tetranychus turkestani, Tetranychus dunhuangensis*) are the main pests in the Northern Xinjiang autonomous region. Cotton bollworm, in addition to cotton aphid and spider mites, are the main pests in the southern area.

A few cultural measures can reduce overwinter sources of pests effectively. For instance, autumn plowing and winter irrigation can be conducted following harvest of cotton, maize and broomcorn. The diversity and abundance of natural enemies can be increased when crops such as alfalfa, rape and safflower are planted around cotton fields providing a source of natural enemies during early stages of crop growth (Zhang et al., 2000). Some physical control techniques such as light traps and yellow sticky traps can suppress certain cotton insect pests and further reduce the use of insecticides to protect natural enemies (Lu et al., 2010a). When chemical control is needed, selective insecticides can be used as an emergency measure. Conservation of natural enemies can also be enhanced by applying lower dosages of insecticides to reduce exposure.

As in other production regions, augmentative biological control can be effectively used to control some pest species. Spider mite can be controlled effectively by release of predatory mites. Trichogramma and *M. mediator* can be released for suppressing populations of cotton bollworm (Lu et al., 2010a). Fungi such as *N. fresenii*, *C. thromboides*, and *P. lilacinus* often infect summer populations of aphids in the field. With high temperatures and aphid densities, pest populations can be well controlled within 5–7 days following disease epidemics.

4.4. Biological control in Bt cotton systems

In China, Bt cotton was officially approved in 1997 for commercial use to control cotton bollworm, pink bollworm and other lepidopteran pests and has steadily been adopted by the bulk of Chinese cotton growers. Planting of insect-resistant transgenic cotton was initially limited to YRR, and then extended to NR and CRR in 1999 (Wu and Guo, 2005). The total area under Bt cotton cultivation was less than 0.1 million ha in 1997, but expanded rapidly to 2.8 million ha by 2003 (58% of the total cotton area) (Wu and Guo, 2005) and to 3.8 million ha, representing 70% of total cotton production, by 2008 (Wu et al., 2009). Presently, Bt cotton comprises about 95% of the total cotton growth in Northern China (Lu et al., 2010b). Bt cotton is highly effective against cotton bollworm, pink bollworm and other lepidopteran species, and has lead to significant reductions in insecticide use in the Chinese cotton system (Wu et al., 2008). The same results have been reported in other Bt cotton adopting nations such as in the USA (Naranjo et al., 2008; Naranjo, 2011). Population increases of natural enemies in Bt cotton fields can effectively prevents outbreak of cotton aphids in late season (Wu et al., 2005). However, populations of mirids plant bugs (Heteroptera: Miridae) have increased dramatically due to spread of Bt cotton, which represents a key problem in Chinese cotton production (Wu et al., 2002; Lu et al., 2010b). Sweetpotato whitefly *B. tabaci* (B and Q biotype) have invaded all cotton production regions of China, and are becoming an important issue as well (Lin et al., 2006).

Recent studies have shown that planting of Bt cotton increases the capability of natural enemies (e.g. predators) to suppress pests in cotton ecological systems (Han et al., 2007; Lu et al., 2012). Arthropod predator abundance and diversity in transgenic cotton are significantly higher than non-transgenic cotton fields treated with insecticides (Wan et al., 2002; Deng et al., 2003; Lu et al., 2012). The abundance of target pests and the quality of the surviving Bt- fed pests are significantly decreased, and this has negatively affected populations of some species of parasitoids that specialize on these pests. For example, the mortality and negative impacts on the development of parasitoids such as *M. mediator* and *Campoletis chlorideae* can be attributed to the poor nutritional quality of surviving cotton bollworm host larvae caused by sublethal effects due to Bt protein ingestion (Yang et al., 2001; Liu et al., 2005a,b). Such indirect effects of Bt proteins on natural enemies mediated by sublethal effects on the host or prey are pervasive in the literature, but do not accurately measure potential risks of Bt crops (Romeis et al., 2006; Naranjo, 2009; Shelton et al., 2009). In contrast, the populations of parasitoids attacking non-target pests such as aphids have significantly increased in Bt cotton compared with non-Bt fields with insecticide application (Li et al., 2003b). In the long term, the diversity of arthropod communities, especially natural enemies, are in general significantly higher in Bt cotton fields than those in non-Bt field sprayed with chemical pesticides during mid and late growing stages (Li et al., 2003a,b). Overall, the cultivation of Bt cotton has enhanced the control of some cotton pests and increased the stability of the cotton system in China (Lu et al., 2012).

However, a new problem has emerged that mirid bugs have become dominant pest and are threatening to cotton industry in China as a consequence of the lowered levels of insecticide use for cotton bollworm control in cotton fields (Lu et al. 2010b). Considerable research is now focused on how to deal with this new pest problem. A few cultural measures can reduce populations of plant bugs in cotton. For example, early spring weeding in areas surrounding cotton fields can reduce plant bug habitats. Interspersing cotton with trap crops such as alfalfa and mung bean not only can attract plant bugs, but also provide habitat for natural enemies, thus enhance naturally occurring biological control of plant bugs and other pests in cotton (Lu and Wu, 2008). In addition, *B. bassiana* can be effective for control of plant bugs when sprayed during the warm and rainy season (Tong et al., 2010). In recent years, two important larval parasitoids of plant bugs, *Peristenus relictus* and *P. spretus* were discovered in Chinese cotton production regions. *P. relictus* has been used for biological control of mirid plant bugs in Europe and Canada (Haye et al., 2006), but *P. spretus* has just been found in China and a successful rearing program has been developed (Luo et al., 2011). Augmentative releases of this parasitoid may contribute to biological control of plant bugs in Bt cotton production regions in the future. Additional research is needed to further enhance the contribution of biological control and to integrate it with other tactics for cotton pest control in China.

5. Conclusion

Cotton is one of the most important crops in China and is plagued by various arthropod pests. Pest complexes vary by production region depending on differences in cropping patterns and climate. In response, different biological control strategies and overall IPM programs have been developed and adopted to meet regional pest management needs over the last several decades. About 500 species of natural enemies have been identified from Chinese cotton systems and many can be effective in controlling pest populations if they are conserved and enhanced through habitat manipulations and use of selective insecticides. Augmentative biological control and biopesticides have been highly developed in China. *Trichogramma*, *M. mediator,* predatory mites, several bacterial insecticides, and viral insecticides had been widely used as biological agents in Chinese cotton IPM systems. Within the last decade, Bt cotton cultivation has expanded greatly, and together with the invasion of some new pests it has led to significant changes in the pest community in the YRR and CRR cotton production regions. The invasion of whiteflies and the loss of collateral control of plant bugs due to reductions in insecticide use in Bt cotton have allowed both of these pests to attain key pest status in Chinese cotton systems. Previous successes with biological control measures for other pests in cotton suggest that the development of biological control agents such as *P. relictus*, *P. spretus* for plant bugs and *E. formosa* and generalist predators for whitefly could be effective for dealing with these new pest problems.

Acknowledgments

We are grateful to funded by the Special Fund for Agro-scientific Research in the Public Interest of the Ministry of Finance of China (201103012) and National Key Basic Research Program of China (2013CB127602).

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