

## The Soybean Aphid in China: A Historical Review

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**ABSTRACT** Since the discovery of the soybean aphid, *Aphis glycines* Matsumura, in North America in the summer of 2000, a great deal of interest has developed in the biology, ecology, and control of this insect in its native range of eastern Asia. Although there is a wealth of literature on *A. glycines* that could help guide the efforts of North American entomologists, much of it is written in Chinese. Here, we review the Chinese-language literature on the biology, ecology, natural enemies, and control of the soybean aphid in China.

**KEY WORDS** soybean aphid, *Aphis glycines*, China

ONE OF THE MOST IMPORTANT cultivated crops, soybean, *Glycine max* (L.) Merrill, has been grown in China for 4,000–5,000 yr, traceable to the Zhou or probably Xia and Shang dynasties (Ma 1984, Chinese Ministry of Agriculture 2001). Soybean spread to other Asian countries nearly 2,500 yr ago, and since then, soybean has been cultivated worldwide because of its ease of growth, geographical adaptability, and broad uses for human and animal food and industrial and medicinal applications. In China, soybean has been planted as a cheap source of protein and oil between 18 and 52° N and 75 and 135° E, except on the Northern and Tibetan plateaus, where it is too cold or dry for growth. Soybean production is concentrated in the northeast and north China plains in eight leading provinces: Heilongjiang, Jilin, Liaoning, Shandong, Henan, Anhui, Jiangsu, and Hebei (Pu and Pan 1984). In 1957, a planting record of 12.73 million hectares was reported with a total yield of 10.05 million tons (Chinese Ministry of Agriculture 2001). In recent years, soybean has been grown on 8 million hectares, on average, with harvests of >13 million tons (Chinese Ministry of Agriculture 2001).

Among numerous insect pests of soybean known in China, the soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), has been the most serious threat to soybean productivity (Wang et al. 1962, 1996; Yue et al. 1989; Wu et al. 1999; Sun et al. 2000). Outbreaks of *A. glycines* occur sporadically in some soybean-growing regions. In 1998, a heavy aphid infestation occurred in Suihua prefecture, Heilongjiang province, causing a 30% yield loss with a total reduction of 112.5 million kilograms (Sun et al. 2000). Yield reductions of 50–70% have been reported when in-

festations are especially heavy (He et al. 1991). The soybean aphid is also known from Japan, The Philippines, South Korea, Indonesia, Malaysia, Thailand, Vietnam, and Russia (APPC 1987, CAB International 2001). It has recently invaded Australia, the United States, and Canada (Baute 2001, Fletcher and Desborough 2002, USDA 2002, Venette 2004). Besides directly feeding on soybean and causing yield reduction, *A. glycines* also threatens the productivity of soybean, because it is an important virus vector (Guo and Zhang 1989, Li and Pu 1991, Luo et al. 1991).

A number of Chinese scientists from universities, research institutes, and government agencies have studied *A. glycines*, conducting numerous research projects and publishing >100 papers on this insect. Here, we summarize important Chinese findings on the soybean aphid with the intention of shedding light on ongoing soybean aphid research in the United States, where *A. glycines* has recently been introduced. Many of the references cited below are collected at Kansas State University's Digital Library as part of a project to translate and copublish important Asian contributions to soybean aphid research. To access the full texts of translations, see the Web site at <http://www.ksu.edu/issa/aphids/reporthtml/citations.html>.

**Biology and Ecology.** The morphological characteristics of *A. glycines* have been described thoroughly by Chen and Yu (1988) and Takahashi et al. (1993). *A. glycines* is a small, light yellow or yellowish green aphid with two distinct black cornicles. A combination of body color, black cornicles, and its colonization on soybean (and buckthorn) distinguishes it from other aphid species (Voegtlin et al. 2004, in this issue). Similar to other common aphid species, its nymphs have four instars (Table 1) and alataids (nymphs with developing wings) occur in the third and fourth instars (Zhang 1988). A crossing study between *A. glycines* and *Aphis gossypii* Glover showed that their offspring could reproduce parthenogenetically and sexually and

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host plants might hinder aphids in their search for a host. This fact may explain the decrease of aphid density when maize and soybean are grown together (Wang and Ba 1998, Wang et al. 2000).

Yan et al. (1994a) examined the electroantennogram responses of several aphid species, including the soybean aphid, to plant volatiles. Du et al. (1995) observed the olfactory sensillae of *A. glycines* antennae by using a scanning electron microscope and confirmed their structure and function for distinguishing different odors. Han and Yan (1995) found that stylet penetration and sucking behavior of *A. glycines* were significantly different on soybean than on other plants. This behavior might explain in part the host specificity of *A. glycines*.

**Population Dynamics.** *A. glycines* has two migration and two dispersal peaks in Jilin province (Chen and Yu 1988). The first migration peak is in the soybean seedling stage when overwintering aphids emigrate from overwintering hosts onto soybean. Migratory aphids in normal years have a much lower density than in years of serious infestation. The first dispersal peak occurs in late June as aphids disperse from patchy, heavily infested soybean plants to healthy plants. The percentage of plants that are infested increases abruptly, but aphid numbers per plant decline, and there is no obvious damage at this stage. The second dispersal peak occurs in mid-July when the soybean plant flowers. Favorable climatic conditions in this critical period may lead to severe infestation. The second migration peak occurs in September when winged females (gynoparae) and winged males migrate to buckthorn. Apterous females (oviparae) produced by gynoparae mate with winged males on buckthorn and then produce overwintering eggs. In Jinan, Shandong province, the soybean aphid is difficult to detect in early September as plant nutrition conditions worsen in the field, and aphids migrate back to buckthorn (Li et al. 2000). In Indonesia, soybean aphid densities peak in the soybean vegetative stage and decrease rapidly thereafter (van den Berg et al. 1997).

*A. glycines* has an aggregated distribution from initial colony development to peak infestation, and individual colonies comprise the basic distribution element (Liu 1986, Huang et al. 1992, Su et al. 1996). Plants with aphids are distributed randomly when the plant infestation rates are low and uniformly as the plant infestation rates increase. After the populations peak, however, the distribution of plants with aphids becomes random again (Shi et al. 1994). Movement of *A. glycines* on soybean plants changes as soybean plants grow, and their nutritional profile changes (Shi et al. 1994). In general, *A. glycines* has a tendency to move from the upper to the lower part of soybean plant early in the season and vice versa as the season progresses.

**Infestation and Outbreak.** Adults and nymphs of *A. glycines* accumulate on the top leaves, tender leaves, and stems. At the seedling stage, they mainly infest the undersides of upper leaves. Aphids move and feed on the leaves in the middle part of plant and stems at the early flowering stage. When soybean flowers peak,

aphids frequently infest the upper leaves, apex buds on branches, flowers, and pods. They are also found on stems, pods, petioles, and the undersides of larger leaves on mature plants. A positive correlation exists between nitrogen content of the apex leaves and the occurrence of *A. glycines* (Hu et al. 1992), whereas lignin content is negatively associated with aphid infestation (Hu et al. 1993).

Heavily infested soybean plants display the following symptoms: wrinkled and distorted foliage, early defoliation, underdeveloped roots, shortened stems and leaves, stunting, reduced branch number, lower pod and seed counts, reduced seed weight, and, under severe infestations, plant death (Wang et al. 1962, 1996; Lin et al. 1992, 1994; He et al. 1995; Wu et al. 1999). The seedling stage usually has smaller aphid populations. From late seedling to early flower, aphid densities increase gradually and then exponential growth lasts for 10–15 d (Lin et al. 1992). Aphid damage usually peaks at the soybean blooming stage, in which aphid densities exceed 20,000 per 100 plants, and 20% of plants are dwarfed (Han 1997). Population densities as high as 60,000–120,000 aphids per 100 plants were reported in south Shandong (Lin et al. 1992). Heavy aphid infestations will cause serious yield losses as soybean blooms and pods start to grow. Honeydew excreted by aphids will lead to the production of sooty mold, affecting plant photosynthesis and resulting in yield and seed quality losses (Chen and Yu 1988).

Several factors affect the outbreak of *A. glycines*, including environmental factors (e.g., temperature, precipitation, humidity), number of overwintering aphid eggs, cultural practices (e.g., cropping, rotation, sowing time, soybean variety), control measures (type and time), natural enemies, and synchronization of soybean and aphid development (Wang et al. 1962, Yue and Hao 1990, van den Berg et al. 1997, Wang et al. 1998, Wu et al. 1999). Based on an analysis of historical data over 10 years in Jilin province, Yue and Hao (1990) found that higher average temperature (22–23°C) and less rainfall (<20 mm) from 21 June to 10 July greatly favored aphid development, whereas light infestations occurred during the years when the average temperature was 20–21°C with precipitation >55 mm. The temperature/precipitation ratio (°C/mm) in this period was significantly correlated to aphid densities per 100 plants on 10 July. Late April–mid-May is a critical period in Heilongjiang province, because overwintering eggs hatch, nymphs develop, and adults reproduce (Wang et al. 1998, Wu et al. 1999, Sun et al. 2000). Sufficient precipitation during this period and the presence of widespread mature buckthorn facilitate high survival and reproduction of aphids. In late June to early July, suitable climatic conditions can lead to the rapid development of *A. glycines* and consequently to serious damage at the blooming stage (Chen and Yu 1988, Wang et al. 1998, Wu et al. 1999, Sun et al. 2000). However, high temperature (>25°C) and humidity (>80%) can have a detrimental effect on aphids (Wu et al. 1999).

Natural enemies play an important role in controlling *A. glycines*, especially at the early stage when aphids have a lower density and uneven distribution. The hypothesis that aphid outbreaks can be attributed in part to the absence of natural enemies is supported by data showing that outbreaks occurred after insecticide use in some studies (Wu et al. 1999, Sun et al. 2000), and by an experimental field cage study (Liu et al., 2004, this issue). van den Berg et al. (1997) found that predation by coccinellid beetles played an important role in suppressing *A. glycines* in Indonesian soybean fields.

**Aphid-Viral Diseases Relationship.** The soybean aphid is an important vector of soybean mosaic virus (SMV), which is widespread in soybean-growing areas in China. This viral disease can have serious impacts on soybean yield and seed quality (Irwin and Goodman 1981, Zhang 1982, Guo and Zhang 1989, Li and Pu 1991, Luo et al. 1991, Quimio and Calilung 1993). SMV is transmitted in a nonpersistent manner and causes high yield loss, spread mainly by infected aphids feeding on healthy plants (Irwin and Goodman 1981, Quimio and Calilung 1993).

Epidemics of SMV are dependent not only on the initial virus source but also on the abundance and development of aphid vectors, especially alatae (Halbert and Goodman 1981, Zhang 1982, Quimio and Calilung 1993). Occurrence of alate aphids in soybean fields was found to be closely associated with the incidence of SMV. *A. glycines* accounted for 64% of total alate aphids caught in soybean fields. Of all SMV-infested alate aphids, *A. glycines* comprised 74% of the total. The incidence of SMV increased with green pan-trap catches (Guo and Zhang 1989).

Li and Pu (1991) found similar results in summer-sown soybean in Nanjing, Jiangsu province, but the incidence of SMV was not always significantly related to the dispersal of alate aphids. The incidence of SMV depends on the time of alate aphid dispersal. If the dispersal of vector aphids peaks in the early soybean stage, an epidemic of SMV will occur, even under lower aphid densities. SMV will not occur if the aphid dispersal peaks after the flowering stage, even with a high number of vector aphids.

In addition to SMV, *A. glycines* has been reported to transmit other diseases, including soybean stunt virus, soybean dwarf virus, abaca mosaic, beet mosaic, tobacco vein-banding mosaic virus, bean yellow mosaic virus, mungbean mosaic virus, peanut mottle virus, peanut stripe poty virus, and peanut mosaic virus (Iwaki 1979, CAB International 2001).

**Natural Enemies.** A number of natural enemies of *A. glycines* have been reported in China, including predators, parasitoids, and pathogens (Table 2). Gao (1985) found that *Lysiphlebia japonica* (Ashmead) (Hymenoptera: Braconidae) was one of the dominant natural enemy species in Jilin province. In late October, parasitoids overwintered as late larvae in an unknown aphid species on motherwort, *Leonurus heterophyllus* Sweet, on sun-facing hillsides or near a river. Adults emerged in late April-early May of

the next year. The parasitism rate of *L. japonica* on *A. glycines* was 10.3–52.6%. This parasitoid effectively depressed soybean aphid populations early in a normal year, with a 34% parasitism rate of the first aphid generation (Gao 1994). However, higher hyperparasitism rates occurred in the overwintering and fourth aphid generations. Hyperparasitoids of *L. japonica* included *Aphidencyrthus aphidivorus* (Mayr), *Ceraphron* sp., and *Pachyneuron aphidis* (Bouché). Hyperparasitism mostly occurred around early to mid-July and the hyperparasitism rate was 27% (or occasionally as high as 83%) in a normal year. Soybean fields planted in monoculture had higher hyperparasitism rates than interplanted fields (Gao 1994). Zhang et al. (1998) pointed out that injury caused by aphid feeding attracted the parasitoid *Lysiphlebia fabarum* (Marshall) to injured soybean plants, and that more *L. fabarum* were attracted to damaged plants with aphids than to undamaged plants or aphids alone. In South Korea, Chang et al. (1994) reported eight primary parasitoid species, including *Aphidius absinthii* Marshall, *Aphidius cingulatus* Ruthe, *Aphidius salicis* Haliday, *Ephedrus persicae* Froggatt, *Ephedrus plagiator* Nees, *Lipolexis gracilis* Förster, *Lysephedrus validus* Haliday, *Lysiphlebia japonica*; and six hyperparasitoid species, including *Ardilea convexa* (Walker), *Asaphes vulgaris* Walker, *Charips brassicae* (Ashmead), *Gastrancistrus* sp., *Dendrocerus carpenteri* (Curtis) (= *Lygocerus testaceimanus* Kieffer), and *Protaphelinus nikolskajae* (Yasnosh), from soybean aphid.

Among the numerous predators of *A. glycines*, lady beetles, lacewings, and syrphid flies are very important. Of the syrphids, *Metasyrphus corollae* F., *Paragus quadrifasciatus* Meigen, *Epistrophe balteata* de Geer, *Ischyrosyrphus laternarius* (Müller), *Scaeva pyrastris* (L.), and *Sphaerophoria scripta* (L.) are common in Chinese soybean fields, of which *M. corollae* and *P. quadrifasciatus* were dominant (Gao 1991). Adults and eggs of *P. quadrifasciatus* are usually found 2–4 d after *A. glycines* occur in soybean fields. Young larvae of this syrphid feed on second and third instars. In one study, syrphid density increased with soybean aphid density, and each fly larva preyed on an average of 53–67 aphids per day with a lifetime predation rate of 500–800 aphids (Gao 1991, Gao et al. 1996). The density of *P. quadrifasciatus* was higher in interplanted fields than in monocultures, and more *P. quadrifasciatus* were found in soybean fields close to a water resource than in fields away from water (Gao et al. 1996). Of the natural enemies of the soybean aphid, lady beetles are thought to play the most important role in suppressing aphid populations in China because of their abundance and high predation rates in the fields (Wang and Ba 1998). *Propylaea japonica* (Thunberg) and *Harmonia axyridis* Pallas are the two dominant lady beetle species in China and accounted for 62% and 10% of all beetles captured, respectively, in one study (Wang and Ba 1998).

Han (1997) found 15 species of natural enemies in Henan province, including *P. japonica*, *Sphaerophoria* sp., *Hylyphantus graminicola* (Sundevall), *Diaeretiella rapae* (M'Intosh), and *Scymnus hoffmanni* Weise, but

Table 2. Natural enemies of *A. glycines* and hyperparasitoids documented in China and South Korea

Category	Family	Species	Reference		
Parasitoid	Aphelinidae	<i>Aphelinus</i> sp.	Qu et al. (1987)		
	Braconidae	<i>Aphidius absinthii</i> Marshall	Chang et al. (1994)		
		<i>Aphidius cingulatus</i> Ruthe	Chang et al. (1994)		
		<i>Aphidius gifuensis</i> Ashmead	Chen and Yu (1988)		
		<i>Aphidius salicis</i> Haliday	Chang et al. (1994)		
		<i>Diaeretiella rapae</i> (M'Intosh)	Han (1997)		
		<i>Ephedrus persicae</i> Froggatt	Chang et al. (1994)		
		<i>Ephedrus plagiator</i> Nees	Chang et al. (1994), Dai and Zhu (1997b)		
		<i>Lipolexis gracilis</i> Förster	Chang et al. (1994)		
		<i>Lysaphidius</i> sp.	Ma and Zhang (1984), Chen and Yu (1988)		
		<i>Lysephedrus validus</i> Haliday	Chang et al. (1994)		
		<i>Lysiphlebia japonica</i> (Ashmead)	Gao (1985), Chang et al. (1994), Li et al. (2000)		
		<i>Lysiphlebus fabarum</i> (Marshall)	Zhang et al. (1998)		
		<i>Trioxys asiaticus</i> Telenga	Chen and Yu (1988)		
		<i>Trioxys auctus</i> (Haliday)	Ma and Zhang (1984), Qu et al. (1987), Wang and Yue (1998)		
		Predator	Anthocoridae	<i>Orius similis</i> Zheng	Ma and Zhang (1984)
			Chamaemyiidae	<i>Leucopis</i> sp.	Wang et al. (1962)
Chrysopidae	<i>Chrysopa japana</i> <sup>a</sup>			Wang et al. (1962)	
	<i>Chrysopa formosa</i> Brauer		Dai and Zu (1997a)		
	<i>Chrysopa phyllochroma</i> Wesmael		Dai and Zu (1997a)		
	<i>Chrysopa septempunctata</i> Pleshanov		Wang et al. (1962), Dai and Zu (1997a), Han (1997), Chen and Yu (1988)		
	<i>Chrysopa sinica</i> Tjeder		Dai and Zu (1997a), Han (1997)		
	<i>Mallada basalis</i> (Walker)		Lee (1994)		
	Coccinellidae		<i>Adonia variegata</i> Goeze	Dai and Zu (1997a)	
			<i>Brunooides lineatus</i> (Weise)	Weng and Huang (1988)	
			<i>Cheilomenes sexmaculata</i> (F.)	Wang (1980)	
			<i>Coccinella septempunctata</i> L.	Wang et al. (1962), Chen and Yu (1988), Dai and Zu (1997a), Han (1997)	
			<i>Harmonia axyridis</i> Pallas	Wang et al. (1962), Chen and Yu (1988), Dai and Zu (1997a), Han (1997) Wang and Ba (1998)	
			<i>Hippodamia tridecimpunctata</i> (L.)	Wang et al. (1962), Chen and Yu (1988), Dai and Zu (1997a)	
			<i>Propylaea japonica</i> (Thunberg)	Wang et al. (1962), Chen and Yu (1988), Dai and Zu (1997a), Han (1997), Wang and Ba (1998), Li et al. (2000)	
	Linyphiidae		<i>Scymnus hoffmanni</i> Weise	Han (1997)	
			<i>Hyllyphantes graminicola</i> (Sundevall)	Han (1997)	
			Lygaeidae	<i>Geocoris pallidipennis</i> (Costa)	Han (1997)
<i>Deraeocoris punctulatus</i> (Fallen)				Han (1997)	
Miridae			<i>Nabis sioferus</i> <sup>a</sup>	Han (1997)	
Nabidae			<i>Epistrophe balteata</i> de Geer	Chen and Yu (1988), Gao (1991), Dai and Zu (1997a), Han (1997)	
			<i>Ischiodon scutellaris</i> (F.)	Han (1997)	
Syrphidae			<i>Ischyrosyrphus laterarius</i> (Müller)	Gao (1991)	
			<i>Metasyrphus corollae</i> F.	Gao (1991), Dai and Zu (1997a)	
			<i>Paragus quadrifasciatus</i> Meigen	Gao (1991), Dai and Zu (1997a)	
			<i>Scaeva pyrastris</i> (L.)	Gao (1991)	
			<i>Sphaerophoria indiana</i> Bigot	Wang et al. (1962)	
	<i>Sphaerophoria scripta</i> (L.)		Gao (1991), Dai and Zu (1997a)		
	<i>Sphaerophoria</i> sp.		Han (1997)		
	<i>Syrphus serarius</i> Wiedemann	Han (1997)			
	Pathogen	Entomophthoraceae	<i>Entomophthora fresenii</i> (Nowak)	Chen and Yu (1988)	
		Hyperparasitoid	Aphelinidae	<i>Protaphelinus nikolskajae</i> (Yasnosh)	Chang et al. (1994)
Ceraphronidae	<i>Asaphes vulgaris</i> Walker		Chang et al. (1994)		
	<i>Ceraphron</i> sp.	Gao (1994)			
	<i>Dendrocerus carpenteri</i> (Curtis)	Chang et al. (1994)			
	<i>Charips brassicae</i> (Ashmead)	Chang et al. (1994)			
	Cynipidae	<i>Aphidencyrus aphidivorus</i> (Mayr)	Gao (1994)		
		<i>Pachymeuron aphidis</i> (Bouché)	Gao (1994)		
	Encyrtidae	<i>Ardilea convexa</i> (Walker) <sup>a</sup>	Chang et al. (1994)		
	Pteromalidae	<i>Gastrancistrus</i> sp. <sup>a</sup>	Chang et al. (1994)		
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<sup>a</sup> The spelling of some of the genus and species names taken directly from the references in some cases may be incorrect.

all of these natural enemies usually lagged 5–7 d behind the soybean aphid. At the soybean seedling stage, *H. graminicola* was dominant, whereas *D. rapae*, *Spha-*

*erophoria* sp., *H. axyridis*, and *H. graminicola* were most prevalent at the vegetative and blooming stages. *D. rapae* became the major species (accounting for

85% of all natural enemies) at the ripe pod stage (Han 1997).

Besides parasitoids and predatory insects, *Entomophthora fresenii* (Nowak) was one of the most common pathogens infecting *A. glycines* in China (Chen and Yu 1988). Infected aphids turn black with their mouthparts piercing into the plant. The mouthparts stay anchored in the leaf or other plant parts after aphids die, leaving killed aphids distributed along the veins of the backside of leaves or stems. The incidence of *E. fresenii* was correlated with humidity and aphid density in the field (Chen and Yu 1988).

**Sampling.** In China, monitoring and prediction of *A. glycines* population trends started in the 1950s (Wang et al. 1962). Factors used in mid- or long-term prediction included the number of overwintering aphid eggs and the meteorological forecast in late April–mid-May and late June–early July (Chen et al. 1984, Sun et al. 2000). The number of overwintering aphid eggs was strongly correlated to aphid density and infestation in the coming year (Chen et al. 1984). Early, severe infestations occurred when overwintering eggs exceeded 10,000 per 100 buckthorn branches. The number of eggs per 100 buckthorn plants was usually <50 in normal years. Several mathematical models were constructed for the prediction of aphid development, including 1) correlation analysis based upon overwintering aphid eggs (Chen et al. 1984), 2) gradual regression analysis based upon aphid density per 100 plants (Tian et al. 1990), 3) ranking order interpolation based upon the number for alates (Liu and Dai 1994), and 4) aggregation index based upon aphid density (Shi et al. 1994). Other indices had been proposed for aphid prediction, including content of lignin or nitrogen, which could predict the infestation level on different soybean varieties (Hu et al. 1992, 1993).

Huang et al. (1992) showed that the number of samples required to accurately estimate soybean aphid densities decreases as aphid density increases. For example, 40 samples of five plants are needed when the plant percentage with aphids is 40%, whereas only ten samples of five plants suffice if this percentage reaches 80%.

**Thresholds.** To effectively manipulate *A. glycines* populations and achieve an optimal benefit/cost ratio for management, a clear knowledge of the economic and control thresholds is necessary. A number of studies have quantified the interactions between *A. glycines* density and damage level and then assessed the feasibility of using such parameters in recommending management decisions. The parameters used as control thresholds have included: aphid numbers per plant or per 100 plants, cumulative daily aphid numbers per plant, plant percentage with aphids, rolled leaf percentage, and the ratio of temperature to precipitation (Liu 1986, Tian et al. 1990, Yue and Hao 1990, He et al. 1991, Lin et al. 1992, Wang et al. 1996).

In Jilin, Yue and Hao (1990) suggested a population density of 3,000 aphids per 100 plants and the percentage of plants with aphids exceeding 60% in late June, along with temperature/precipitation (during

21 June–10 July) ratio >1, and over 4% of rolled leaves in early July, as a composite control threshold. Predictions were 80% accurate when the regression of temperature/precipitation ratio on aphid numbers per 100 plants on 10 July was used to predict the development of *A. glycines*. He et al. (1991) argued that it was impractical to use aphid numbers per 100 plants or cumulative daily aphid density per 100 plants. Because the percentage of rolled leaves was closely associated with aphid density and was easy to use in the field, they chose this parameter instead as a control threshold. He et al. (1991) concluded that when the percentage of rolled leaf reached 8–10% (depending on soybean variety), aphids should be controlled immediately. Wang et al. (1994b) suggested that control is necessary in Zhejiang province when aphid density exceeds 500 per 100 plants and the proportion of plants with aphids was >35% at the seedling stage. But Wang et al. (1994a, 1996) proposed a much higher control threshold at the same stage in Jilin: >10,000 aphids per 100 plants with >90% of plants infested. Lin et al. (1992) also suggested an average population density of 10,000 aphids per 100 plants at the flowering and podding stages as a control threshold and suggested that this threshold might be adjusted on the basis of regional soybean production variability.

Research on the economic impact of *A. glycines* focuses mainly on the relationships between aphid density, damage level, and yield loss, which is reflected in the reduction of pod and seed numbers and seed weight (Dai and Fan 1991; Lin et al. 1992, 1993; Wang et al. 1994a,b; He et al. 1991, 1995). Plant height and branch number are also measurable indices of loss assessment (Dai and Fan 1991; He et al. 1991, 1995). High aphid densities at and before pod set can have significant negative impacts on several major economic characters (Lin et al. 1993). This is reflected by a negative correlation between aphid density and seed weight and by a positive correlation of aphid density with the proportion of shriveled pods.

At the early soybean stage, minor damage or severe damage with timely control had no significant impact on soybean yields in at least one study, indicating that soybean had resilience or tolerance after aphid infestation (He et al. 1995). Continuous and serious infestation caused a 20–30% yield reduction, whereas infestation occurring late in the season had a trivial influence on yields (Dai and Fan 1991).

**Control.** Control of *A. glycines* involves a number of distinct tactics, including chemical control, cultural control, biological control, and host plant resistance. These control options can be used individually or together. Integrated pest management (IPM) recognizes the negative ecological impact of chemical control, and it encompasses all control options available on the basis of ecological and economic considerations and avoids preemptive measures. Wang and Ba (1998) and Wang et al. (2000) attempted to use an IPM strategy against *A. glycines*. They found that >80% control of *A. glycines*, a yield increase of >16%, and more than twice the natural enemy densities were achieved when soybean and maize were cosown or

interplanted, integrated with (organic and inorganic) fertilizer, fertilizer seed-coating, and pesticide applications.

**Chemical Control.** Numerous pesticides have been tested and applied to deal with *A. glycines*, including cyhalothrin, fenvalerate, omethoate, aldicarb, carbofuran, imidacloprid, pirimicarb, chloromethiuron, phosalone, deltamethrin, Phorate and sumi-alpha (Qu et al. 1987; Chen and Yu 1988; Wang et al. 1993, 1994a,b, 1998; Huang et al. 1998; Fu et al. 1999; Wu et al. 1999; Li et al. 2000; Sun et al. 2000). Many of these insecticides are highly toxic and have a broad spectrum of activity. Besides the soybean aphid, chemicals are often used to control other insect pests at the same time. Seed coating and spraying are the most popular methods of application. The soybean aphid can be controlled efficiently if insecticides are used before the second dispersal peak (i.e., at the flowering and podding stages) (Chen and Yu 1988).

Although use of insecticides can be a quick, easy way to control *A. glycines*, frequent applications of broad-spectrum pesticides can lead to the buildup of aphid resistance to chemicals, resulting in more chemicals being used with potentially severe environmental side effects. Another obvious consequence of chemical use is the reduction of biodiversity in agricultural systems (Gao et al. 1993b, Wang et al. 1993, Qu et al. 1987, Sun et al. 2000). Deltamethrin, dichlorvos, and omethoate showed significant, negative effects on the survival of *L. japonica* larvae and adults, although dichlorvos has little impact on mummies (Gao et al. 1993b). Wang et al. (1993) discovered that phosalone effectively controlled the soybean aphid at the seedling stage without obvious, negative impact on beneficial pentatomid bugs and parasitoids. Qu et al. (1987) reported that treatments of omethoate and fenvalerate at the seedling stage and diflubenzuron at the flowering and podding stages efficiently controlled *A. glycines*, without harming most natural enemies.

"G-P compound," a mixture of a bacterial metabolite and plant extract compound, effectively controlled *A. glycines* (Dai and Zu 1997a). Under laboratory conditions, aphid mortality was >77 and 91%, at 24 and 48 h after the compound was sprayed, respectively, whereas aphid mortality was >91% in the field. This compound was less toxic to natural enemies than omethoate. It was noninjurious to adults and pupae of several dominant species of natural enemies, but the toxicity to larvae and eggs depended on the species, with *M. corollae* more sensitive than three other species: *Chrysopa septempunctata* Wesmael, *Ephedrus plagiator* (Nees), and *Propylaea japonica* (Dai and Zu 1997b).

**Cultural Control and Host Plant Resistance.** Cultural control is an important alternative to traditional chemical control or other control options. Wang and Ba (1998) and Wang et al. (2000) conducted experiments of optimal control techniques and analyzed the impact of various controllable factors, including cropping system, soybean variety, sowing time, fertilizer, and pesticide application on the soybean aphid. A significant yield increase and effective control of

*A. glycines* by natural enemies were achieved by interplanting soybean and maize (4:1) or sowing soybean and maize seeds (9:2) in the same holes. Under the optimal control technique using monoculture of soybean, the soybean aphid was effectively controlled and the yield increase was substantial, but considerable decreases in natural enemies occurred. In at least one study, however, this practice increased the number of natural enemies and led to decrease of aphid densities (Wang and Yue 1998).

Breeding programs for the selection of insect pests or disease-resistant varieties exist in China. Soybean varieties differ significantly in resistance to *A. glycines*, and two highly aphid resistant varieties were selected from 181 varieties screened (Fan 1988). He et al. (1995) found that, compared with the resistant varieties, the susceptible varieties had 1) significantly higher aphid density; 2) younger aphid population (i.e., the proportion of nymphs on the susceptible variety was higher but the proportion of alatae was lower, implying that the susceptible variety facilitated aphid growth and reproduction); 3) less tolerance to aphid damage and lower compensation capability after infestation; and 4) colonization and feeding preference by aphids. Hu et al. (1992, 1993) reported that soybean varieties with higher nitrogen content were more susceptible to aphid damage, whereas higher lignin content helped inhibit aphid infestation.

Yue et al. (1988, 1989) found three highly resistant strains from nearly 1,000 strains of the wild soybean, *G. soja*, and these three strains demonstrated higher resistance to aphids than other resistant varieties selected from the cultivated soybean, *G. max*. From the observations of crosses between the wild and cultivated soybean, Sun et al. (1991) hypothesized that aphid resistance in the wild soybean might be controlled by two independent recessive loci and some other minor genes. China contains >90% of the wild soybean resources worldwide (Xu 1989), and this abundant reserve certainly will provide a valuable gene reservoir for aphid resistance studies.

**Biological Control.** Biological control programs using several natural enemy species have been carried out in Jilin and Taiwan. In a 5-yr release experiment of *L. japonica*, parasitism rates ranged between 56 and 76% (Gao 1985). Developmental time for *L. japonica* is 12–15 days at 19–23 ±5°C, and this species was deemed a promising biological control agent for the soybean aphid partly because of its rapid development (Gao 1985).

A number of studies on soybean aphid predators have also been conducted in China. Gao (1991) found that the syrphids *M. corollae* and *P. quadrifasciatus* were the dominant species in Tonghua, Jilin province. Optimal temperatures for preserving adults and pupae of *P. quadrifasciatus* were 2–4°C and 0–4°C, respectively. In the field, *P. quadrifasciatus* overwinter as pupae in the soil 4 cm underground and emerge in mid-April–early May (Gao et al. 1992, 1993a). About one-half of the overwintering pupae survive naturally in open sunny or sandy fields, whereas the survival rate was >80% when pupae were kept indoors under ar-

tificial conditions (Gao et al. 1992). A release experiment of *H. axyridis* demonstrated that this beetle was able to efficiently control the soybean aphid without aid of chemical application (Yan et al. 1994b). Additionally, mass rearing of the chrysopid *Mallada basalis* (Walker) has been conducted in Taiwan for control of *A. glycines* (Lee 1994). In Indonesia, van den Berg et al. (1997) found that the coccinellid *Harmonia arcuata* (F.) played an important role in suppressing soybean aphids, and they suggested that applications of pesticides should be avoided to protect these predators in the early season.

In conclusion, the soybean aphid has been studied extensively in China over the last half-century. Factors including the development of *A. glycines*, its impact on soybean production, and its relationships with host plants and other organisms have been explored. Interactions between the soybean aphid and its natural enemies are complicated and dynamic and are mediated by other cultural practices and environmental factors. Sizable yield losses are expected if heavy aphid infestation occurs. However, the migration patterns and the extent of direct impact by aphids on soybean quality (e.g., protein and oil content) are still undetermined from the Chinese research literature. Appropriate and timely monitoring of *A. glycines* on a yearly basis are needed, followed by application of comprehensive IPM measures.

Many challenges face U.S. entomologists as they begin to make management decisions and recommendations for soybean aphid. Urgent issues include the development of realistic treatment thresholds, identification of resistant and tolerant germplasm, and the development of cultural practices that minimize damage due to soybean aphid. The role of natural enemies in keeping soybean aphid under control in North America also needs to be clarified, as has been discussed in two contributions to this series (Heimpel et al. 2004 and Rutledge et al. 2004, this issue). Although these challenges are all formidable, they will be more easily met by using the contributions made by Chinese scientists over the past four decades as a starting point.

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