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Biological pest management by predators and parasitoids in the greenhouse vegetables in China

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HIGHLIGHTS

- China has the largest area in the world under greenhouse vegetable.
- Whiteflies, aphids, spider mites and thrips cause 18% production loss.
- 14 Natural enemies used against 8 pests in 8 crops between 1988 and 2007.
- More than 40 species of predators and parasitoids have been applied in greenhouse.
- The importance of using native species rather than non-native agents is increasing.

GRAPHICAL ABSTRACT

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ABSTRACT

China has the highest greenhouse-based production in the world. In 2010, the area of greenhouses devoted to vegetable production was estimated at 4.7 million ha. With the increasing costs of pest control, expanding pesticide resistance and the growing consumer concern regarding pesticide residues in fresh vegetables, a strong demand for applying non-chemical control methods is emerging in China. Biological control in the greenhouse environment is a viable alternative to pesticide use from both environmental and economic perspectives. Although we have only 17 cases of fully documented, successful biological control operations from China, involving 8 crops, 8 pest species and 14 species of natural enemies, the use of the biological control agents is much more widespread. There are 7 commercial companies and facilities producing 21 species of natural enemies, and most of them are available countrywide. Several of these employ a rearing system using artificial diets, and many now move to an integrated

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production system, including the mass production of the biocontrol agents, quality control, methods of long-distance transportation, release recommendations, and user feedback. While initially these systems relied on introduced natural enemies, they increasingly develop modified systems using native natural enemies. The increasing demand for pesticide-free, high quality vegetable produce year-round and the existing certification schemes make it very likely that the use of biocontrol agents will continue to increase in China.

1. Introduction

Greenhouses protect crops against adverse environments, providing plants with improved environmental conditions. In greenhouses, crops can be produced year-round, with yields and qualities often higher than those produced in the open field. In recent years, great progress has been made by the greenhouse vegetable industry in China. Now, China has the highest greenhouse-based vegetable production in the world, on an estimated 4.7 million ha, nearly twice the area in 2004 (Yu, 2011). The output value of greenhouse vegetables was US$110 billion in 2010, which accounted for more than 65% and 20% of output value of vegetables and crops, respectively (Zhang et al., 2010a,b). The per capita production of greenhouse vegetables was more than 200 kg, and about 40 million people employed by the industry.

Most of the greenhouse vegetable production is labour- and energy- intensive, thus requires a high level of technology to obtain adequate economic returns. Quality is a high priority for greenhouse vegetables, requiring great care in pest and disease management, not only to secure yields but also to obtain a high cosmetic standard (Gullino et al., 2002). With the increasing costs of chemical control, expanding pesticide resistance and the growing awareness of the risks of pesticide residues in fresh vegetables from consumers, strong demand for non-chemical control methods is emerging in China. Biological control in the greenhouse environment has been shown to be a viable alternative to pesticide use from both an environmental and economic perspective.

The aim of this review is to summarize the progress made by the greenhouse vegetable industry in China, the occurrence of pests, and the suitability of greenhouses for biological control. We summarize the production of natural enemies and their utilization in greenhouse IPM regimes. Finally, we discuss the future opportunities and challenges in biological control in the greenhouse vegetable industry in China.

2. The greenhouse environment and the occurrence of pests

Over the last thirty years, several types of greenhouse facilities, production modes and technology systems were established in different geographical regions in China. The structures adopted for vegetable production include 4 main types: low tunnels (plastic row cover), high tunnels (walk-in tunnels), sunlit greenhouse (Chinese solar greenhouse) and multi-span greenhouse (plastic and glass covered) (Fig. 1).

2.1. Low tunnels

They account for 40% of the total greenhouse area. These are small structures that provide temporary protection to vegetables, and are mostly used in small, family farms. Their height is generally 1.0 m or less, with a width of 2.0–3.0 m. Since there is no aisle for walking, cultivation must be performed from the outside. The framework of such "greenhouses" is mostly built of bamboo, and covered with plastic film.

2.2. High tunnels

This structure accounts for about 40% of the total greenhouse area. Their height is generally 2.4–3.2 m, and width is 8.0–12.0 m. The framework is built of bamboo canes, wood or steel, and covered with plastic film. About half of the area covered by such structures is distributed in the middle and lower reaches of Yangtse River, located in Central and Eastern China. They are used for year-round production of vegetables. Most of these structures are used on small farms.

2.3. Sunlit greenhouse

These are typical structures developed to fit the special climate in China, and they account for about 20% of the total greenhouse area. They are also called Chinese solar greenhouse. Sunlit greenhouses are mainly used in northern China, where sufficient solar energy is available. This type of greenhouse typically has a single slope normally covered by plastic on the southern side, and the other three sides are solid walls. They generally have a height of 2.8–3.5 m, width of 6.0–9.0 m, and their length is 40–120 m; the north wall thickness is usually 0.6–1.5 m. These greenhouses are warmed up by solar energy during the day; during the night, the temperature is maintained by covering the southern side by an insulating cover, made of waterproof puffed polyethylene (PE), cotton felt, or straw, and related materials. In these structures, year-round production of vegetables could be achieved even in cold regions without additional heating. This type of greenhouse is used both by small farms and large agricultural corporations.

2.4. Multi-span greenhouse

This structure accounts for no more than 0.5% of the total greenhouse area. Multi-span greenhouses have a protective surface area smaller than a number of single span greenhouses of equivalent production capacity (soil area). This results in less heat loss and substantial energy savings, contributing to a better cost of production per unit ratio. Moreover, multi-spans are typically more robust in design, and thus suffer less damage during storms or high wind. This type of greenhouse is covered by glass or plastic foil. When covered by glass, they can provide optimal conditions for use of natural enemies. There is about 1300 ha of glass greenhouse area in China, making up only 0.1% of the total greenhouse area (Zheng et al., 2005). The temperature can be maintained at 15–35 °C and the humidity can be reduced or raised to an optimal level through the use of heaters, fans and other devices.

Greenhouse internal climatic regimes, influenced by the type of greenhouse structures and location, have important consequences on the occurrence of pests and their natural enemies. Greenhouses have high plant densities with non-stop production systems which lend themselves to the spread of pests; additionally, well fertilized and irrigated crops are often more sensitive to outbreaks of pests than outdoor crops (Gullino et al., 2002). According to a report from the Ministry of Agriculture of China, the annual losses of vegetable production caused by pests reach 18%. The main pests in greenhouses are sucking pests like whiteflies, aphids, thrips and

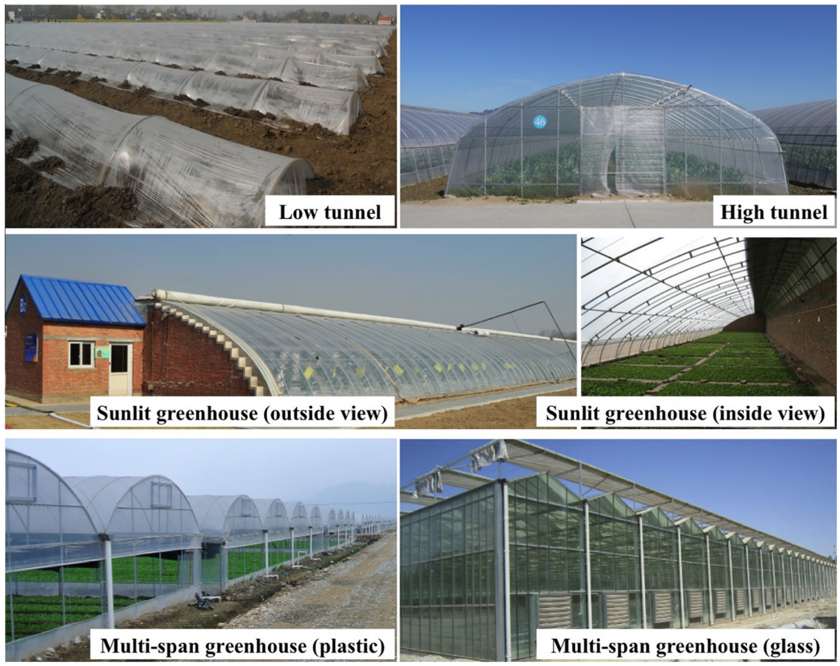

Fig. 1. The greenhouse structures adopted for vegetable production. Low tunnels (plastic row cover), high tunnels (walk-in tunnels), sunlit greenhouse (Chinese solar greenhouse) and multi-span greenhouse (plastic and glass covered).

mites. These pests are typically polyphagous insects, and are generally more problematic in greenhouses than in the field because of the ideal warm and moist protected environment, as well as the isolation from the natural enemies of these pests (Tian, 2000).

The development of the greenhouse vegetable industry brought several changes in pest distribution. Before the 1970s, greenhouse whitefly (*Trialeurodes vaporariorum*) rarely occurred in the northeastern and northern parts of China. When suitable environments became available due to the year-round production of vegetables in greenhouses, the conditions for continuous reproduction of this species (including the winter) were also provided, and this pest became a serious threat to the vegetable industry (Hu and Wu, 2001). Under field conditions, several species, including the diamondback moth (*Plutella xyllostella*), the cabbage white butterfly (*Pieris rapae*), the green peach aphid (*Myzus persicae*) and the cotton aphid (*Aphis gossypii*) had to hibernate during winter and would not be active until the following spring. However, they can develop and reproduce successfully throughout the year without hibernation under glasshouse conditions, producing more generations per year and causing more serious damage than under open field conditions (Tian, 2000). The international trade has accelerated the spread and establishment of pests all over the world. At least ten new pests, including the very damaging whitefly, *Bemisia tabaci* biotypes B and Q, and western flower thrips, *Frankliniella occidentalis*, have been recorded occurred on protected vegetables in China during the past fifteen years (Wan et al., 2009). The increasing range of pests and the pursuing of high cosmetic standards of vegetable products have led growers to apply intensive chemical pesticide treatment regimes, resulting in the quick development of resistance, which, in turn, increased control costs.

3. Suitability and necessity of biological control in greenhouses

In China, the pressure from the consumer public against chemical pesticides in food, water and the environment has strongly increased in recent years. This directed the producers' attention to biological control agents, especially predators and parasitoids, which are effective and environmental friendly management tools for insect pests control in protected environments. Several biocontrol agents prefer the regulated glasshouse environment. For instance,*Encarsia formosa* performs poorly at the temperature lower than 18 °C or higher than 32 °C, but has strong controlling effects under greenhouse conditions (Zhang et al., 2004).

Another reason why biological control has found a niche in the greenhouse market is because of the increasing demand for high quality vegetables. Certification of agricultural products in China began in the early 1990s, when the Ministry of Agriculture of China implemented the green food certification. In the late 1990s, organic food standards were introduced into China, and organic food certification was implemented. In 2001, the Ministry of Agriculture started to implement the "Pollution-free Food Action Plan". By 2003, national pollution-free agricultural products certification system, including standard procedures, logo, management and supervision systems, were achieved. These became collectively known as the "Three Grades", which refers to pollution-free agricultural products, green food and organic food (and agricultural products). The use of chemicals in producing the Three Grades vegetables is limited or forbidden.

4. Production of insect natural enemies for pests control in greenhouses

Biological control by natural enemy release in vegetable crops has been practiced in China since 1950s. Among the first organisms, *Trichogramma* spp. and the lady beetle *Rodolia cardinalis* were used to control *Ostrinia furnacalis*,*Helicoverpa armigera* and*Icerya purchasi* (Gu et al., 2000; Wan et al., 2000). Since then, many successful pest-host-natural enemies regulation system were established in agricultural ecosystems (Guan and Sun, 2002; Guo and Wang, 2008; Qiu et al., 2008). Also, techniques for mass-rearing insect natural enemies have been adopted on a large scale. The currently available, mass-produced natural enemies used in greenhouse in China are listed on Table 1, as well as the commercial companies and institutes that provide these products (Table 2).

Table 1
List of natural enemies (predators and parasitoids) applied in greenhouse plant protection in China.

Natural enemy agent	Control target	References	Artificial rearing[*]				References
			Full artificial rearing	Semi-artificial rearing	Factory massive production	Established commercial application system	
Predatory mites							
Acari: Phytoseiidae							
Amblyseius aizawai	Spider mite	He et al. (1992)	✓	✓			He et al. (1992)
Amblyseius cucumeris	Spider mite, thrips (e.g. *Frankliniella occidentalis*)	Sun et al. (2009), Zhang et al. (2010c)	✓	✓	✓	✓	Zhang et al. (2002)
Amblyseius makuwa	Spider mite	Pu et al. (1991)		✓			Pu et al. (1991)
Amblyseius nicholsi	Spider mite	Hu et al. (2007)		✓			Zhang and Cao (1993)
Erigonidium graminicolum	Aphid, spider mite, diamondback moth	He et al. (1991)					
Euseius finlandicus	Spider mite (e.g. *Eotetranychus pruni*; *Tetranychus urticae*)	Guan and Sun (2002)					
Phytoseiulus persimilis	Spider mite (e.g. *Tetranychus kanzawai*, *Tetranychus urticae*)	Li et al. (2004), Zhang et al. (1996)	✓	✓	✓	✓	Li et al. (2004)
Acari: Trombidiidae							
Allothrombium ovatum	Aphid	Dong (2001)					
Predatory ladybird							
Coleoptera: Coccinellidae							
Adonia variegata	Aphid, leafhopper	Yang et al. (2007)					
Cryptolaemus montrouzieri	Mealybug	Pu et al. (1959), Zhao et al. (2001)		✓			Pang et al. (1996)
Delphastus catalinae	Whitefly (e.g.*Aleurotuberculatus takahashi*; *Bemisia tabaci*)	See review by Lin et al. (2008)		✓	✓		Fu et al. (2002)
Harmonia axyridis	Aphid, whitefly, leafhopper, louse (e.g. *Cyamophila willieti*), Spider mite, mealybug, moth	e.g. Guo and Wang (2008), Shen et al. (2009)	✓	✓	✓	✓	Guo and Wan (2001), Zhang et al. (2008)
Leminia biplagiata	Aphid, whitefly (*Aleurodicus dispersus*)	Zhao et al. (1998), Wu et al. (2010)	✓	✓	✓	✓	
Menochilus sexmaculatus	Aphid, whitefly (*Aleurodicus dispersus*)	Wu et al. (2010)		✓			Yu et al. (2010)
Nephaspis oculatus	Whitefly	See review by Lin et al. (2008)					
Propylea japonica	Aphid, stinkbug, thrips, louse, whitefly, leafhopper	e.g. Zhang et al. (2007), Qiu et al. (2008), Lin et al. (2006)	✓	✓			Zhang et al. (2007), Guo and Wan (2001)
Rodolia cardinalis	Coccid	Pu and Deng (1957)					
Scymnus hoffmanni	Whitefly	See review by Lin et al. (2008)					
Serangium japonicum	Whitefly	See review by Lin et al. (2008)					
Serangiella sababensis	Whitefly	See review by Lin et al. (2008)					
Stethorus parapauperculus	Spider mite	Lin and Chen (1984), Cheng et al. (1989)					
Stethorus siphonulus	Spider mite	Huang and Cai (1997)					Huang and Cai (1997)
Synonycha grandis	Aphid	Ou (2008)					Deng et al. (1986)
Predatory stink bug							
Hemiptera: Anthocoridae							
Orius minutus	Aphid, whitefly, thrips	Tang et al. (2007)					
Orius sauteri	Aphids, spider mite, thrips	Wang et al. (2010)	✓	✓	✓	✓	Zhou and Wang (1989), Tan et al. (2010)
Orius similis	Aphid, spider mite, thrips	Zhou and Lei (2002)					
Hemiptera: Miridae							
Campylomma chinensis	Aphid, thrips, whitefly, spider mite, moth	Jin et al. (2005), Qin et al. (2001)					
Macrolophus caliginosus	Aphid, spider mite, whitefly, thrips	Wu et al. (2004)					
Nesidiocoris tenuis	Aphid, whitefly, diamond back moth	Li et al. (2008)					
Hemiptera: Pentatomidae							
Eocanthecona furcellata	Aphid, diamondback moth	Zhang and Xie (2001)		✓			Zhang and Lu (1996)
Lacewing							

(*continued on next page*)

Table 1 (*continued*)

Natural enemy agent	Control target	References	Artificial rearing*				References
			Full artificial rearing	Semi-artificial rearing	Factory massive production	Established commercial application system	
Neuroptera: Chrysopidae							
Chrysopa formosa	Aphid, whitefly	Li et al. (2010)					
Chrysopa pallens	Aphid, whitefly, thrips, looper	Liu et al. (2007a, 2011)					
Chrysopa sinica	Aphid, looper, gallmidge	Liu et al. 2007a; Lin et al., 2006	✓	✓	✓	✓	Hou et al. (2000)
Parasitoid							
Hymenoptera: Aphelinidae							
Encarsia aleurochiton	Whitefly (e.g. *Bemisia tabaci*; *Aleurochiton aceris*)	Luo et al. (1989)					
Encarsia formosa	Whitefly (e.g. *Bemisia tabaci*, *Trialeurodes vaporariorum*)	e.g. Li et al. (2007), Zhang et al. (2003, 2004)	✓	✓	✓	✓	Huang et al. (2007)
Encarsia sophia	Whitefly (e.g. *Bemisia tabaci*; *Aleurodicus dispersus*; *Trialeurodes vaporariorum*)	Zang and Liu (2007), Xiao et al. (2011), Zang et al. (2011a,b)					
Eretmocerus hayati	Whitefly (*Bemisia tabaci*; *Trialeurodes vaporariorum*)	Yang and Wan (2011)					
Hymenoptera: Aphidiidae							
Aphidius gifuensis	Aphid	Wu (2007)		✓	✓		Deng et al. (2006), Xin et al. (2001)
Diaeretiella rapae	Aphid (*Brevicoryne brassicae*; *Lipaphis erysimi*)	Yu et al. (1993)					

* 'Full artificial rearing' means pure artificial diets (without insect materials); 'Semi-artificial rearing' means the artificial diets contain some insect material; 'Factory mass production' represents a special mass rearing process, where all influential factors, such as environmental conditions, manipulation activities, food quality and quantity are manipulated and harmonized; 'Established commercial application system' means an integrated commercial system, including the production, conservation, long distance transportation, release procedure and an evaluation system based on user feedback.

4.1. Predators

4.1.1. Predatory mites

The most often used predatory mites belong to the families of Phytoseiidae and Trombidiidae (Archnida) (Table 1). The use of *Amblyseius deleoni* to control red spider mote in Sichuan Province in 1960s was the initial application of predatory mites in China (Gao et al., 1990; Xu et al., 2002). Thereafter, more than 120 predatory mites, especially phytoseiid species were explored by field surveys during the 1970s and 1980s (Tang et al., 2004). Eighteen phytoseiid species were included in the list of the major predatory mites used in biological control in China (Tang et al., 2004). *Phytoseiulus persimilis* is the most popular biological control agent for pest mites control in greenhouse vegetables, tropical fruits, ornamental plants, and medicinal herbs (Dong et al., 1986). The proportion of greenhouse agriculture situation in which this agent was applied in spider mite control increased from 15% in the 1980s to 45% in the 1990s (Zhang et al., 1996). Other phytoseiid species, including *Amblyseius cucumeris*, *Amblyseius largoensis*, *Amblyseius longispinosus*, *Amblyseius pseudolongispinosus*, *Amblyseius nicholsi* and *Typhlodromus serrulatus*, were also introduced into greenhouse agriculture (Hu et al., 2007; Sun et al., 2009; Tian, 2000; Dong et al., 2011).

The low density of predatory mites occurring under open- field conditions limits the successful management of greenhouse pests by these agents. Artificial (mass) rearing technology is the key point of success. *A. cucumeris,* a dominant natural enemy of *Panonychus citri*, has been mass-produced using an artificial diet since 1998 by the Academy of Agricultural Science of Fujian Province in Fuzhou (Zhang et al., 2002). The procedure has seven consecutive steps from collecting mites to packaging. Eleven to 12 billion mites can be produced by this factory per year at a cost of about $50 per million mites. A package container, a patented innovation (LandGreen™) could extend the conservation period for long distance transportation. In addition, utilize sawdust and vermiculite as ancillary filler decreases the mortality of the predator from 33% to 17% during the first week of containment.

4.1.2. Predatory ladybirds

Many species of ladybirds, among them *R. cardinalis* and *Cryptolaemus montrouzieri*, have been used as biological control agents in China since the 1950s (Bao and Gu, 1998). The majority of them (e.g. 8 of 16 listed coccinellid specz listed on Table 1) consume aphids (e.g. *M. persicae*) as their primary food. *Harmonia axyridis* could attack *M. persicae*, *Toxoptera piricola*, *Hyaloperus pruni* (=*arundinis*) and*A. gossypii* (Wang and Shen, 2002). *Hippodamia variegata*, *Coccinella septempunctata* and*Propylea japonica* are dominant predators of aphids in various agricultural systems (Hou and Wan, 2004; Zhang et al., 2007). Other Coccinellidae species, including *Delphastus catalinae*,*Nephaspis oculatus*, *Serangium japonicum* and *Serangiella sababensis* were imported to suppress *B. tabaci*, and have been applied in southern China (Lin et al., 2008). In addition, Coccinellidae are also used to control spider mites: *Stethorus punctillum* and *Stethorus siphonulus* can effectively suppress *P. citri* in greenhouse kumquat (Jiang et al., 1982; Huang and Cai, 1997), and *Stethorus parapauperculus* can supplement *P. persimilis* to control *Tetranychus cinnabarinus* in southern China (Cheng et al., 1989).

The development of artificial mass rearing methods tackled questions related to diet composition, recipes for artificial media, rearing conditions and corresponding biological characters (Zhang et al., 2008). An integrated mass-rearing technique for *H. axyridis* was promoted by the laboratory of natural enemy research, Institute of Plant and Environment Protection, Beijing Academy of Agriculture and Forestry Sciences; this establishment can now produce more than 2 million insects annually. Originally, adult *H. axyridis*

Table 2
Companies and commercial facilities devoted to biological control production in China.

Company/commercial facility location	Main natural enemies produced		Note	Greenhouse type where product is used	Approach
Companies					
Quentian™ Bio-Tech Co., LTD, Beijing	Parasitoids	*Encarsia formosa*	Independent research	High tunnel, sunlit greenhouse, multi-span greenhouse	Inoculation
		Encarsia sophia			Inoculation
		Trichogramma chilonis			Inoculation
		Trichogramma japonicum			Inoculation
		Mesocomys cameron			Inoculation
		Eretmocerus mundus			Inoculation
		Microplitis mediator			Inoculation
	Ladybirds	*Harmonia axyridis*		High tunnel, sunlit greenhouse	Inoculation/ inundation
		Propylea japonica			Inoculation/ inundation
		Coccinella septempunctata			Inoculation/ inundation
		Delphastus catalinae			Inoculation/ inundation
		Serangium japonicum			Inundation
	Predatory mites	*Neoseiulus cucumeris*		High tunnel, sunlit greenhouse, multi-span greenhouse	Inundation
		Phytoseiulus persimilis			Inundation
	Predatory lacewings	*Chrysopa pallens*		High tunnel, sunlit greenhouse	Inundation
		Chrysoperla sinica			Inundation
	Flower bugs	*Orius sauteri*		High tunnel, sunlit greenhouse	Inoculation
		Orius insidiosus			Inoculation
		Orius minutus			Inoculation
NewLand™ BioControl Service Co., Ltd, Changchun, Jilin Province	Parasitoids	*Encarsia formosa*	Without independent research	Sunlit greenhouse	Inoculation
	Ladybirds	*Harmonia axyridis*		High tunnel, sunlit greenhouse	Inoculation
		Coccinella septempunctatac			Inoculation
LandGreen® BioTech Service, Beijing	Parasitoids	*Encarsia formosa*	Independent research	High tunnel, sunlit greenhouse	Inoculation
		Encarsia sophia			Inoculation
		Trichogramma chilonis			Inoculation
		Trichogramma japonicum			Inoculation
	Ladybirds	*Harmonia axyridis*		High tunnel, sunlit greenhouse	Inoculation
		Propylea japonica			Inoculation
		Coccinella septempunctata			Inoculation
		Delphastus catalinae			Inoculation
	Predatory mites	*Neoseiulus cucumeris*		Low tunnel, high tunnel, sunlit greenhouse	Inoculation/ inundation
		Phytoseiulus persimilis			Inoculation/ inundation
	Predatory lacewings	*Chrysopa pallens*		High tunnel	Inoculation/ inundation
		Chrysoperla sinica			Inoculation/ inundation
	Flower bugs	*Orius sauteri*		High tunnel, sunlit greenhouse	Inoculation/ inundation
TIANYI® Biologicaol Control, Hengshui, Hebei Province	Parasitoids	*Encarsia formosa*	Independent research	Sunlit greenhouse, multi-span greenhouse	Inoculation/ inundation
		Encarsia sophia			Inoculation/ inundation
Fujian Yanxuan Bio-preventing and Controlling Technology Co., Ltd. , Fuzhou, Fujian Province	Predatory mites	*Neoseiulus cucumeris*	Independent research	Low tunnel, high tunnel	Inoculation/ inundation
		Phytoseiulus persimilis			Inoculation/ inundation
		Amblyseius barkeri			Inoculation/ inundation
Commercial facilities					

(*continued on next page*)

Table 2 (*continued*)

Company/commercial facility location	Main natural enemies produced		Note	Greenhouse type where product is used	Approach
Beijing Academy of Agriculture and Forestry Sciences, Beijing	Parasitoids	*Encarsia formosa* *Encarsia sophia*	Independent research	High tunnel, sunlit greenhouse	Inoculation/ inundation
	Predatory ladybirds	*Harmonia axyridis*			Inoculation/ inundation
Beijing XISHAN Forest Centre Forestry Biocontrol Station, Beijing	Parasitoids	*Chouioia cunea*	Independent research	Sunlit greenhouse	Inoculation

were collected from the mountain area north of Beijing over the first two years. The adults were maintained on a liver-based artificial diet, with bean aphids (*Aphis fabae*) added as oviposition stimulation supplement to ensure reproductive efficiency. The produced *H. axyridis* were separated and delivered by development stages (larvae, newly enclosed adults) and sex for use in biological control applications. Currently, *H. axyridis* egg production in the laboratory is 25,000 eggs per day. The beetles are produced in three environmental regimes to rear different populations suitable for the climates in different areas of China.

4.1.3. Predatory bugs

The main Anthocoridae species are used in greenhouse biocontrol (Table 1). Research on artificial diet and rearing technology for *Orius* spp. found that flower pollen is a key component in artificial diets for Hemiptera, and this, mixed with other animal-based materials could ensure adequate nutrition (Zhou and Wang, 1989). A liquid artificial diet, with beer yeast (*Saccharomyces cerevisiae*) and egg yolk as supplements added to a standard parasitoid pupae recipe, is used to rear *Orius sauteri*. Recently, microencapsulation technology was introduced to prevent the death of predator nymphs caused by the sticky liquid (Tan et al., 2010).

4.1.4. Predatory lacewing

As early as the 1970s, lacewings (e.g. *Chrysopa pallens*) were released in Henan, Hebei, Shandong and Hubei Provinces to control *H. armigera* (Bao and Gu, 1998). Now, two widespread species, *C. pallens* and *Chrysoperla sinica* are used in more than 20 provinces, and over 40 agricultural crops, to control several pests, especially in greenhouse vegetables (Liu et al., 2007a, 2011).

For mass rearing of *Chrysoperla*, Hou et al. (2000) compared the suitability of *C. sinica* fed on pupae of *Trichogramma* spp. reared on artificial eggs, with the suitability of those that fed on *Corcyra cephalonica* eggs or the aphid *Lipaphis erysimi*. Development time of the larvae and pupae feeding on *Trichogramma* pupae are 0.4 d longer than those feeding on the aphid, while the fecundity did not change.

4.2. Parasitoids

Parasitoids, particularly those released in greenhouse systems, are often highly host-specific (Lynch et al., 2001). Twenty-seven species of parasitoids in China, all belong to Aphelinidae, 21 in genus *Encarsia*, and 6 in genus *Eretmocerus*, are the main natural enemies of *B. tabaci* and *T. vaporariorum* (Li et al., 2011). *E. formosa*, *En. bimaculata*, *Encarsia sophia*, *En. aseta* and *En. longifasciata* are the most important natural enemies of the whitefly used in greenhouses (Li et al., 2011). In the*Eretmocerus* genus, *Er. eremicus* is used to control *T. vaporariorum* on greenhouse cucumber in Shandong Province (Han and Hua, 2005). *Eretmocerus hayati* was introduced from the USA in 2008 and is a good biological control candidate against *B. tabaci* in China (Yang and Wan, 2011). Application of Aphidiid in greenhouses is less common than in field applications. As one of the primary pests in greenhouse crops, *M. persicae* could be controlled by *Aphidius gifuensis* on tomato, chili, cabbage and related crops (Wu, 2007). Parasitism of *Cotesia plutellae* on *Plutella xylostella* was documented on cabbage and successful control was observed (Shi et al., 2002).

Mass rearing technology of parasitoids has been well developed. Two commercial companies, Beijing Quentian™ and Hengshui TIANYI™ have developed a standardized mass-rearing system to produce *E. formosa* for commercial use since 2004. *T. vaporariorum* nymphs kept on tobacco plants are used as optimum hosts, at 27–28 °C, RH 60–70%. About 35millions of *E. formosa* wasps are produced annually (Zheng et al., 2005). In 2010, a new packaging technology for parasitoids was introduced ("Feasible Package" by Beijing Quentian™ and LandGreen®). This package includes 3 paper cards carrying 200 pupae of *E. formosa* and 5 yellow sticky traps for monitoring the whitefly hosts.

5. Biological control of the major pests using natural enemies in greenhouses

A wide range of climatic conditions, related to geographic and physiognomic differences across the country, results in different insect pest profiles in different areas. Generally, most of the greenhouse pests in China are sucking insects like whiteflies, aphids, spider mites and thrips. Most studies on the use of natural enemies in protected culture in China began with the introduction of *E. formosa* and *P. persimilis* from the UK in the 1970s. Since then, remarkable achievements in the introduction of exotic natural enemies, conservation and augmentation of indigenous natural enemies and mass production of predators and parasitoids have been made. Today many greenhouse pests in China may be suppressed using natural enemies (Table 3).

5.1. Whiteflies

E. formosa, the most successful natural enemy used for bio-control of whiteflies in the world, was initially imported into China from the UK in 1978, and has been widely released against *T. vaporariorum* and *B. tabaci* in Hebei, Beijing, Xinjiang, Liaoning, Shandong and Inner Mongolia Provinces. Since the 1990s, the *B. tabaci* B and Q biotypes, two cryptic species of whitefly invaded China (Liu et al., 2007b), and have become major pests of greenhouse vegetables In addition to *E. formosa*, the use of imported *D. catalinae* as well as indigenous *Eretmocerus* sp. has also attracted great attention as biocontrol agents against *B. tabaci*. The oligophagous predator, *Delphastus cataliae* exhibits good bio-control effectiveness, especially under high density of whitefly nymphs (Zang and Liu, 2007). Recently, Zang and Liu (2008) found that *E. sophia*, a heteronomous hyperparasitoid, is also an effective biological control agent of *B. tabaci*. These parasitoid species can suppress whiteflies through parasitism and host feeding better than *E. formosa*, if the release of numbers of male adults could be controlled (Zang et al., 2011a). The efficiency of *E. sophia* in biological control can be readily manipulated by controlling the duration of food deprivation (Zang and Liu, 2009). Furthermore, the success of using *E. sophia* is mainly dependent on the mating status of females, which is related to the availability of males (Zang et al., 2011b). In addition,

Table 3
A list of documented successful cases of greenhouse pest control by natural enemies in China, 1988–2007.

Pest group	Target insect species	Infested crop	Natural enemies used	Releasing strategies	Proportion of pests controlled % (days after introduction)	Area of application	Source
Whiteflies	*Trialeurodes vaporariorum*	Tomato	*Encarsia formosa*	15 wasps/plant	90	Beijing	Tian (2000)
		Cucumber	*Eretmocerus sp.*	5 wasps/plant	73 (21 d)	Guangzhou	Qiu et al. (2004)
	Bemisia tabaci	Broccoli	*Delphastus catalinae*	59 predators/m^2	91 (30 d)	Fuzhou	Luo (2005)
		Eggplant	*Campylomma chinensis*	0.75 predators/m^2	100 (30 d)	Shenzhen	Yu et al. (2005)
Aphids	*Myzus persicae*	Brassica	*Eupeodes corollae*	Ratio of predator: prey = 1:30	96 (6 d)	Shanghai	Sun et al. (1992)
			Episyrphus balteatus	Ratio of predator: prey = 1:50	98 (6 d)		
		Pepper	*Aphidoletes aphidimyza*	Ratio of predator: prey = 1:20	86 (10 d)	Beijing	Cheng et al. 1992)
			Aphidius gifuensis	82 wasps/m^2	99 (25 d)	Shenyang	Xin et al. (2001)
	Aphis gossypii	Cucumber	*Aphidius gifuensis*	82 wasps/m^2	100 (25 d)	Shenyang	Xin et al. (2001)
				13 wasps/m^2	97 (60 d)	Shanghai	Jiang et al. (1982)
		Strawberry	*Harmonia axyridis*	Ratio of predator: prey = 1:100	91 (6 d)	Shanghai	Wang et al. (2007)
Spider mites	*Tetranychus cinnabarinus*	Bean	*Amblyseius pseudolongispinosus*	Ratio of predator: prey = 1:3	100 (21 d)	Shanghai	Wu and Chen (1988)
		Eggplant	*Campylomma chinensis*	0.75 predators/m^2	100 (30 d)	Shenzhen	Yu et al. (2005)
	Tetranychus urticae	Eggplant	*Amblyseius longispinosus*	Ratio of predator: prey = 1:100	98 (21 d)	Fuzhou	Tian (2000)
	Undetermined	Eggplant	*Phytoseiulus persimilis*	Ratio of predator: prey = 1:10	77 (30 d)	Nanchang	Yang et al. (1989)
Thrips	*Frankliniella occidentalis*	Sweet pepper	*Amblyseius cucumeris*	5–10 predators/plant in seedling stage & 20–30 predators/plant in fruit-setting stage	93 (35 d)	Shandong	Zhang et al. (2010a,b,c)
	Thrips palmi	Eggplant	*Campylomma chinensis*	0.75 predators/m^2	100 (30 d)	Shenzhen	Yu et al. (2005)

E. hayati has also been proven an effective biological control agent against *B. tabaci* in the USA and in Australia (Goolsby et al., 2005; De Barro and Coombs, 2009). This parasitoid species was imported from the USA in 2008 by the Institute of Plant Protection, Chinese Academy of Agriculture Sciences, with the objective of controlling the exotic B and Q whiteflies, and proved to be a good bio-control candidate (Yang and Wan, 2011).

5.2. Aphids

In China, the aphid midge, *Aphidoletes aphidimyza*, the coccinellid *H. axyridis*, the syrphids *Eupeodes corollae*, *Episyrphus balteatus* as well as the parasitoid *A. gifuensis* are used for controlling aphids in vegetables. *A. aphidimyza* was imported from Canada in 1986, and has been released against greenhouse aphids in Beijing, Hebei and Fujian Provinces. After *A. aphidimyza* were released at a predator to prey ratio of 1:20 for 10 days, aphid densities could be reduced by 70–90%. In Shanghai and Liaoning, *A. gifuensis* were reared on *M. persicae* using radish seedlings as host plant. They were successfully used against *M. persicae* or *A. gossypii* on cucumber and pepper (Xin et al., 2001; Deng et al., 2006). The multicolored Asian ladybird, *H. axyridis*, is one of the most popular indigenous predators in China. This generalist ladybird has been successfully used for biological control against aphids in greenhouses and on outdoor crops, such as *A. gossypii* on strawberry and cucumber, and *M. persicae* on soybean (Wang et al., 2007). *H. axyridis* are often collected from the wild, in northeastern China, utilizing the swarming behavior before overwintering in the autumn. Massive number is easily collected manually or mechanically from the walls of buildings. More than 80% of *H. axyridis* adults collected in October survived for 150 d at 3–6 °C, with no adverse effects on their reproductive and predatory capacity (Ruan CC, Du WM and Zang LS, unpublished data).

5.3. Spider mites

Tetranychus urticae, *Polyphagotarsonemus latus* and *T. cinnabarinus* are the most common spider mites in greenhouse vegetable crops in China. Since *P. persimilis* was imported from Sweden in 1975, remarkable success has been achieved in the application of imported and indigenous predatory mites to control these pests. Among the indigenous species, *A. longispinosus* and *A. pseudolongispinosus* have been widely used for controlling spider mites. For instance, *A. longispinosus* released at a predator: prey ratio of 1:100, successfully decreased the population of *T. urticae* on eggplants 3 weeks after release (Tian, 2000).

5.4. Thrips

Thrips flavus and *Thrips tabaci* are the major native thrips on vegetables in China. Since 2003, they have been displaced by *F. occidentalis*, an invasive species that was first found in Beijing. Today *F. occidentalis* is a universally occurring pest in Chinese greenhouses (Xu et al., 2005). Numerous studies using predatory mites and bugs to control thrips have been documented (Castane et al., 1996; Shipp and Wang, 2003). *A. cucumeris*, released alone, can successfully suppress *F. occidentalis* on sweet pepper in greenhouse settings in Shandong Province (Zhang et al., 2010c). However, combined release of both predatory mites and heteroptera could provide a much better suppression of thrips compared to single species applications (Xu et al., 2005).

P. xylostella and *Spodoptera litura* are serious pests on greenhouse brassica vegetable crops in some areas. Although over 130 parasitoid species attack them, most control worldwide is achieved by relatively few hymenopteran species (Sarfraz et al., 2005). Currently, microbial insecticides developed from *Bacillus thuringiensis*, *Zoophthora radicans*, *Beauveria bassiana* and nucleopolyhedrovirus, as well as botanical insecticides from *Azadirachta indica* are widely being applied in China (Wang et al., 2006; Yang, 2007).

The vast reserves of native natural enemy resources can provide more options, which could be selected to fit the requirements of various agroecosystems in different regions of China. In some cases, the release of biological control agents in different provinces also means crossing geographical barriers, and the potential consequences of such introductions have to be considered.

6. Conclusions and perspectives

Compared with chemical control, biological control tends to be long-term and delayed. Successful programs of biological control should always involve information for growers, pointing out the advantages because demand from growers is essential in ensuring that research is conducted into the practical application of beneficial organisms. Biological control has general advantages, including reduced exposure of growers and workers to toxic pesticides, the lack of residues on the marketed product and the extremely low risk of environmental pollution – these, however, may not be priority concerns of Chinese growers. The main interests and concerns of growers are for no phytotoxic effects on young plants, reduced application time and more pleasant work conditions during the release natural enemies compared to applying chemicals in a humid and warm greenhouse, the avoidance of the safety period between application and harvesting vegetables, and the persistent effects against insect pests. In China, government programs combine the production of natural enemies with extension information for growers. This seems an effective way of promoting biological control among small-scale growers in China.

In addition to information, costs and returns of the biological approach to pest control are important factors for acceptance by growers. Low costs essentially depend on effective methods of mass production. Research to find the optimal conditions take a long time and regional exchange of such information would reduce the production cost of biological control agents. Quality control and storage methods are major issues in mass rearing and gather increasing focus in research.

Although scientists may work on the control of a single pest, in reality, growers are faced with a complex of pest species. Biological control today considers these complexes of pest species, and also combinations of plant pests and pathogens. Reduced pesticide use and the protection of natural enemies are emphasized, in order to allow the natural balance between pests and their predators and parasites to be restored and maintained. With more research under Chinese conditions, better supply and distribution of beneficial organisms, and the closer connection between scientists and growers, biological control of greenhouse vegetable pests can benefit an increasing number of Chinese growers.

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