EFFECTS OF INTRAGUILD PREDATION AND INTERSPECIFIC COMPETITITON AMONG BIOLOGICAL CONTROL AGENTS IN AUGMENTATIVE BIOLOGICAL CONTROL IN GREENHOUSES

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ABSTRACT

Two natural enemy species are frequently released simultaneously to control one pest species in augmentative biological control in greenhouses. Intraguild predation (IGP) and interspecific competition between natural enemies might affect the biological control. IGP occurs between two parasitoids, between one parasitoid and one predator, and between two predators. Although unidirectional IGP has been found in many studies about IGP between natural enemies used in the biological control of greenhouse pests, no significant effects of IGP on biological control have been recognized. On tomatoes in greenhouses, *Liriomyza trifolii* is usually controlled by the combined release of *Dacnusa sibirica* and *Diglyphus isaea*. *Trialeurodes vaporariorum*, another pest of greenhouse tomatoes, can be controlled by the combined use of *Encarsia formosa* and *Eretmocerus eremicus*. Simulation models incorporating IGP or interspecific competition between these parasitoid species have been constructed for evaluating biological control using two parasitoid species. These simulation models suggested no significant negative effects of IGP or interspecific interactions between two parasitoids on biological control.

INTRODUCTION

The number of biological control agents (BCAs) released in greenhouses has increased greatly. Today, over 125 BCAs are commercially available in Europe (Weintraub and Cheek, 2005).0Thirty-two BCAs were registered as biopesticides by 2004, and some are widely used in commercial greenhouses in Japan.

Biological control agents are frequently used in combination. In some cases, two species which have complementary effects are released simultaneously. In recent release systems, first a less costly species is released preventively to control the target pest. When the pest density reaches a high level, another more expensive species (often generalist predators) may be released curatively to suppress the pest population.

Biological control can be disrupted by direct or indirect interactions such as competition, apparent competition, intraguild predation (IGP), and behavioral interference between natural enemies. Rosenheim *et al.* (1995) reviewed theoretical and empirical evidence to discuss the significance of IGP in biological control. IGP occurs when two species that share a host or prey also engage in a trophic interaction with each other (parasitism or predation). They hypothesized that IGP by predators is particularly likely to influence the efficacy of biological control.

Brodeur *et al.* (2002) argued the significance of IGP by generalist predators released curatively in greenhouse systems. Generalist predators may disrupt biological control by interfering with natural enemies released preventively. They concluded that IGP by generalist predators is less important in greenhouses than in annual or perennial agroecosystems.

In this article, recent studies about the significance of IGP in augmentative biological control in greenhouses are first reviewed. Then simulation models for evaluating IGP or interspecific competition between parasitoids released to control whiteflies or leafminers in greenhouse tomatoes are described.

INTERACTIONS BETWEEN TWO NATURAL ENEMIES

INTERACTION BETWEEN TWO NATURAL ENEMIES IN BIOLOGICAL CONTROL IN GREENHOUSES

Table 1 shows the list of studies about IGP among arthropod natural enemies used in augmentative releases in greenhouses. Three types of IGP are considered, i.e., IGP between two parasitoids, between one predator and one parasitoid, and between two predators. IGP between predators has been studied for many interactions. There have only been a few studies about IGP between two parasitoids, and IGP of a parasitoid by a predator. Most of the studies are IGP experiments with or without alternative hosts. Thus, the effects of IGP on the population dynamics of both natural enemies and a host or a prey in biological control have been found for only several cases. In most cases listed in Table 1, IGP is unidirectional.

IGP AND INTERSPECIFIC COMPETITION BETWEEN TWO PARASITOIDS

Liriomyza trifolii (Burgess) (Diptera: Agromyzidae), a pest of greenhouse tomatoes, is usually controlled by a combined release of *Dacnusa sibirica* Telenga (Hymenoptera: Braconidae) and *Diglyphus isaea* (Walker) (Hymenoptera: Eulophidae). Two whitefly species, *Trialeurodes vaporariorum* (Westwood) and *Bemisia argentifolii* Bellows and Perring (Homoptera: Aleyrodidae) can be controlled by a combined use of *Encarsia formosa* Gahan (Hymenoptera: Aphelinidae) and *Eretmocerus eremicus* Rose and Zolnerowich (Hymenoptera: Aphelinidae).

D. isaea is always superior to *D. sibirica* in their interaction.0*D. isaea* adults kill parasitized leafminer larvae by *D. sibirica*. *D. sibirica* adults cannot attack dead larvae killed by *D. isaea*. This interaction can be regarded as IGP. When whitefly larvae were parasitized by both *E. formosa* and *E. eremicus, E. eremicus* always survived and *E. formosa* was killed in the direct interference between two species (Mitsunaga, unpublished).

IGP BETWEEN ONE PARASITOID AND ONE PREDATOR

Two types of unidirectional IGP by arthropod predators on parasitoids are recognized. First, predators may prey directly on immature stages of ectoparasitoids or on free-living parasitoid adults. Second, predators may prey on parasitized hosts. Once a host is encountered,

Table 1. Intraguild predation (IGP) among arthropod natural enemies used in biological control in greenhouses.

Study Type	**Interaction**	**IGP Species (E=exploiter; V=victim)**	**Biocontrol Target**	**Reference**
Laboratory experiment, Simulation	Parasitoid-parasitoid	*Dacnusa sibirica* (V) *Diglyphus isaea* (E)	*Liriomyza trifolii*	This study
Laboratory experiment	Predator- parasitoid	*Anthocoris nemorum* (E) *Aphidius colemani* (V)	*Myzus persicae*	Meyling et al. 2002
Laboratory experiment	Predator- parasitoid	*Aphidoletes aphidimyza* (E) *Aphidius colemani* (V)	*Aphis gossypii*	Enkegaard et al. 2005
Laboratory experiment, Greenhouse experiment	Predator- predator	*Neoseiulus californicus* (E, V) *Phytoseiulus persimilis* (E, V)	*Tetranychus urticae*	Walzer & Schausberger 1999ab; Schausberger & Walzer 2001
Laboratory experiment	Predator- predator	*Orius tristicolor* (E) *Neoseiulus cucumeris* (V)	*Frankliniella occidentalis*	Gillespie & Quiring 1992
Laboratory experiment	Predator- predator	*Orius tristicolor* (E) *Phytoseiulus persimilis* (V)	*Tetranychus urticae*	Cloutier & Johnson 1993
Laboratory experiment	Predator- predator	*Orius majusculus, O. insidiosus* (E) *Neoseiulus cucumeris* (V)	*Frankliniella occidentalis*	Sanderson et al. 2005
Laboratory experiment	Predator- predator	*Orius majusculus* (E) *Iphiseius degenerans* (V)	*Frankliniella occidentalis*	Brodsgaard & Enkegaard 2005
Laboratory experiment	Predator- predator	*Orius majusculus* (E) *Aphidoletes aphidimyza* (V)	*Aphis gossypii*	Christensen et al. 2002
Laboratory experiment	Predator- predator	*Orius majusculus* (E) *Macrolophus caliginosus* (V)	*Frankliniella occidentalis*	Jakobsen et al. 2002
Laboratory experiment	Predator- predator	*Dicyphus tamaninii* (E) *Macrolophus caliginosus* (V)	*Trialeurodes vaporariorum*	Lucas & Alomar 2001, 2002

predators may have different probabilities of attacking unparasitized versus parasitized hosts (Rosenheim *et al.* 1995).

Prey preference between *Aphidius colemani* Viereck (Hymenoptera: Braconidae), parasitized *Myzus persicae* Sulzer (Homoptera: Aphididae) (mummy stage) and unparasitized aphids was evaluated for female *Anthocoris nemorum* L. (Heteroptera: Anthocoridae) in the laboratory. *A. nemorum* preyed readily on the immature parasitoids contained within mummies, and showed no preference for either of the two prey types (Meyling *et al.* 2002).

The intraguild predation between the aphid predator *Aphidoletes aphidimyza* Rondani (Diptera: Cecidomyiidae) and the parasitoid *A. colemani* was examined in the laboratory. Gallmidge larvae readily killed parasitized but not yet mummified aphids. The predator showed a slight preference for parasitized over unparasitized aphids. Aphid mummies were not predated at all (Enkegaard *et al.* 2005).

IGP BETWEEN TWO PREDATORS

Many predators are generalists and consume a broad array of prey. IGP among predators is widespread and both unidirectional and bidirectional IGP appear to be common. The presence of alternative prey is often critical in modulating the occurrence of IGP (Rosenheim *et al.* 1995). The relative size of two predators is crucial in unidirectional IGP. In general, the larger predator exploits the smaller one. Bidirectional IGP often takes the form of late instars or adults of two species feeding on each other during earlier developmental stages.

IGP and the cannibalism of the generalist *Neoseiulus californicus* McGregor (Acarina: Phytoseiidae) and the specialist *Phytoseiulus persimilis* Athias-Henriot (Acarina: Phytoseiidae) were examined. *N. californicus* distinguished con- and heterospecific larvae and fed more by IGP than cannibalism. *P. persimilis* had a higher predation rate by cannibalism than IGP (Walzer and Schausberger 1999a,b). Combined and single species release of *N. californicus* and *P. persimilis* for suppressing *Tetranychus cinnabarinus* Boisduval (Acarina: Tetranichidae) were compared on greenhouse gerbera. The population growth of *P. persimilis* was greater and the population decline steeper in a combined release than a single species release. *N. californicus* grew and declined more gradually in a combined release than in single species one. These differences in the population dynamics of two phytoseiid mites can be attributed to contrasting properties in competition, IGP, and cannibalism (Schauberger and Walzer 2001).

IGP by *Orius* spp. on phytoseiid mites has been studied for many combinations of species (Table 1). *O. majusuculus* and *O. insidiosus* showed different preferences for *N. cucumeris* versus *F. occidentalis. O majusculus* showed no preference. In contrast, *O. insidiosus* preferred *N. cucumeris* over thrips (Sanderson *et al.* 2005). *O. majusculus* showed a clear preference for *F. occidentalis* over *Iphiseius degenerans* (Berlese) (Acrina: Phytoseiidae) in choice tests (Brodsgaard and Enkegaard 2005).

O. majusculus preyed on the eggs and larvae of *A. aphidimyza*. However, the extent of IGP was affected by the presence of *A. gossypii* (Christensen *et al.* 2002).

Macrolophus caliginosus (Wagner) (Heteroptera: Miridae) is preyed on by *O. majusculus* and *Dicyphus tamaninii* Wagner (Heteroptera: Miridae) (Jakobsen *et al.* 2002; Lucas and Alomar 2001). IGP by *D. tamaninii* on *M. caliginosus* did not disrupt whitefly predation by *M. caliginosus* in tomato greenhouses (Lucas and Alomar 2002).

SIMULATION STUDIES FOR EVALUATING BIOLOGICAL CONTROL USING TWO PARASITOIDS

STRUCTURE OF THE SIMULATION MODELS

A simulation model has been developed for evaluating the IGP between *D. sibirica* and *D. isaea* for the biological control of *L. trifolii* with these parasitoids. The model comprises the leaf area growth submodel, the Type I functional response model of the parasitoids to the host density, and the IGP submodel between the two parasitoid species. The aging processes in immature stages were described using "the boxcar train method" (Goudriaan and van Roermund 1989).

D. isaea is a synovigenic species and needs host feeding for egg production. The interactions between egg load, oviposition, and the host feeding of *D. isaea* were considered in the model based on the results of laboratory experiments (Ozawa, unpublished). The life history parameters of the leafminer and the two parasitoid species and the parameters of the functional responses were calculated from the results of glasshouse experiments or from the literature (Minkenberg 1990; Ozawa unpublished; Sugimoto unpublished).

A similar simulation model was developed to predict the biological control with the release of *E. formosa* and *E. eremicus* to control *T. vaporariorum* on tomatoes. The model comprises the leaf area growth submodel, the Type I functional response model of the parasitoids to the host density, and the competition submodel between two parasitoid species. The ageing processes in immature stages were described using "the boxcar train method".

PREDICTION FROM THE SIMULATIONS

The simulations of these models suggested no significant negative effects of the interspecific interactions between two parasitoids on biological control. However, the unidirectional interactions between the two parasitoids resulted in the extinction of the inferior species in the later cropping period. When both parasitoid species were released simultaneously at different release ratios, the intermediate ratios resulted in better control than the single species release of one of the two species (Figs.1, 2).

In both cases, the systems could not persist for a long period. That is one of the reasons IGP has less effect on biological control. Actually, pest–natural enemy systems in biological control in greenhouses persist only for a shorter period than in annual or perennial agroecosystems. Brodeur *et al.* (2002) pointed out that the spatial scale of the greenhouse system is small and persists for a short period, which makes the system transient and unstable. Since the model in this simulation study did not have a spatial structure, the effect of spatial scale was not studied.

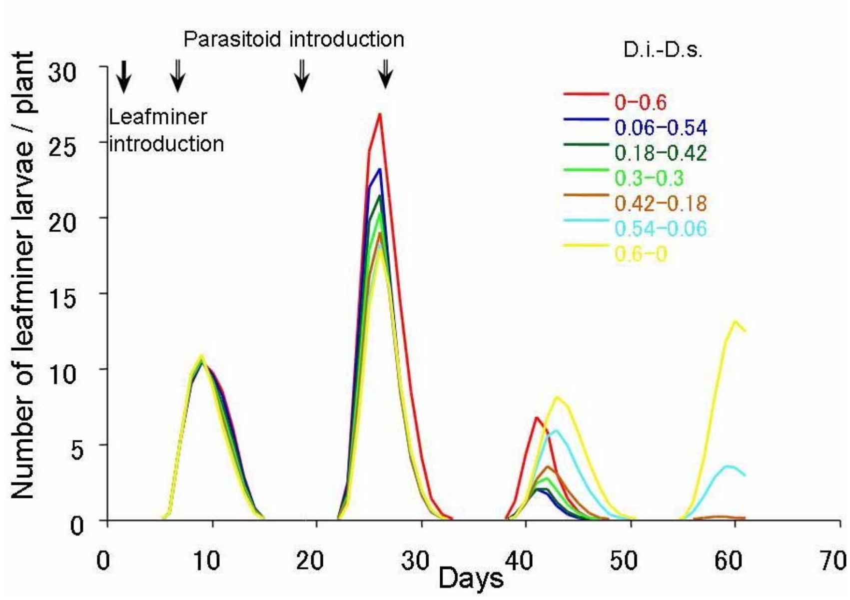

Figure 1. Evaluation of different release ratios of *D. isaea* (D.i.) and *D. sibirica* (D.s.) in the biological control of *L. trifolii*. Total number of released parasitoids was 0.6 female adults / plant per introduction.

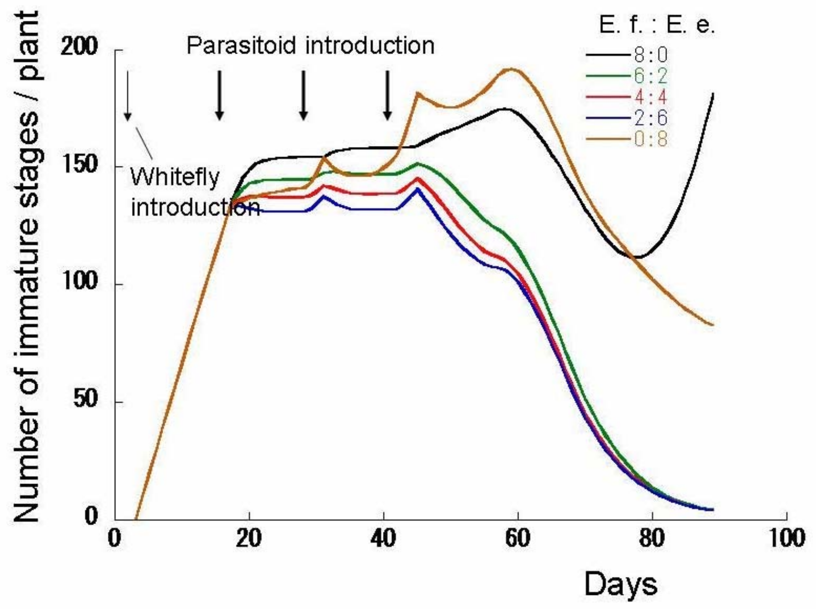

Figure 2. Evaluation of different release ratio of *E. formosa* (E.f.) and *E. eremicus* (E.e.) in the biological control of *T. vaporariorum*. Total number of released parasitoids was 8 female adults / plant per introduction.

CONCLUSIONS

IGP among natural enemies in biological control in greenhouses might commonly occur. Most of the IGP interactions seem to be unidirectional, because two natural enemies for combined use should be different in size and belong to different taxa. Although the effects of IGP on the population dynamics of pests and natural enemies have been studied for only several cases, the effect of IGP is expected to be less important in greenhouses than in annual or perennial agroecosystems.

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IMPLEMENTATION OF BIOLOGICAL CONTROL IN GREENHOUSES IN LATIN AMERICA: HOW FAR ARE WE?

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ABSTRACT

Application of biological control in greenhouse production areas in Latin America is growing. However, there are many factors negatively affecting this development, although there are currently also important positive factors stimulating biological control. This paper discusses the development of biological control in the largest developing greenhouse regions in Latin America as Brazil, Colombia and Mexico, and the factors which are affecting the implementation of such strategies.

INTRODUCTION

The world greenhouse area is currently estimated at approximately 310,000 ha, 40,000 ha of which is covered with glass, 270,000 ha with plastic. Vegetable crops are grown in about 65% of greenhouses, and ornamentals in the remaining 35%. In the past 24 years the surface areas with greenhouse have increased more than 100%, with an increase of 4.4% per year (Bueno 2005; van Lenteren 2000). Production under protected cultivation in Latin America started in the 1970's and now several countries are showing a strong increase in protected areas attracted by cultivation of high-value crops. Ornamentals occupy the largest area under protected cultivation in Latin America.

Pest and disease management form a crucial aspect of greenhouse production. Various insect and mite pests occur in the different vegetable and ornamental crops. Most of the pests are similar to those in the other greenhouse areas of the world. For many years, not enough attention has been paid to exploiting and amending production technology for the integrated management of pests in Latin America, and pest control is still mainly by chemicals. Most Latin America countries produce flowers and vegetables for the local market (with the exception of Colombia), and these products are not subjected to only very limited control regarding pesticides residues. But the situation of the export market (primarily for flowers) is quite different, mainly because of the norms and standards of protocols as EUREPGAP or ISO.

Currently biological control of greenhouse pests is being implemented in several Latin America countries, although application is still limited considering the total area of over 15,000 ha with greenhouses. But several stimuli are pushing growers to use fewer pesticides and adopt more sustainable ways to protect crops from pests as world markets become more global, and biological control is a corner stone of sustainable production.

The approach for development and implementation of biological control in protected crops in Latin America areas should not be based on mere import and release of commercially produced exotic natural enemies (van Lenteren and Bueno 2003). The first priority is to study which pest species occur in unsprayed plots, and which of these pests are kept under natural control by native natural enemies. In the next phase a good biological control solution should be developed for those pest species that are not kept under reliable natural control, for example by timely introduction of mass produced native natural enemies.

Biological and integrated control programs can then be developed making use of the most effective native natural enemies, which might be supplemented with exotic natural enemies for those pests where native biological control agents are ineffective. Interestingly, in Latin American countries natural control of pests occurs very generally and, therefore, plays an important role. In several countries, like Brazil, Colombia and Mexico, biological control programs exist or are implemented on pilot greenhouse farms. Below, a number of examples are presented from these countries to demonstrate the progress achieved to date. Also, factors that frustrate or stimulate the implementation of biological control are discussed.

EXAMPLES OF BIOLOGICAL CONTROL STRATEGIES IN GREENHOUSE REGIONS IN LATIN AMERICA

COLOMBIA

Colombia was one of the first countries in Latin America starting with the production of ornamentals in greenhouses 35 years ago. This country is now the second largest cut flower exporter in the world after The Netherlands. About 98% of the flowers produced in Colombia are for exportation. The current official figure for cut flowers produced for export in greenhouses is 6,016 ha. A quarantine pest in the case of export flowers is *Thrips palmi* Karny (Thysanoptera: Thripidae).

Over the years the flower industry has experienced many problems and to solve them, Asocolflores (Colombian Association of Flowers Exporters) representing 75% of Colombia's flower production, has in the past years made a tremendous investment in the newest varieties and also in technology to offer the best quality. In 1996, the Florverde® Program (Green Flower) was created by Asocolflores. The program is a code of conduct aimed at sustainable production of flowers involving several areas such as human resources, natural resources, IPM, waste management and landscaping. Florverde promotes the implementation of IPM programs which are based on three principles: (1) use of reliable and timely monitoring systems that provide guidance and support to decision-making efforts; (2) give priority to the use of control strategies other than chemical controls; (3) rational and safe use of pesticides, that is, only at the times they are actually required and only in the required amounts, so as to minimize impact on human health and the environment (Rebecca Lee, pers. comm., Colombia).

Biological control of a range of pests on greenhouse ornamentals occurs on 9 ha of flowers. Biological control of leafminers has been developed and implemented in *Gypsophyla paniculata* L. by introduction and conservation of the parasitoid *Diglyphus begini* (Ashmead) (Hymenoptera: Eulophidae) (Cure and Cantor 2003). However biological control is still very little used due the complicated legislation in Colombia for import and use of exotic natural enemies. The predatory mite *Phytoseiulus persimilis* Athias-Henriot (Acari: Phytoseiidae) was registered for use as natural enemy a year ago, but still is not used very much in flowers. Local companies have focused on the elaboration of botanical pesticides as well fungal based biological control.

Production of vegetables in greenhouses in Colombia is a more recent development, and takes place in cold climate zones. In tomato crops at altitudes from 1,800 to 2,600 meters natural control of leafminers and aphids has been observed. For control of whiteflies, studies are conducted with species of *Encarsia*, *Eretmocerus* and the native species *Amitus fuscipennis* MacGaen and Nebeker (Hymenoptera: Platygastridae) (De Vis 2001; De Vis and Fuentes 2001; Manzano 2000).

MEXICO

The greenhouse area in Mexico is around 3,000 ha. The first commercial operations of vegetable production in greenhouses started in the 1990's on 50 ha, and they increased to around 2,208 ha today. The main vegetable crops under protected cultivation are tomato, pepper and cucumber. For the largest greenhouse vegetable crop, tomato, Mexico is known to apply biological control on 110 ha. For pepper grown in greenhouses, biological control is used on 30 ha (all information, pers. comm. Mario Steta and Rigoberto Bueno, Mexico).

Mexico, in comparison with other Latin American countries, has imported and released a number of exotic natural enemies. The legislation procedures for importation seem to be clearly defined and more advanced than in other Latin American countries. Natural enemies have been imported for biological control of whiteflies [*Encarsia formosa* Gahan and *Eretmocerus eremicus* Rose and Zolnerowich (Hymenoptera: Aphelinidae)]; of leafminers [*Dacnusa sibirica* Telenga, *Diglyphus isaea* (Walker) (Hymenoptera: Eulophidae)]; of mites [*Phytoseiulus persimilis* Athias-Henriot, *Amblyseius cucumeris* (= *Neoseiulus cucumeris* (Oudemans) (Acari, Phytoseiidae), *Feltiella acarisuga* (Vallot) (Diptera, Cecidomyiidae)]; of aphids [*Aphidius ervi* Haliday, *Aphidius colemani* Viereck (Hymenoptera: Braconidae, Aphidiinae), *Aphelinus abdominalis* Dalman (Hymenoptera, Aphelinidae), *Aphidoletes aphidimyza* (Rondani) (Diptera: Cecidomyiidae), *Epysirphus balteatus* De Geer (Diptera: Syrphidae)].

BRAZIL

Production under protected cultivation is a relatively recent development in Brazil. The first initiatives took place around 1970's in the South and Southeast region, and nowadays are spreading all over the country. The total greenhouse area is about 2,500 ha and most of this area is used for production of ornamentals (60%). Tomato, lettuce and sweet pepper are among the main vegetables grown in greenhouses. Chrysanthemums and roses are the largest crops grown under protected cultivation for cut flower production. In these two flower crops the major pests are thrips, aphids and mites. Frequent sprays with pesticides (it is not uncommon to spray three times per week during the whole production cycle) result in quick development of resistance and in killing of the natural enemies, and are now also creating problems for the exportation of the products.

Studies are conducted with aphid parasitoids *Lysiphlebus testaceipes* (Cresson), *Aphidius colemani* Viereck and *Praon volucre* (Haliday) (Hymenoptera: Braconidae, Aphidiinae), and *Orius* species to control aphids and thrips in chrysanthemums and vegetables crops (Bueno *et al.* 2003; Rodrigues *et al.* 2001; Rodrigues *et al.* 2005; Silveira *et al.* 2004). All these species of natural enemies were found in Brazilian agro-ecossystems. We have set the following goals: (1) follow development of the pests and their native natural enemies in commercial greenhouses; (2) studies on biology, behavior and influence of environmental conditions on pests and natural enemies, (3) development of methods of mass rearing of the native natural enemies, and (4) release of natural enemies in commercial crops, including studies on release rates (Bueno 2005; Bueno *et al.* 2003).

For the aphid *Aphis gossypii* Glover (Hemiptera: Aphididae) and the thrips *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), both key pests in chrysanthemum, we have now developed satisfactory biological control. Control of *A. gossypii* populations was achieved by seasonal inoculative releases of the parasitic wasp *L. testaceipes.* The predator *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) showed to effectively control agent thrips in cut chrysanthemum in commercial greenhouses (Bueno *et al.* 2003; Silveira *et al.* 2004).

The development of biological control of lepidopteran pests [mainly *Tuta absolu*ta (Meirick) (Lepidoptera: Gelechiidae)] by seasonal inoculative releases of *Trichogramma pretiosum* (Riley) (Hymenoptera: Trichogrammatidae) is now evaluated in Brazil. Further, the control of mites (*Tetranychus* spp.) by *Phytoseiulus macropilis* (Banks) and *Neoseiulus californicus* (MacGregor) (Acari: Phytoseiidae) is currently tested.

CHILE

The greenhouse area in Chile is around 1,500 ha. Some experimental biological control programs have been developed in tomato crops where greenhouse whitefly, *Trialeurodes vaporariorum* Westwood (Homoptera: Aleyrodidae), is controlled with several *Encarsia* and *Eretmocerus* species, and a leafmining caterpillar, *Tuta absoluta* (Meirick), with a native egg parasitoid *Trichogramma nerudai* Pintureau and Gerding (Hymenoptera: Trichogrammatidae)

ECUADOR

The area of ornamentals under protected cultivation in Ecuador is about 1,200 ha. Ecuador together with Colombia provide the United States with 80% of its cut flower imports, and 70% of the flowers produced by Ecuador are exported to the USA. However the demand to apply ISO standards is creating problems for flower exportation by Ecuador. An IPM and biological control program of pests has been conducted in roses on about 10ha.

OTHER COUNTRIES

Bolivia has a growing commercial flower production in greenhouses. The greenhouse area in Argentina is around 1,000 ha. In both countries biological control is not yet applied, although development of biological control is being considered.

FACTORS LIMITING APPLICATION OF BIOLOGICAL CONTROL IN LATIN AMERICA

Several problems complicate the implementation of biological control in greenhouses in Latin America. These factors include the following:

1. Lack of commercial availability of natural enemies. There are only some producers and the production is limited to one or a few species of natural enemies.
2. Bureaucratic and time-consuming procedures concerning importation and release (quarantine regulations) of natural enemies that have shown to be effective elsewhere. Often legislation is not ready yet and under discussion.
3. The excessive use of pesticides pushed by aggressive marketing strategies of pesticides dealers, connected with the power of the chemical industry.
4. The wide variety of ornamental crops (> 300 species) and cultivars (can be > 100 per crop species) each demanding specific biological control/IPM programs.
5. Limited greenhouse technology. Greenhouse frames may be constructed of wood, which harbor pests and they are very difficult to clean. There are exceptions such as in Brazil, Colombia and Mexico.
6. Control of microclimatological conditions. Most climate control is limited to opening and closing of the greenhouses, the use of shade screens or whitewashing of the plastic. The mild climate outside enables pests to develop year around and pest pressure is, therefore, very high. Ventilation leads to continuous migration of organisms in and out of the greenhouse.
7. Lack of biological control and IPM technology transfer. An efficient exchange of information between university, institute and grower is often not available, and also extension services are often not well informed about IPM and biological control. Most of the growers in Latin America are often less specialized that those in e.g. Europe, but there are important exceptions such as in Brazil, Colombia and Mexico (van Lenteren and Bueno 2003).

FACTORS STIMULATING APPLICATION OF BIOLOGICAL CONTROL IN LATIN AMERICA

Although there are quite a number of factors frustrating the implementation of biological control in greenhouses in Latin America, there are the following positive factors for its development:

1. The most important stimulating factor is that there are many local natural enemy species available. For example, while doing the first biological control experiments in greenhouses, we found spontaneous invasion of natural enemies into the greenhouse, resulting in good control of the major pests (Bueno 1999; Bueno *et al.* 2003). This may mean that we can control most pests with native natural enemies, and, thus, prevent the problems related to import of exotic natural enemies (van Lenteren *et al.* 2003)

2. Recently, the commercial mass production of a number of natural enemies started in Latin America. With the availability of these natural enemies, biological control becomes a realistic option for pest control (Parra 2002)
3. For small scale farming, the money for chemical pesticides is usually not available, and farmers therefore appreciate the use of biological control.
4. The recent revival of the Neotropical Regional Section of IOBC may stimulate collaboration in this field, which then will result in easier access to and exchange of information about new natural enemies. The formation of an IOBC-NTRS working group on IPM in greenhouses might speed up development of biological control in greenhouses.

CONCLUSIONS

Greenhouses are of very different construction in Latin America, and this strongly affects pest development and control. Some greenhouses are very simple structures with hardly any possibilities for climate management, the growers are only part time involved in production and have other primary professions; the result is poor pest management and no interest in knowledge intensive biological control programs. Other greenhouses are of the same high technological quality as those in Europe, and have professional pest managers. With good education of these managers and growing availability of natural enemies, biological control is a realistic possibility.

The area with greenhouses is strongly growing in Latin America countries. Pest control is still mainly by chemical pesticides and several factors currently limit application of biological control. However, many native beneficial insects occur in Latin America and have proven to be good natural enemies for control greenhouse pests. The next step should be to stimulate research in this area and to develop greenhouse biological control networks in Latin America under the guidance of IOBC, so that the Latin American region can use the excellent knowledge developed earlier in Europe.

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AUGMENTATIVE BIOLOGICAL CONTROL IN GREENHOUSES: EXPERIENCES FROM CHINA

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ABSTRACT

To enhance biological control of insect pests in greenhouses, facilities and procedures for mass production of the parasitoids, *Eretmocerus* sp., *Encarsia formosa*, and *Trichogramma brassicae*, and the predator, *Aphidoletes aphidimyza* were successfully developed in Hengshui, Hebei province, China. Mass production of the aphelinid wasps was achieved by using different plant varieties and host insect species, as well as specific rearing procedures and techniques. Production of *T. brassicae* was greatly enhanced through the design of special devices and improved rearing techniques. Annual production of natural enemies in our institution reached 2 billion individuals. Biological control experiments conducted in sunlight greenhouses and plastic greenhouses allowed innovative techniques to be developed. Inoculative release techniques were established, including preparation before release, appropriate release time, release rate and special measures. Through experimental results and demonstrations, populations of aphelinid parasitoids and cecidomyid predators were able to establish and play very important roles in pest control on tomato, cucumber, and ornamental crops grown in greenhouses. Parasitism of the whiteflies, *Trialeurodes vaporariorum* and *Bemisia tabasi* was as high as 85% to 96%. Natural enemies released also effectively suppressed aphid populations on tomato and cabbage crops. Egg parasitism of the cabbage butterfly, *Pieris rapae*, and the cotton bollworm, *Helicoverpa armigera*, by *Trichogramma* wasps reached 78% to 95% on average. It was shown that natural enemies can suppress populations of target insect pests to below the economic threshold in greenhouse vegetable crops. When these techniques are combined with other non-chemical means of control for diseases and non-target insect pests, such as application of target specific fertilizers, augmentative biological control practices could greatly reduce the utilization of chemical pesticides, making non chemically-polluted vegetable products possible. A great economic benefit was acheived in 11,000 ha of biological control demonstration areas in Hebei, Beijing and Tianjin, by implementing the above augmentation biocontrol techniques from 2001 to 2004.

INTRODUCTION

As the most important method of vegetable production, greenhouses are becoming more and more prevalent in North China, and people are paying more attention to greenhouse pests.

Controlling greenhouse pests using chemical pesticides raises environmental concerns and can result in problems such as the development of resistance in pests. The use of biological control can overcome these problems while still providing adequate pest control.

ARTHROPOD PESTS AND THEIR NATURAL ENEMIES IN GREENHOUSES

The main arthropods that are greenhouse pests in North China are the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood), tobacco whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), cabbage aphid, *Brevicoryne brassicae* (L.) (Hemiptera: Aphididae), and several acarid species. There are also other pests in greenhouse, such as *Tetranychus urticae* Koch (Hemiptera: Tetranychidae), *Polyphagotarsonemus latus* Banks (Hemiptera: Hemisarcoptidae), *Liriomyza sativae* Blanchard (Diptera: Agromyzidae) and some coccids, etc. (Cheng 2002; He 1996; Qu *et al.* 2002; Shi *et al.* 1995; Zhang *et al.* 1997) These pests cause significant damage on the vegetables produced in these greenhouses.

There are many species of parasitic wasps that attack whitefly, including 34 from the genus *Encarsia*, 14 of the genus *Eretmocerus*, and several species of *Amitus* and *Metaphycus*. In China there are about 19 species of parasitic wasps which include *Encarsia formosa* Gahan, *Encarsia pergandiella* Howard and *Eretmocerus mundus* Mercet (Hymenoptera: Aphelinidae). Approximately 114 species (9 orders, 13 families) of whitefly predators are known to exist in China. Some of the most important of these are *Lygus pratensis* L. (Hemiptera: Miridae), *Chrysoperla sinica* Tjeder (Neuroptera: Chrysopidae) and several predatory mites (Zhang *et al.* 2003; 2004).

Some predators of greenhouse aphids were found to be: *Leis axyridis* Pallas, *Propylea japonica* Thunberg, *Coccinella septempunctata* L., *Adonia variegata* Coeze (Coleoptera: Coccinellidae), *Syrphus corollae* F., *Epistrophe balteata* De Geer, *Lasiopticus Pyrastri* L., *Sphaerophoria scripta* L. (Diptera: Syrphidae), *Aphidoletes apidimyza* Rondani (Diptera: Cecidomyiidae), *Eringonidium graminicolum* Sundevall (Araneae: Erigonidae), *Pardosa T-insignita* Boes *et* Str. (Araneae: Lycosidae), *Chrysopa sinica* Tjeder, *Chrysopa septempunctata* Wesmael, *Chrysopa formosa* Brauer (Neuroptera: Chrysopidae), *Hemerobius humuli* Linnaeus (Neuroptera: Hemerobiidae), *Nabis sinoferus* Hsiao, *Nabis stenoferus* Hsiao (Hemiptera: Nabidae), *Orius minutus* L. (Hemiptera: Anthocoridae), and *Deraeocoris punctulatus* Fall (Hemiptera: Miridae). Parasitoids that help control these greenhouse aphids include species from the hymenopteran families: Ichneumonidae, Braconidae, and Chalcidae. As well, a parasitic fungus (Chen 2002; Chinese Academy of Science (Zooscopy Institute) 1978; He *et al.* 1986; Liu 2000; Xia *et al.* 2004).

Non-parasitic natural enemies of phytophagous mites found in China include ladybird beetles, the anthocorid, *Phytoseiulus persimilis* Athias-Henriot (Acariformes: Phytoseiidae), and *Campylomma chinensis* Schuh (Hemiptera: Mirridae). It has been reported that *P. persimilis* successfully controls phytophagous mites both in its native habitat, and in other habitats abroad (Dong *et al.* 1986; Liang 2004; Yang *et al.* 1989).

Worldwide, arthropod natural enemies of thrips include species of Nabidae, Miridae, Anthocoridae, Sphecidae, Eulophidae, Trichogrammatidae, Mymaridae, Coccinellidae, Syrphidae, Dolichopodidae, Cecidomyiidae, Aeolothripidae, and some predatory mites (Ananthakrishnan 1973; Lewis 1973).

In China, there are few reports about the natural enemies of common thrips. Qing *et al.* (2004) found that predatory arthropods include *Campylomma chinensis*, *Cyrtorhinus lividipennis* Reuter (Hemiptera: Miridae), *Orius simillis* Zheng (Hemiptera: Anthocoridae), *Geocoris pollidipennis* F. (Hemiptera: Lygaeidae), *Scolothrips takahashii* Piesneer (Thysanoptera: Thripidae), some ladybird beetles, spiders, and ants. A total of 10 families and about 20 species of predators; among them, *C. chinensis* are the dominant natural enemies (Qing *et al.* 2004).

The known predatory arthropods of leaf miners include *Propylaea japonica*, *C. septempunctata*, *E. graminicolum*, and *P. T-insignita*. The parasitic wasps include *Opius spp.* and *Dacnusa spp.* (Lu *et al.* 2000); species of *Chrysocharis*, *Dacnusa*, *Diglyphus*, *Opius*, *Neochrysocharis*, *Hemiptarsenus* and *Halticoptera* are some of the more common parasitoids found to control leaf miner (Chen *et al.* 2001).

MASS-REARING OF BENEFICIALS IN CHINA

In recent years, techniques for mass-rearing beneficials have been developed and improved, to efficiently control major arthropod greenhouse pests. Several species can now be produced on a large-scale, and released in greenhouses in China. Beneficials such as *Trichogramma spp.*, *E. formosa*, *Eretmocerus spp.*, *P. persimilis* and *Aphidoletes apidimyza* have been successfully mass-produced by the Hengshui Tianyi Bio-control Company, Dryland Farming Institute.

TRICHOGRAMMA SPP.

In order to rear *Trichogramma spp.* with high selectivity to vegetable pests, *Sitotroga cerealla* eggs were used as host eggs. Several species, including *T. evanescens*, *T. pretisum*, *T. brassicae*, *T. embryophagum*, and *T. cacoaciae* can be mass-produced using this system. For mass-production of *S. cerealla* eggs, new production line and rearing techniques were developed. A specially made egg auto-collection machines were used and over 10 million eggs could be collected in 24 hours, provided there is an ample supply of emerged moths. Other equipment for use in moth rearing and egg purification was also developed by Hengshui Tianyi Bio-control Company in Hebei, China (Zheng 2003; 2004).

ENCARSIA FORMOSA AND *ERETMOCERUS* SP.

It is very important to find a proper variety of fod plants to feed to the insect hosts of both *Encarsia* and *Eretmocerus*. Since tobacco can be perennially cultured in greenhouses, varieties of tobacco were screened for their suitability as host plants for whitefly. Selection of these varieties ensures that sufficient numbers of whiteflies survive for a longer time, offering ample host accessibility to both *Encarsia* and *Eretmocerus*. Wasps oviposit into the young whitefly larvae, and when they develop to their pupal stage they are harvested. A special mass-production procedure of *Encarsia* and *Eretmocerus* has been developed by HTBC in Hebei, China (Zheng 2004).

APHIDOLETES APIDIMYZA

For mass rearing of *A. apidimyza*, insect hosts and their host plants were selected. The HTBC has also developed mass-rearing techniques of *A. Apidimyza* (Zheng 2004).

OTHER BENEFICIALS

Jiexian Jiang studied the mass-rearing and application of *Aphidius gifuensis*, and found that this parasitoid could be used to control the damage caused by aphids (Jiang *et al.* 2003). Although there are many natural enemies of aphids worldwide, only *A. apidimyza* has been reared on a large scale, and used in greenhouses.

It is very difficult to mass-rear ladybird beetles with artificial food. It has been reported however, that an artificial food diet, suitable for a female ladybird beetle to lay eggs on, has been successfully produced in China. An artificial diet for lacewings has also been successfully made, what's more, all stages of lacewing could develop on artificial eggs.

RELEASE OF BENEFICIALS AND BIO-CONTROL IN GREENHOUSES

PREPARATION BEFORE RELEASE

To satisfy the need for a controlled effect, some preparatory measures need to be taken before the release of natural enemies. These measures include: growing clean seedlings for transplanting, cleaning and sterilizing greenhouses for about 15 days and fixing screens on ventilation devices to prevent access by outside insects. The above precautions allow inoculative releases of beneficials to be successfully made after transplanting seedlings into greenhouses.

RELEASE OF *ENCARSIA FORMOSA* TO CONTROL WHITEFLY

These tiny wasps lay eggs inside the scales of developing whitefly larvae. The parasitoids then complete their development inside the whitefly larvae, killing the host in the process. Upon emergence, adults immediately begin to search for other larvae. Parasitized whitefly larvae are easy to recognize, as they will turn black over time.

When the average number of adult whitefly reaches 1000 in one greenhouse (about 0.05ha.), it is time to release *E. formosa*. The ratio of enemy versus adult pests is 3:1 (3000-5000 wasps per house). Wasps are introduced every 7-10 days, and after 3-4 releases, a balance is reached between wasps and whiteflies, and the introduction of the parasitoids to the greenhouse can be stopped. The temperature of the greenhouse containing the wasps should be controlled and maintained between 15-35 °C.

RELEASE OF *APHIDOLETES APIDIMYZA* TO CONTROL APHIDS

To control aphids successfully, *A. apidimyza* was introduced into the greenhouse before the aphid could damage the vegetables. These predators cripple the aphids by quickly injecting a paralyzing toxin, then sucking out the body fluid, leaving a shriveled aphid husk still attached to the leaf. When aphid numbers are high, they may kill many more aphids than they eat. Fully-grown predator larvae leave the plant to pupate in the soil.

If some wheat plants containing wheat aphid are brought into the greenhouse, *A. apidimyza* will survive on these aphids and the aphids will not feed on the greenhouse vegetables. As a result, initial aphid numbers can be controlled at low-density levels. At the first occurrence of aphids, *A. apidimyza* was released in the ratio of 1 larvae for every 20 aphids, and had a controlling effect after 2-3 continual releases.

RELEASE OF *TRICHOGRAMMA* SPP. TO CONTROL PESTS OF LEPIDOPTERA

In greenhouses without screen or ventilation, pests of *Lepidoptera* may seriously damage vegetables. In this case, *Trichogramma* spp. should be introduced. Several days after their introduction into the greenhouse, *Trichogramma* spp. wasps will emerge from parasitized eggs and seek out a new lepidopteran host.

RELEASE OF *PHYTOSEIULUS PERSIMILIS* TO CONTROL PHYTOPHAGOUS MITES

The predatory mite, *P. persimilis*, is a very good natural enemy to control phytophagous mites. To efficiently control these mites, the ratio between *P. persimilis* and phytophagous mites should be about 1:10 to 1:20. *P. persimilis* was released every 7-10 days, and after 3-4 weeks the number of phytophagy mites dropped notably (Dong *et al.* 1986; Li *et al.* 2004).

This predator does not feed on the plant or shrub and is fully dependent on the spider mite and its eggs for food. Generally, only one introduction of *P. persimilis* is required each season, because the predator population remains in low numbers once control is gained. To obtain optimal reproduction rates, the temperature of the greenhouse should be maintained between 21-27°C.

OTHER BIOLOGICAL CONTROL METHODS IN GREENHOUSES

PATHOGENIC FUNGI OF INSECT PESTS

Most pathogenic fungi used for the control of whitefly are Hyphomycetes including species of *Paecilomyces*, *Verticillium*, and *Aschersonia*. *Aschersonia aleyrodis* Webber (Sphaeropsidales: Sphaeriodaceae) is an important pathogenic fungus of whitefly and coccids, and much attention was given to *Paecilomyces fumosoroseus* Wize and *Verticillium lecanii* Zimmermann (Moniliales: Moniliaceae) (Xiao 2002; Zhang 2003; 2004).

There are 37 species of pathogenic fungus that can be used for the control of aphids. These are included within 9 genera of Entomophthorale and 7 genera of Hyphomycetes; among these, *Beauveria bassiana* Balsamo (Moniliales: Moniliaceae) and *V. lecanii* can also be used to control common thrips (Li *et al.* 2005; Qin *et al.* 2001).

BIOLOGICAL PESTICIDES

The main biological pesticides used in greenhouses today include *Bacillus thuringiensis* (Berliner) [*Bt*], abamectin, Azadirachtin and Polynactin. Athough pheromones were used to control pests during the 1960's, there are few reports on this topic. Due to the closed conditions within a greenhouse environment, kairomones that are produced by insect pests are not useful to many natural enemies. Some plants can produce metabolites such as terpene, alkene, alkaloid, lignin, steroid, flavone and polysaccharide, which can then be used to control greenhouse pests. Naturally occuring pesticides such as plecocidin, which is developed from plants, can be used in greenhouses to control pests and will not lead to environmental problems.

YELLOW BOARDS

The use of yellow boards within a greenhouse environment can efficiently monitor the effects of biological control efforts. Approximately 20 yellow boards are sufficient in one house, and when hung properly in greenhouses, can attract whiteflies, aphids and leaf miners.

GREENHOUSE CONDITIONS IN CHINA

Currently, the total greenhouse area in China is over 2 million ha. These all fall within three different categories:

Glasshouse. The glasshouse is the style of greenhouse that provides the optimal conditions for use with natural enemies. There are about 1300ha of glasshouse in China, making up no more than 0.1% of the total greenhouse area. The main advantage to using this type of greenhouse is the control one has over the environmental conditions through the use of heaters, fans and other devices. The temperature can be maintained above 15°C during the cold season and below 35°C during the hot season, and the humidity in these glasshouses can also be reduced or raised to an optimal level. Optimal control can easily be reached after the release of the beneficials into the glasshouse; however, much attention should be paid to monitoring the development of the insect pests while different crops with different growing seasons are harvested in the same house.

Cold plastic house. One of the most extensively used greenhouse styles in China is the cold plastic house. These are covered only by plasticand crops cannot be grown during the wintertime; instead crops are produced during two growing seasons. For the first season, crops are planted in spring and harvested in summer. Since pests are not a serious problem in spring, farmers usually neglect to control them at the beginning of planting. Farmers also pay little attention to the pests in the summer, since the vegetables are beginning to be harvested. For the second season, crops are planted in summer or the beginning of autumn, and it is at this time when high populations of pests occur. Most farmers grow seedlings without using effective pest prevention methods; as a result, many pests are easily transported from outside into the plastic house when vegetables are transplanted. These high populations of pests make control much more difficult when releasing natural enemies.

Warm plastic house. Another style of greenhouse, used most extensively in China, is the warm plastic house. A thick wall built on the north side of the house prevents penetration of the strong wind during cold winters, and allows crops to grow year-round. During most of the year, throughout each growing season temperature and humidity are satisfactory to release beneficial arthropods. It is only during the wintertime, because there is generally no heating temperature and humidity levels are unfavourable and the use of natural enemies is not possible.

In China, most of the greenhouses used are made of plastic, and are either a warm house or a cold house. To obtain efficient control of arthropod pests after the release of beneficials, we strongly suggest that farmers grow clean seedlings and use screen on the ventilation systems of their greenhouse, before applying biological control techniques.

With the improving demand for green food and the increasing greenhouse area, bio-control in greenhouses will have a more important place with regards to pest control and safe-food production. Improving bio-control and rearing measures will provide more efficient control over greenhouse pests.

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COMPATIBILITY CONFLICT: IS THE USE OF BIOLOGICAL CONTROL AGENTS WITH PESITICIDES A VIABLE MANAGEMENT STRATEGY?

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ABSTRACT

Biological control or the use of natural enemies is an alternative pest management strategy for dealing with arthropods. However, natural enemies may not always provide adequate control of plant-feeding insects and mites in greenhouses. As a result, research has assessed the concept of using natural enemies in conjunction with pesticides and the potential compatibility when both pest management strategies are implemented together. There are a variety of factors that influence the ability of using natural enemies with pesticides, these include whether the natural enemy is a parasitoid or predator, natural enemy species, life stage sensitivity, rate of application, timing of application, and mode of action of a particular insecticide or miticide. Pesticides may impact natural enemies by affecting longevity (survival), host acceptance, sex ratio, reproduction (fecundity), foraging behavior, percent emergence, and development time. In our studies, we have found a number of pesticides to be compatible with the natural enemies of the citrus mealybug, *Planococcus citri* and fungus gnats, *Bradysia* spp. For example, we have demonstrated that foliar and drench applications of the insecticides novaluron and pyriproxyfen, and the fungicides fosetyl-Al and mefenoxam to be compatible with the predatory mite, *Stratiolaelaps scimitus*. We have also shown that the insecticides azadirachtin and pyriproxyfen are compatible with the citrus mealybug parasitoid, *Leptomastix dactylopii*. Additionally, the insecticides buprofezin, pyriproxyfen, and flonicamid were not harmful to the adult stage of the mealybug destroyer, *Cryptolaemus montrouzieri*. Despite the emphasis on evaluating the compatibility of natural enemies with pesticides, it is important to assess if this is a viable and acceptable pest management strategy in greenhouses.

INTRODUCTION

Biological control or the use of natural enemies such as parasitoids, predatory mites, predatory bugs, and/or beneficial bacteria, fungi, and nematodes is an alternative strategy to manage greenhouse pests (Van Driesche and Heinz 2004). However, the sole use of biological control may not always be sufficient to control plant-feeding insect or mite populations in greenhouses (Medina *et al.* 2003). As a result, research within the last 5 to 10 years has investigated the possibility of using so-called “biorational” or “reduced risk” insecticides or miticides in conjunction with biological control agents (=natural enemies) to determine if there is compatibility when both management strategies are implemented together. Those insecticides and miticides that are classified as biorational or reduced risk include insect growth regulators, insecticidal soaps and horticultural oils, and microbials including beneficial bacteria and fungi, and related compounds.

If a given insecticide or miticide kills a particular target pest or pests, why would it not kill a natural enemy? It is equally important to define what is meant by “compatibility?” Biorational insecticides and miticides are considered to be more selective to natural enemies and potentially more compatible than most conventional insecticides and miticides because they are active on a broad range of target sites or systems (Croft 1990). In fact, several commercially available biorational insecticides/miticides state that their products are not disruptive to beneficial insects and mites. However, research conducted worldwide has shown that biorational insecticides/miticides may in fact be harmful to certain natural enemies. Although biorational insecticides/miticides may not be directly toxic to a particular natural enemy there may be indirect effects such as delayed development of the host and natural enemy inside, delayed adult emergence, and/or decreased natural enemy survivorship (Croft 1990). In general, the harmful effects of biorational insecticides and miticides may be due to direct contact, host elimination, residual activity, or sublethal effects (Parrella *et al.* 1999):

Direct contact: directed sprays of biorational insecticides/miticides may kill natural enemies or in the case of parasitoids they are killed while in developing hosts.

Host elimination: biorational insecticides/miticides may kill hosts, which may lead to natural enemies dying or leaving because they are unable to locate additional hosts.

Residual activity: although spray applications of biorational insecticides/miticides may not directly kill natural enemies, any residues may have repellent activity thus influencing the ability of parasitoids or predators to locate a food source.

Sub-lethal effects: biorational insecticides/miticides may not directly kill a natural enemy, but may affect reproduction such as sterilizing females, reducing the ability of females to lay eggs or impact the sex ratio (number of females vs. males). Additionally, foraging behavior may be modified thus influencing the ability of a parasitoid or predator to find a host (Elzen 1989). Also, those parasitoids that host feed such as the greenhouse whitefly parasitoid, *Encarsia formosa* may inadvertently consume residues on hosts after a spray application. Residues on a potential host may make them unacceptable to a parasitoid or predator.

Differences in natural enemy susceptibility to biorational insecticides/miticides may be due to a number of factors including 1) whether the natural enemy is a parasitoid or predator, 2) species of natural enemy, 3) life stage (i.e., egg, larva, pupa, and adult) sensitivity, 4) developmental stage of host, 5) rate of application, 6) timing of application, and 7) type or mode of action of biorational insecticide or miticide used. All these differences are complex primarily due to the interactions that may occur among the factors mentioned above and the variability in natural enemy sensitivity. Further complicating the "picture," the harmful effects from biorational insecticides/miticides may not be associated with the active ingredient but due to inert ingredients such as carriers or solvents (Cowles *et al.* 2000).

Biorational insecticides/miticides are generally more specific in pest activity and more physiologically sensitive to natural enemies than conventional insecticides/miticides (Croft 1990). A number of biorational insecticides/miticides used in greenhouses have been evaluated for both their direct and indirect effects on natural enemies. Below are descriptive examples, based on studies, on the compatibility of biorational insecticides and miticides with various natural enemies.

EFFECTS OF PESTICIDES ON NATURAL ENEMIES

INSECT GROWTH REGULATORS

The insect growth regulators that have been evaluated for both their direct and indirect effects on natural enemies include the juvenile hormone mimics pyriproxyfen, and kinoprene; the chitin synthesis inhibitors diflubenzuron and buprofezin; and the ecdysone antagonists tebufenozide and azadirachtin.

Pyriproxyfen. Pyriproxyfen, in laboratory studies, is non-toxic or harmless to the larval and adult stages of the green lacewing, *Chrysoperla carnea* (Medina *et al.* 2003) and predatory bugs, *Orius* spp. with no harmful effects on adult female oviposition and egg viability (Nagai 1990). Pyriproxyfen is also non-toxic to the predatory bug, *Orius laevigatus* via ingestion and residual contact (Delbeke *et al.* 1997). Although harmless to certain predatory insects, pyriproxyfen is toxic to immature parasitoids developing inside the silverleaf whitefly, *Bemisia argentifolii* nymphs (Hoddle *et al.* 2001). Natural enemy species may influence compatibility as demonstrated with pyriproxyfen, which appears to be harmless to *Eretmocerus eremicus* (Hoddle *et al.* 2001) and *Encarsia pergandiella*, but is highly toxic to *Encarsia formosa* (Liu and Stansly 1997).

Kinoprene. This insect growth regulator is consistently harmful to certain natural enemies, especially parasitoids. As mentioned above, the rate used may influence natural enemy susceptibility. For example, kinoprene reduces adult emergence of the leafminer parasitoid, *Opius dimidiatus* (Lemma and Poe 1978) and the aphid parasitoid, *Aphidius nigripes* (McNeil 1975) at all rates tested. Applications of kinoprene may inhibit adult emergence when applied to hosts containing the larval and pupal stages of certain parasitoids (McNeil 1975). It has been shown that kinoprene is extremely toxic to the aphid parasitoid, *Aphidius colemanii* when exposed to directed sprays and one-day old residues (Olson and Oetting 1996). Furthermore, kinoprene-treated poinsettia (*Euphorbia pulcherrima*) leaves are harmful to the silverleaf whitefly parasitoid, *Eretmocerus eremicus* six and 96 hours after treatment (Hoddle *et al.* 2001). Although harmful to parasitoids, kinoprene is less toxic to certain predators and different life stages. For example, applications of kinoprene did not negatively affect ladybird beetle eggs (Kismali and Erkin 1984).

Diflubenzuron. Diflubenzuron has minimal impact on natural enemies when applied either directly or indirectly under laboratory conditions. However, the life stage (egg, larvae, pupae, and adult) treated influences the effects of this chitin synthesis inhibitor. For example, diflubenzuron is harmful to the early larval stages of green lacewing (*Chrysoperla carnea*) whereas later larval stages are not affected (Medina *et al.* 2003; Niemczyk *et al.* 1985). It has been demonstrated that the young larvae of the mealybug destroyer, *Cryptolaemus montrouzieri* when treated with diflubenzuron fail to develop into adults whereas diflubenzuron has minimal impact on the citrus mealybug parasitoid, *Leptomastix dactylopii* (Mazzone and Viggiani 1980).

Buprofezin. Buprofezin is toxic to the larval stage of predatory ladybird beetles whereas it is less toxic to adult ladybird beetles (Smith and Papacek 1990), although it may have a sterilizing effect on some species (Hattingh and Tate 1995). Buprofezin is less harmful to other predators as demonstrated in a laboratory study where applications of buprofezin did not negatively effect the development (nymph to adult) of the predatory bug, *Orius tristicolor* (James 2004). In general, buprofezin is less toxic to parasitoids (Jones *et al.* 1998). For example, buprofezin does not effect oviposition of the two whitefly parasitoids, *Eretmocerus* sp., and *Encarsia luteola* when the young or adults are exposed to spray residues. Additionally, buprofezin has no effect on the foraging behavior of adult *Eretmocerus* sp. (Gerling and Sinai 1994).

Tebufenozide. In laboratory studies, tebufenazide is harmless to the green lacewing, *Chrysoperla carnea* (Medina *et al.* 2003). This insect growth regulator, which is primarily used against caterpillar larvae, does not affect adult green lacewing female reproduction (Medina *et al.* 2003).

Azadirachtin. Azadirachtin applications have been shown to negatively affect green lacewing, *Chrysoperla carnea* females by inhibiting oviposition (Medina et al. 2003). However, in a large-scale laboratory study, applications of azadirachtin were not toxic to the egg and adult stages of the predatory mites *Phytoseiulus persimilis* and *Amblyseius cucumeris* when exposed to treated bean leaves (Spollen and Isman 1996). Studies have also shown that the number of eggs laid by the aphid predator, *Aphidoletes aphidimyza* are not negatively affected by azadirachtin (Spollen and Isman 1996).

INSECTICIDAL SOAP AND HORTICULTURAL OIL

Direct spray applications (wet sprays) and short-term residues of insecticidal soap and horticultural oil are toxic to most natural enemies, especially parasitoids. However, once the residues have dissipated they are less harmful. Studies with the western flower thrips predatory mite, *Neoseiulus* (=*Amblyseius*) *cucumeris* have indicated that this mite is more sensitive to horticultural oil than insecticidal soap (Oetting and Latimer 1995). Direct applications of horticultural oil are harmful to the predatory mite, however, 1 to 2% concentrations have been shown to be less toxic. Although insecticidal soap appears to be minimally harmful to the predatory mite, sprays of a 4% insecticidal soap have been shown to be very toxic (90% mortality after 48 hours) (Oetting and Latimer 1995). Direct spray applications of insecticidal soap are extremely toxic to the twospotted spider mite predatory mite, *Phytoseiulus persimilis* (100% mortality), whereas there are no harmful effects 3 days after release (Osborne and Petitt 1985).

BACTERIA

In general, sprays of *Bacillus thuringiensis* (*Bt*) are safe to most predators including ladybird beetles, green lacewing, and certain predatory bugs. However, initial sprays may delay the development of certain natural enemies. The effects of *Bt* on the different life stages of natural enemies have been shown to be highly variable (Croft 1990). Additionally, the effects of *Bt* may take longer to impact natural enemies compared to other biorational insecticides. It appears that the larval stage of certain natural enemies such as green lacewing (*Chrysoperla* sp.) and ladybird beetles are more susceptible to *Bt* sprays than adults (Kiselek 1975). It is important to note that any lethal or sub-lethal effects may not be directly caused by the bacteria, but indirectly by altering the available food source or killing hosts before they complete development (Marchal-Segault 1975).

FUNGI

Entomopathogenic fungi vary in how they impact natural enemies depending on whether natural enemies consume spores or they are directly affected by sprays. Natural enemies may ingest fungal spores when either grooming (cleaning themselves) or when feeding on a contaminated host or food source. The fungi *Metarhizium anisopliae* and *Beauveria bassiana* can infect and harm ladybird beetles, depending on the concentration. Direct sprays of *M. anisopliae* and *B. bassiana* results in 97% and 95% mortality, respectively of adult ladybird beetles. However, the severity of the effect is very much dependent on the concentration of spores applied (James and Lighthart 1994). Applications of entomopathgenic fungi may indirectly affect predators that feed on hosts that have been sprayed. For example, 50% of mealybug destroyer (*Cryptolaemus montrouzieri*) larvae died when they consumed mealybugs that were sprayed with a *B. bassiana* product. However, the product was harmless to the adult (Kiselek 1975). Direct applications of the fungus, *Cephalosporium lecanii* had no impact on the longevity of the leafminer parasitoid, *Diglyphus begini* (Bethke and Parrella 1989). In contrast, direct sprays of this same fungus were shown to be harmful to the aphid parasitoid, *Aphidius matricariae* (Scopes 1970) and the greenhouse whitefly parasitoid, *E. formosa* (Ekbom 1979).

SPINOSAD

The impact of spinosad on natural enemies has been extensively studied since its introduction. It has been demonstrated that direct applications (wet sprays) of spinosad are extremely harmful to parasitoids including *Aphidius colemani* and *E. formosa*, however, any toxic effects generally decrease as the spray residues age (Miles *et al.* unpublished). Spinosad applications have been shown to be toxic to the eggs of *Trichogramma* spp. parasitoids and the larval stage (Consoli *et al.* 2001). Applications of spinosad have exhibited toxic effects to *E. formosa* and *Orius laevigatus* shortly after treatment—but populations of both were not seriously affected after 2 to 3 weeks. Spinosad has been shown to not harm the larval stage of the aphid predatory midge, *Aphidoletes aphidimyza* (Miles *et al.* unpublished).

Spinosad appears to be very compatible with many predatory insects and mites. Studies have demonstrated that spinosad has no direct or indirect negative affects to green lacewing (*Chrysoperla carnea*) (Medina *et al.* 2001), ladybird beetle (*Hippodamia convergens*), minute pirate bug (*Orius laevigatus*), big-eyed bug (*Geocoris punctipes*), and damsel bug (*Nabis* sp.) (Thompson *et al.* 2000). Spinosad has also been shown to not directly harm predatory mites including *Amblyseius californicus*, *P. persimilis*, *A. cucumeris*, and *Hypoaspis miles* at the rates tested (Miles *et al.* unpublished).

UNIVERSITY OF ILLINOIS RESEARCH

A major part of our research effort at the University of Illinois is to assess the compatibility of commercially available insecticides and miticides with natural enemies. For example, we have conducted several studies to test the direct and indirect effects of insect growth regulators on the natural enemies of fungus gnats and mealybugs. In our research, we found that foliar and drench applications of the insect growth regulators novaluron and pyriproxyfen were not directly or indirectly harmful to the soil-predatory mite, *Stratiolaelaps scimitus* (Cabrera *et al.* 2004; Cabrera *et al.* 2005). We have also demonstrated that azadirachtin is safe to use with the citrus mealybug parasitoid, *Leptomastix dactylopii*. Pyriproxyfen was found to be slightly toxic whereas both direct and indirect applications of kinoprene were extremely toxic to this parasitoid (Rothwangl *et al.* 2004). We have also demonstrated that applications of the insecticides buprofezin, pyriproxyfen, and flonicamid are not harmful to the adult stage of the mealybug destroyer, *C. montrouzieri* (Cloyd and Dickinson, unpublished data)

CONCLUSIONS

It is important to note that many studies are conducted under laboratory conditions, which represents a “worse-case scenario” and that if there are no harmful effects under these conditions then it is likely that the biorational insecticide or miticide will not be harmful when used in the greenhouse. In addition, the concentration or rate also influence whether biorational insecticide/miticide will negatively impact natural enemies. In order to avoid any harmful effects to natural enemies it is recommended to make releases several days after an application although applying biorational insecticides or miticides may still decrease host quality thus increasing parasitoid or predator mortality. For example, parasitoid females may not lay eggs in un-suitable hosts and predators may not consume hosts that are an inadequate food source (=poor quality). Applications of biorational insecticides/miticides may also kill a majority of the hosts thus reducing the amount available for natural enemies. Finally, the fact that many biorational insecticides and miticides may need to be applied frequently (depending on the pest population) in order to obtain sufficient control of insect or mite pests increases the likelihood that natural enemies will be exposed to sprays or spray residues, which may have a deleterious effect on foraging behavior or reproduction.

It is apparent that there is variability in the compatibility of natural enemies to biorational insecticides/miticides based on the type of biorational insecticide or miticide, whether the natural enemy is a parasitoid or predator, and stage of development. Biorational insecticides/miticides are effective for controlling many different types of greenhouse pests and are generally less harmful to natural enemies than conventional insecticides/miticides, which suggest that they are more likely to be compatible with natural enemies. However, it is important to know which biorational insecticide/miticide is compatible or not compatible with natural enemies in order to avoid disrupting successful biological control programs.

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BIOLOGICAL CONTROL OF WHITEFLIES AND WESTERN FLOWER THRIPS IN GREENHOUSE SWEET PEPPERS WITH THE PHYTOSEIID PREDATORY MITE *AMBLYSEIUS SWIRSKII* ATHIAS-HENRIOT (ACARI: PHYTOSEIIDAE)

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ABSTRACT

Currently, western flower thrips (*Frankliniella occidentalis*) is controlled in greenhouse sweet peppers with the phytoseiid predatory mite *Amblyseius cucumeris*, the anthocorid flower bug *Orius laevigatus* and the phytoseiid mite *Iphiseius degenerans*. Whiteflies (*Trialeurodes vaporariorum* and *Bemisia tabaci* are controlled by releasing parasitoids and mirid bugs (Miridae).

Cage trials and trials in commercial greenhouse crops with the phytoseiid predatory mite *Amblyseius swirskii* (Athias-Henriot, 1962) have shown a high efficacy against *Frankliniella occidentalis* and against *Bemisia tabaci* in sweet peppers. When the predatory mites were released preventively on flowering sweet pepper plants in a greenhouse in the Netherlands the establishment of *Amblyseius swirskii* was successful. In all trials *Amblyseius swirskii* has shown a very high numerical response to the presence of prey. Biological control of whiteflies with phytoseiid predatory mites, which can be economically reared in large quantities, might be a major step forwards for biological control in greenhouse crops, especially in areas with high whitefly and thrips populations such as Southern Europe.

INTRODUCTION

The greenhouse whitefly, *Trialeurodes vaporariorum*, and the tobacco whitefly, *Bemisia tabaci*, are major pests in greenhouse crops. In commercial greenhouses whiteflies are mainly controlled by releases of the parasitoids *Encarsia formosa* and *Eretmocerus eremicus* against *T. vaporariorum* and *Eretmocerus mundus* against *B. tabaci*. Whitefly parasitoids are not able to establish in a greenhouse when released preventively. Mirid bugs (Miridae) such as *Macrolophus caliginosus* Wagner are expensive and their use is limited to greenhouse tomatoes. Therefore, a biological control agent which is able to establish in a crop before whiteflies enter the greenhouse would be a supplement to the system.

Nomikou *et al.* (2003) showed that the phytoseiid mite *Amblyseius swirskii* (Athias-Henriot), predates on eggs and crawlers of *B. tabaci* and develops well on this prey. Since the late 1980's the predatory mites *Amblyseius cucumeris* is successfully used for control of Western Flower Thrips (*Frankliniella occidentalis*) in greenhouse cucumbers, sweet pepper, eggplants and a large range of greenhouse ornamentals. Although very effective in winter crops in greenhouses in Southern Europe *A. cucumeris* appears not very effective in summer crops. This might be caused by the high temperatures in combination with low humidity conditions during summer. *Iphiseius degenerans* is more adapted to the conditions of the Mediterranean and has proven to be an effective thrips predator in greenhouses in Northern Europe, but this predator is difficult to rear in large quantities. Messelink and Steenpaal (2003) and Messelink *et al.* (2005) showed that *A. swirskii* is a very effective predator of Western Flower Thrips in greenhouse cucumbers. Also in greenhouse trials against greenhouse whiteflies on cucumbers, excellent control was achieved (Messelink, pers. comm.). *A. swirskii* is a common predatory mite in the eastern part of the Mediterranean. The mites used in the following studies have been collected in Israel.

PREDATION AND OVIPOSITION RATE

Rates of predation and oviposition on a diet of thrips larvae were determined according to the method described by van Houten *et al.* 1995. Leave discs of cucumbers (4.5 cm^2) were placed upside down on pads of moist cotton wool, in a climate room at L16:D8, 25° C and 70% relative humidity. Single gravid female mites were placed on each leaf disc. The mites originated from cohorts of young nymphs of the same age which were reared on a diet of cattail pollen (*Typha latifolia*). At the start of the experiment the mites had been laying eggs for 2 days.All leave discs were infested with 12 first instar *F. occidentalis*. During four days the predators were transferred each day to fresh leave discs with 12 newly emerged thrips larvae. It was ascertained that the number of live prey never dropped below 6 per disc. Number mite eggs and killed thrips were assessed daily. Data of the first day were omitted from calculations of predation and oviposition rates. A total of eleven female predatory mites were assessed.

Using the same protocol, 10 gravid female predatory mites were assessed for there oviposition rate when fed with eggs of greenhouse whiteflies (*Trialeurodes vaporariorum*). Each day the predatory mites were transferred to fresh cucumber leaves with eggs of *T. vaporariorum*.

Table 1. Rates of predation and oviposition of *Amblyseius swirskii* on a diet of first instar *F. occidentalis* larvae and *T. vaporariorum* eggs, on cucumber leaf discs (4.5 cm^2 at 25°C and 70% r.h. Predation rate: mean number of larvae killed per female, per day. Ovipostion rate: mean number of eggs laid per female per day. N= number of predatory females; s.e= standard error.

Prey species	N	Predation rate (mean ± s.e.)	Oviposition rate (mean ± s.e.)
F. occidentalis	11	4.9 ± 0.3	2.1 ± 0.2
T. vaporariorum	10	-	2.3 ± 0.1

DIAPAUSE

Diapause experiments were performed according to the method described by van Houten *et al.* 1995. Predatory mites were reared on small plastic arena's (8 x 10 cm) placed on pads of moist cotton. A small roof (2 x 2 cm) made from a piece of transparent plastic was placed on the arena to provide shelter and as an oviposition site. The arena's were provided every second day with fresh cattail pollen and with purple pollen of the iceplant (*Mesembryanthemum* sp.). Iceplant pollen contains ²-carotene. In the absence of ²-carotene in their diet, some mite species do not respond to photoperiod or thermoperiod. Another advantage of the purple iceplant pollen is that egg production by individual non-diapausing females can easily be determined, as the white egg stands out clearly against the surrounding purple intestines. Pollen was provided by dusting it on the arena with a small brush. The colonies were kept in a climate room at 25°C, 70% relative humidity and L16:D8

A cohort of eggs, from 0-16 h after deposition was transferred to a new rearing unit in a climate cabinet under diapause inducing conditions of 19°C, 70% relative humidity and L10:D14. Once the eggs have hatched, 30 young females were carefully transferred to a unit identical to the rearing units and placed in a climate cabinet under diapause inducing conditions of 19°C, 70% relative humidity and L10:D14. It was ensured that ample males were present for insemination of the females. When no egg was seen in a female it was concluded that this female would not lay eggs and, hence, was in a state of reproductive diapause. The female mites with a visible egg were removed. If no egg was seen in a female within 3 days, the conclusion was that it had entered a reproductive diapause.

All 30 female mites were ovipositing. This proves that under the conditions of 19°C, 70% r.h. and L10:D14 this strain of *Amblyseius swirskii* is non-diapausing.

DROUGHT TOLERANCE

The influence of relative humidity on egg-hatching was examined in closed plastic boxes (18 x 14 x 9 cm) at 25°. Eggs from 0-16 h after deposition were transferred to small plastic arena's and floated on different supersaturated salt solutions. Three different relative humidities were obtained by using supersaturated salt solutions of $Ca(NO3)2$ (50.5% r.h.), KI (69% r.h.) and NaCl (75% r.h.) (Winston and Bates 1960).

Table 2. Egg survival of *Amblyseius swirskii* at different relative humidities at 25°C. N= number of eggs.

Salt solutions	Relative humidity	N	Eggs hatched
Ca(NO3)2	50.5%	154	3%
KI	69%	251	45%
NaCl	75%	160	84%

ESTABLISHMENT OF *AMBLYSEIUS SWIRSKII* IN SWEET PEPPERS

A field trial was conducted in a 7,000 m² commercial sweet pepper crop (var. Derby) in the Netherlands. The goal of this trial was to verify if *A. swirskii* is able to establish in a sweet pepper crop in the absence of prey with only plant pollen as food. When the trial started the plants were flowering, 80cm high and free from pests. *A. swirskii* was released in a plot of 1,500 m². The predatory mites were released in weeks 7 and 10 at a rate of 25 individuals per m² per release. Other natural enemies which were released in the entire greenhouse are: *Orius laevigatus*, *E. mundus*, *Phytoseiulus persimilis* and *Aphidius ervi*. Observations were done every other week. Per observation 50 leaves from the higher part of the plants and 25 flowers were chosen randomly. The number of *A. swirskii, B. tabaci* and *O. laevigatus* was assessed.

A. swirskii established well. On the leaves a population of 4 to 5 predatory mites (all stages together) per leaf was reached within 4 weeks and remained at that level until the end of the trial (Fig. 1). In the flowers the *A. swirskii* population reached a peak of 3 predatory mites per flower 10 weeks after the last introduction, but afterwards the population decreased, probably due to the presence of *O. laevigatus* in the flowers (Fig. 2).

The pest level remained low throughout the entire trial period. *F. occidentalis* was not observed at all and *B. tabaci* was found at a level of 1 or 2 individuals per 50 leaves. The only pest which was found frequently was *Tetranychus urticae* Koch at an incidence between 0 – 12% of the leaves.

Despite low pest levels, *A. swirskii* remained present on the plants throughout the season which indicates that *A. swirskii* can be released preventively in a sweet pepper crop. The establishment, speed of population development and persistence in the crop are much better than for *Amblyseius cucumeris.*

BIOLOGICAL CONTROL OF *BEMISIA TABACI* WITH *AMBLYSEIUS SWIRSKII*

A semi field trial was conducted in an 400 m2 experimental plastic tunnel in Aguilas, Spain starting at the end of May until the end of July. The plastic tunnel was divided by 50 mesh screens in 6 compartments of 8 m². 10 poorly flowering sweet pepper plants of 50cm height were planted in each compartment at the start of the trial. *A. swirskii* was released in 3 compartments while the other 3 remain untreated (3 replicates per treatment). *B. tabaci* was released in all compartments. The release schedule is shown in table 3.

To assess the *A. swirskii* and *B. tabaci* population, 3 leaves (top, middle and bottom) from 5 plants per compartment were randomly chosen and observed weekly. All stages of *A. swirskii* and *B. tabaci* were counted separately.

A. swirskii managed to keep the *B. tabaci* population low in all compartments where this predatory mite was released, while in the untreated compartments the *B. tabaci* population increased rapidly. (Fig. 3)

A. swirskii established in all 3 compartments where it was released. After some weeks the first *A. swirskii* was also found in the untreated control cages and the population increased very rapidly. (Fig. 4)

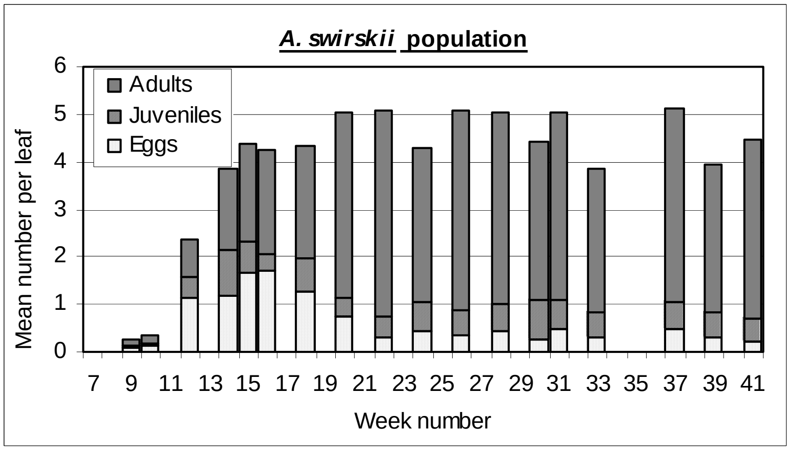

Figure 1. Mean number of *A. swirskii* per leaf. (n = 50).

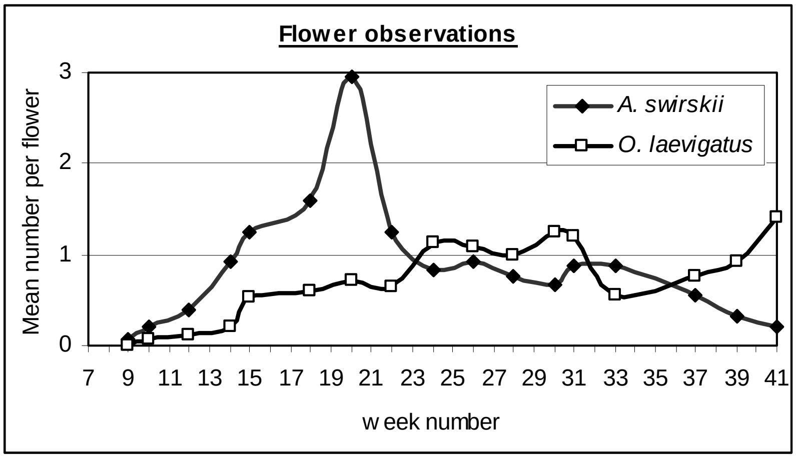

Figure 2. Mean number of *A. swirskii* and *O. laevigatus* per flower. (n = 25).

Table 3. Release schedule (number of adults released per plant) per treatment.

	Day 0		Day 6		Day 7		Day 14	
Treatment	*B.tab.**	*A.swi.**	*B. tab.*	*A. swi.*	*B. tab.*	*A. swi.*	*B. tab.*	*A. swi.*
A. swirskii	2	-	-	80	2	-	4	-
Untreated control	2	-	-	-	2	-	4	-

**B. tab.* = *B. tabaci* and *A. swi.* = *A. swirskii*.

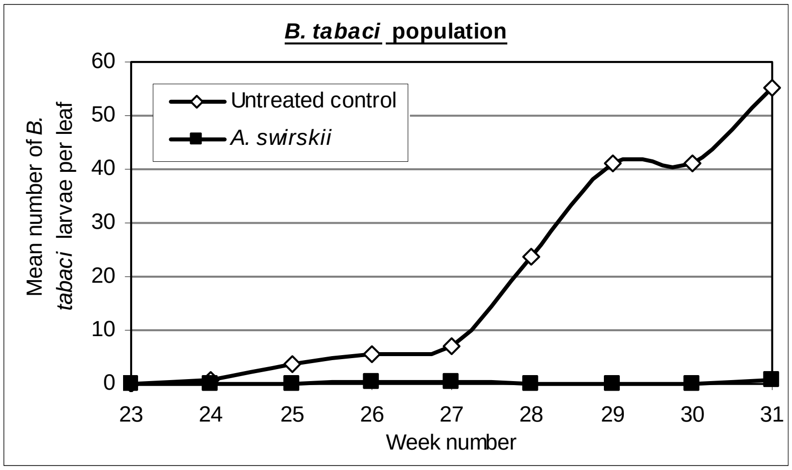

Figure 3. Mean number of *B. tabaci* larvae per leaf. Average of 15 leaves per compartment and 3 compartments per treatment.

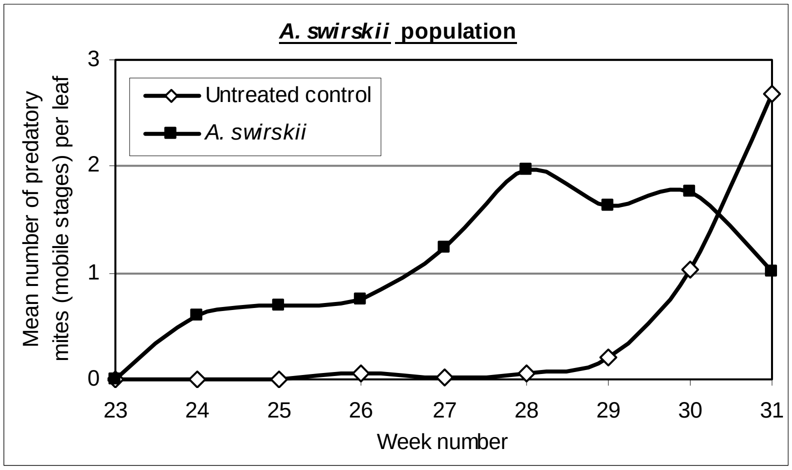

Figure 4. Mean number of *A. swirskii* (mobile stages) per leaf. Average of 15 leaves per compartment and 3 compartments per treatment.

COMPARISON OF FOUR PREDATORY MITE SPECIES AGAINST WESTERN FLOWER THRIPS

This experiment was carried out in 23 walk-in cages of 100 m^2, each cage having 1 row of 13 sweet pepper plants. When the plants had started to flower the western flower thrips and predatory mites were released in the numbers as shown in table 4. The trial was done in the summer period. The maximum day temperature was between 28-30°C with peaks up to 40°C. To monitor thrips and predator populations, samples of 30 leaves and 10 flowers were taken every week.

Iphiseius degenerans and *A. swirskii* established more successfully than *A. cucumeris* and *A. andersoni* (Fig. 5). *Iphiseius degenerans* performed best: the predator population increased rapidly and reached higher densities than *A. swirskii*, particularly in the flowers but also on the leaves,.

The thrips population in the flowers at the last counting is presented in figure 6. *Amblyseius swirskii* was most succesfull in thrips control, followed by *A. cucumeris* released by means of a slow-release breeding sachet, *I. degenerans, A, andersoni* and *A. cucumeris,* in descending order.

Table 4. Release rates of predatory mites and thrips in 23 different cages.

Predatory Mite Species	**Release rate of predatory mites per plant in wk 24**	**Release rate of *F. occidentalis* per plant in wk 23, 24, 25, and 26 per cage**	**Number of Replicates**
A. swirskii	30 females	(4 x) 2 females	4
A. andersoni	30 females	,,	4
A. cucumeris	30 females	,,	3
A. cucumeris	1 sachet	,,	4
I. degenerans	30 females	,,	4
Control	-	,,	4

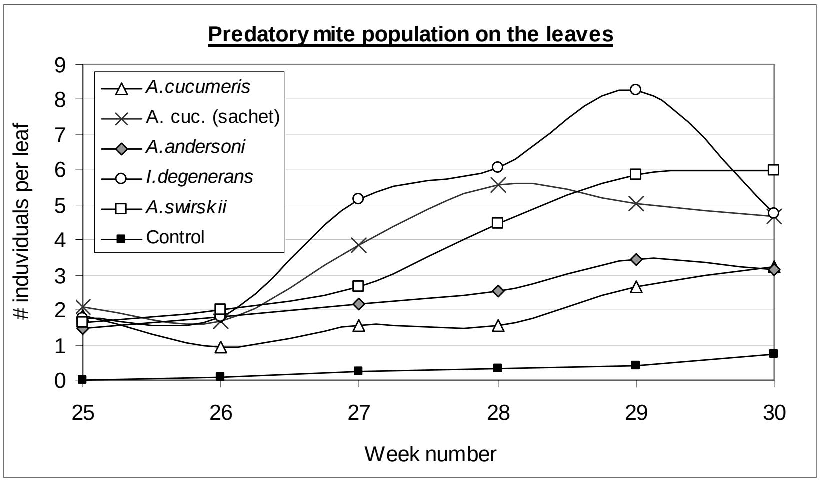

Figure 5. Population fluctuations of 4 predatory mite species on leaves of sweet pepper plants in 23 greenhouses.

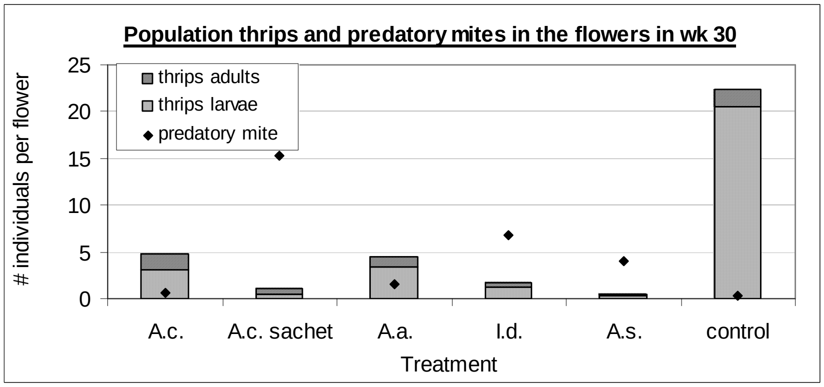

Figure 6. Mean numbers of *F. occidentalis* and 5 predatory mite species in flowers of sweet pepper plants in 23 greenhouses. Ac. = *A. cucumeris,* Aa. = *A. andersoni,* Id. = *I. degenerans,* As. = *A. swirskii* and Ac. sachet = a slow release sachet with *A. cucumeris.*

COMPARSION OF *A. SWIRSKII* AND *A. CUCUMERIS* FOR THRIPS CONTROL

This experiment was performed in 4 cages (3x1x2 m) in an experimental greenhouse. 5 flowering sweet pepper plants of 60 cm height were placed in each cage. Releases of 1 *A. swirskii* per leaf were compared with releasing either 1 *A. cucumeris* per leaf or 3 releases of 10 *A. cucumeris* per leaf at weekly interval. The latter treatment simulates the effect of using slow-release breeding sachets, which is standard practice when releasing *A. cucumeris.* To monitor western flower thrips and predator populations, 5 leaves and 1 flower per plant (25 leaves and 5 flowers per cage) were monitored every week from day 13 onwards.

The cage experiment showed that even when *A. swirskii* was released in dosage 30 times lower than *A. cucumeris*, the establishment of *A. swirskii* was better (Fig. 7). The impact of both predators on the thrips population at these release rates was comparable. Based on these results, *A. swirskii* can be regarded as a promising candidate for thrips control in sweet pepper.

Table 5. Release rates of predatory mites and western flower thrips in 4 different cages.

Predatory mite species	Release rate of predatory mites per cage (number/ leaf)	Release rate of *F. occidentalis* per cage
cage 1: *A. swirskii*	150 adults (1/leaf) on day 6	(3 x) 10 females (day 0, 7, 14)
cage 2: *A. cucumeris*	150 adults (1/ leaf) on day 6	,,
cage 3: *A. cucumeris*	3x 1500 adults (3x10/leaf) day 6, 13, 20	,,
cage 4: control	-	,,

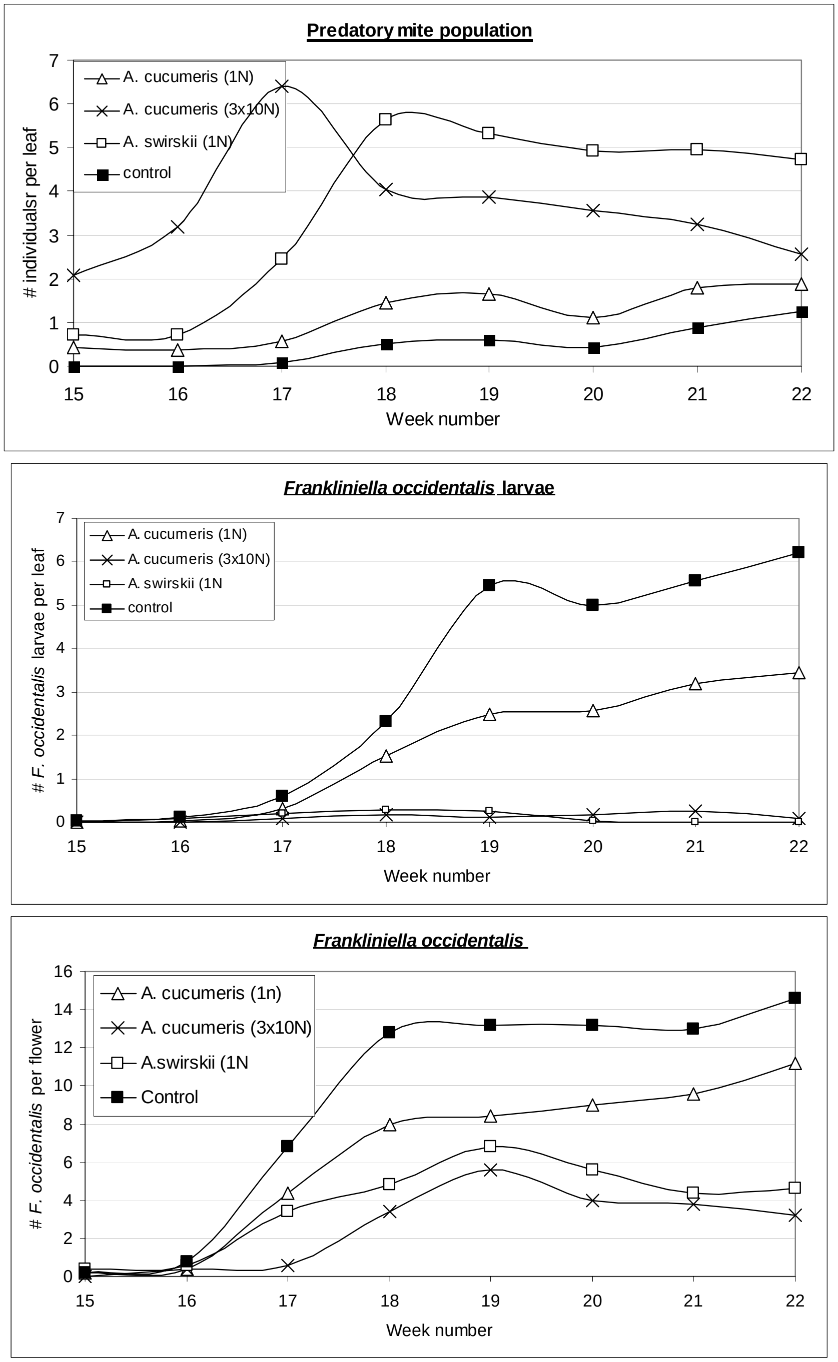

Figure 7. Population fluctuations of *Frankliniella occidentalis* and the phytoseiid mites, *Amblyseius cucumeris* and *A. swirskii,* on leaves and flowers of sweet pepper plants in 4 cages.

CONCLUSIONS

Amblyseius swirskii predates, reproduces and develops well on western flower thrips, greenhouse whiteflies and tobacco whiteflies. Under short day conditions of 19°C and L10:D14 this predatory mite is not sensitive to diapause. Draught tolerance of its eggs is similar to the draught tolerance of eggs of A. cucumeris with an RH_{50} around 70%.

A. swirskii is a promising control agent of whiteflies and western flower thrips on sweet pepper. Moreover, *A. swirskii* can be released preventively when the crop is flowering and remains present in the crop throughout the entire growing season, even while pests levels are very low. The establishment, speed of population development and persistence in the crop are much better than for *A. cucumeris*. Therefore *A. swirskii* may be a new solution for biological control of western flower thrips and of tobacco whitefly in sweet pepper in Northern and Southern Europe. *A. swirskii* is expected to replace *Iphiseius degenerans* and *A. cucumeris* in the future.

Because the biological control system for sweet peppers can be simplified and its robustness greatly enhanced by using this highly efficient predatory mite, *A. swirskii* is expected to become one of the keys to successful development of biological control in sweet peppers in areas with high pest pressures of thrips and whiteflies.

A. swirskii may be a new solution for biological control of both pests in sweet pepper in Northern and Southern Europe. A mass rearing technique for *A. swirskii* has already been developed.

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