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Amblyseius swirskii: What made this predatory mite such a successful biocontrol agent?

F. Javier Calvo · Markus Knapp · Yvonne M. van Houten · Hans Hoogerbrugge · José E. Belda

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Abstract The predatory mite *Amblyseius swirskii* quickly became one of the most successful biocontrol agents in protected cultivation after its introduction into the market in 2005 and is now released in more than 50 countries. There are several key factors contributing to this success: (1) it can control several major pests including the western flower thrips, *Frankliniella occidentalis*, the whiteflies *Bemisia tabaci* and *Trialeurodes vaporariorum* and the broad mite, *Polyphagotarsonemus latus*, simultaneously in vegetables and ornamental crops; (2) it can develop and reproduce feeding on non-prey food sources such as pollen, which allows populations of the predator to build up on plants before the pests are present and to persist in the crop during periods when prey is scarce or absent; and (3) it can be easily reared on factitious prey, which allows economic mass production. However, despite the fact that *A. swirskii* provides growers with a robust control method, external demands were initially a key factor in promoting the use of this predator, particularly in Spain. In 2006, when exports of fresh vegetables from Spain were stopped due to the presence of pesticide residues, growers were forced to look for alternatives to chemical control. This resulted in the massive adoption of biological control-based integrated pest management programmes based on the use of *A. swirskii* in sweet pepper. Biological control increased from 5 % in 2005, 1 year before *A. swirskii* was commercially released, to almost 100 % of a total 6,000 ha of protected sweet pepper in Spain within 3 years. Later, it was demonstrated that *A. swirskii* was equally effective in other crops and countries, resulting in extensive worldwide use of *A. swirskii* in greenhouses.

Keywords Augmentative biological control · External demands · Effectiveness · Application techniques

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F. J. Calvo · J. E. Belda
R&D Department, Koppert España, Calle Cobre, 22, Polígono Ind. Ciudad del Transporte,
04745 La Mojonera, Almería, Spain

M. Knapp (✉) · Y. M. van Houten · H. Hoogerbrugge
R&D Entomology, Koppert Biological Systems, P.O. Box 155, 2650 AD Berkel en Rodenrijs,
The Netherlands
e-mail: mknapp@koppert.nl

Introduction

Biological control has been one of the most environmentally safe and most economical modes of pest management for growers (Cock et al. 2010). Augmentative biological control, i.e. the release of mass-reared natural enemies in large numbers to obtain control of pests, has been an environmentally and economically sound alternative to chemical control in several agricultural systems, mainly in protected cultivation (van Lenteren and Bueno 2003). The biocontrol industry has made great advances in the last decades in the identification of natural enemies and development of commercial products, leading to more than 230 species of natural enemies available for augmentative biological control worldwide (van Lenteren 2012). The predatory mite *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) is one of the most successful of these biocontrol agents and is currently released in more than 50 countries all over the world.

In this paper we describe the development of *A. swirskii* into a biocontrol agent, putting emphasis on factors we consider important for its success in the market as well as on the importance of *A. swirskii* for the breakthrough of augmentative biological control in greenhouse vegetable production in Spain first, and other countries thereafter. The Spanish case constitutes an example for the successful switch from purely chemical pest management to biocontrol-based integrated pest management (IPM) stimulated by the availability of an effective biocontrol agent and other factors.

Use of Phytoseiidae as biocontrol agents

The Phytoseiid mite *Phytoseiulus persimilis* Athias-Henriot (Acari: Phytoseiidae), used for biological control of the two spotted spider mite *Tetranychus urticae* Koch (Acari: Tetranychidae), was one of the earliest biocontrol agents commercially available in Europe in 1968. However, the use of Phytoseiidae as biocontrol agents for insect pests started considerably later with the use of *Neoseiulus barkeri* Hughes and *Neoseiulus cucumeris* (Oudemans) (Acari: Phytoseiidae) for thrips control, which have been on the market since 1981 and 1985, respectively (van Lenteren 2012). Further research on the use of phytoseiids as biocontrol agents of insect pests was conducted in the 1990s after the invasion of the western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), into Europe (van Houten et al. 1993, 1995). The invasion of new biotypes of *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) into the New World (Brown et al. 1995) and Europe (Fransen 1994) triggered the interest in Phytoseiidae as biocontrol agents of whiteflies (Nomikou et al. 2001).

The development of *Amblyseius swirskii* into a biocontrol agent

Origin, distribution and early research

Amblyseius swirskii originates from the East Mediterranean coast and was described in 1962 from almond (*Prunus amygdalus*) in Bet Dagan, Israel (Athias-Henriot 1962). It naturally occurs in citrus crops along the Israeli coast (Porath and Swirski 1965). In addition, it has been found on other fruit trees, grapes, vegetables, cotton, wild trees and shrubs, as well as in various annual and perennial plants in this country (Swirski and Amitai 1997). In addition to Israel, it has been reported from other Middle Eastern countries, Southern Europe, West, Central and East Africa and North, Central and South America (Demite et al. 2014).

The first short study on its biology was published by Teich (1966) who discovered that eggs and larvae of *B. tabaci* in a laboratory culture were eaten by *A. swirskii* and *Amblyseius rubini* Swirskii and Amitai (Acari: Phytoseiidae). Shortly thereafter, Swirski et al. (1967) published a detailed study showing that *A. swirskii* has a wide prey range and can feed on several mite and insect species as well as pollen of many plant species. Thereafter, only a few scattered laboratory studies were conducted on the biology of *A. swirskii* feeding on different prey and non-prey food (Ragusa and Swirski 1975, 1977; Metwally et al. 1984; Hoda et al. 1986; El-Laithy and Fouly 1992; Momen and El-Saway 1993; for details see Table 1).

Development of *Amblyseius swirskii* as a biocontrol agent for whiteflies and thrips

Amblyseius swirskii can develop and reproduce on a wide range of arthropod prey (Table 1; see section Feeding on other pests and non-prey food), but it is mainly used for augmentative biological control of the whiteflies *B. tabaci* and *Trialeurodes vaporariorum* (Westwood) (Hemiptera: Aleyrodidae) and the thrips *F. occidentalis* (Cock et al. 2010). After the publications of Teich (1966) and Swirski et al. (1967) several other papers were published on the ability of Phytoseiidae to prey on whiteflies mainly in the 1960s and early 1970s (see Nomikou et al. 2001 for a summary); however, these findings were not taken up by the biocontrol industry. Biocontrol of whiteflies largely relied on the parasitoids *Encarsia formosa* Gahan, *Eretmocerus eremicus* Rose and Zolnerowich and *Eretmocerus mundus* Mercet (all Hymenoptera: Aphelinidae), and predatory bugs such as *Macrolophus pygmaeus* (Rambur) (then named *Macrolophus caliginosus* Wagner) and *Nesidiocoris tenuis* Reuter (both Hemiptera: Miridae) (van Lenteren and Martin 1999; Calvo and Urbaneja 2004; Stansly et al. 2004, 2005; Calvo et al. 2009, 2012).

Interest into phytoseiid mites as biocontrol agents for whiteflies re-emerged in the late 1990s. Worldwide outbreaks of *B. tabaci* caused serious yield losses in many crops as a result of direct feeding damage and transmission of viruses (Brown et al. 1995; Gerling and Mayer 1996; De Barro et al. 2011). In addition, development of resistance to most of the available insecticides made control more difficult (Cahill et al. 1996a, b; Nauen and Denholm 2005; Fernández et al. 2009). Hence, *B. tabaci* rapidly became a serious pest in protected crops and there was renewed interest in alternative control methods. As part of this search for alternative control options, surveys were started in Israel and Jordan to search for predatory mites feeding on *B. tabaci* in the field (Nomikou et al. 2001).

In laboratory experiments conducted with the species collected during these surveys, *A. swirskii*, *Typhlodromus athiasae* Porath and Swirski, *N. barkeri* and *Euseius scutalis* (Athias-Henriot) (all Acari: Phytoseiidae) oviposited with *B. tabaci* as prey. *A. swirskii* and *E. scutalis* were selected for further evaluation because they had higher intrinsic rates of increase (r_m) than the other two species (Nomikou et al. 2001). Both *A. swirskii* and *E. scutalis* were able to suppress *B. tabaci* populations on isolated cucumber plants in a greenhouse experiment when *Typha* sp. pollen was provided as supplementary food (Nomikou et al. 2002).

In a comparison with other predatory mite species, *A. swirskii* also provided good control of *F. occidentalis* in cucumber. It was much better than *N. cucumeris*, the predatory mite commonly used for augmentative biological control of thrips in cucumber and other crops at that time, although *Amblydromalus limonicus* Garman and McGregor (Acari: Phytoseiidae) provided even better thrips control than *A. swirskii.* Thrips control with *E.*

Table 1 List of pest species on which *Amblyseius swirskii* has been reported to develop and/or oviposit in laboratory experiments

Order/ subclass	Family	Species	Development	Oviposition	Source
Acari	Eriophyidae	*Aceria ficus*	x	x	Abou-Awad et al. (1999)
		Aceria mangiferae	x	x	Abou-Awad et al. (2010)
		Aculops lycopersici	x	x	Momen and Abdel-Khalek (2008) and Park et al. (2010, 2011)
		Cisaberoptus kenyae	x	x	Ali and Zaher (2007) and Abou-Awad et al. (2010)
		Eriophyes discordis	x	x	Momen and El-Saway (1993)
		Metaculus mangiferae	x	x	Abou-Awad et al. (2010)
		Phyllocoptruta oleivora		x	Swirski et al. (1967)
		Rhyncaphytoptus ficifoliae	x	x	Abou-Awad et al. (1999)
	Tarsonemidae	*Polyphagotarsonemus latus*	x	x	Stansly and Castillo (2009), Van Maanen et al. (2010), Onzo et al. (2012) and Abou-Awad et al. (2012a, b)
	Tenuipalpidae	*Brevipalpus phoenicis*		x	Swirski et al. (1967)
		Raoiella indica	x	x	Peña et al. (2009)
	Tetranychidae	*Eutetranychus orientalis*		x	Swirski et al. (1967), Metwally et al. (1984), Hoda et al. (1986) and Ali and Zaher (2007)
		Oligonychus mangiferus	x	x	Abou-Awad et al. (2010)
		Panonychus ulmi	x	x	Ali and Zaher (2007)
		Panonychus citri	x	x	Ji et al. (2013)
		Tetranychus cinnabarinus		x	Swirski et al. (1967)
		Tetranychus urticae	x	x	Yousef et al. (1982), El-Laithy and Fouly (1992), Momen and El-Saway (1993), Ali and Zaher (2007) and Xiao et al. (2012b)
	Tydeidae	*Tydeus californicus*	x		Ali and Zaher (2007)

Table 1 continued

Order/ subclass	Family	Species	Development	Oviposition	Source
Hemiptera	Aleyrodidae	*Bemisia tabaci*		x	Swirski et al. (1967), Nomikou et al. (2001), Ali and Zaher (2007) and Fouly et al. (2011)
		Trialeurodes vaporariorum		x	Bolckmans et al. (2005) and Messelink et al. (2008)
	Aphididae	*Aphis gossypii*		x	Hoda et al. (1986)
		Aphis duranta	x	x	Ali and Zaher (2007)
	Diaspididae	*Aonidiella aurantii*		x	Swirski et al. (1967)
		Chrysonphalus ficus	x	x	Ali and Zaher (2007)
		Coccus hesperidium	x	x	Ali and Zaher (2007)
		Insulaspis pallidula	x	x	Abou-Ellela et al. (2013)
	Phoenicococcidae	*Phoenicococcus marlatti*	x	x	Abou-Ellela et al. (2013)
	Pseudococcidae	*Pseudococcus* aff. *citriculus*	x	x	Swirski et al. (1967)
Lepidoptera	Noctuidae	*Spodoptera litura*		x	Swirski et al. (1967)
	Pyralidae	*Ectomyelois ceratoniae*		x	Swirski et al. (1967)
	Yponomeutidae	*Prays citri*		x	Swirski et al. (1967)
Thysanoptera	Thripidae	*Echinothrips americanus*		x	Hoogerbrugge et al. (2014)
		Frankliniella occidentalis	x	x	Bolckmans et al. (2005), Messelink et al. (2008), Wimmer et al. (2008), Buitenhuis et al. (2010) and Zannou and Hanna (2011)
		Retithrips syriacus		x	Swirski et al. (1967)
		Scirthothrips dorsalis	x	x	Arthurs et al. (2009) and Kumar et al. (2014)
		Thrips tabaci	x	x	Hoda et al. (1986) and Wimmer et al. (2008)

scutalis was not successful despite the fact that this mite developed much higher populations on cucumber plants than *N. cucumeris*. *Euseius scutalis* was mainly present on the lower leaves of the cucumber plants whereas the thrips reached high densities on the upper leaves (Messelink et al. 2005, 2006). Further research in The Netherlands focused on *A. swirskii* because it had the potential to control both pests and because it was easier and cheaper to rear than *A. limonicus* and *E. scutalis* (Nomikou et al. 2003, 2010; Messelink et al. 2008, 2010; Knapp et al. 2013).

The results of these experiments caught the attention of Koppert Biological Systems, a commercial biocontrol company. *Amblyseius swirskii* was obtained from the University of Amsterdam and additional experiments were conducted. Major outcomes of these trials were that *A. swirskii* also developed and multiplied with the greenhouse whitefly *T. vaporariorum* as prey and was able to establish on flowering sweet pepper with only pollen as food source in commercial greenhouses in The Netherlands (Bolckmans et al. 2005). Control of *F. occidentalis* in sweet pepper with *A. swirskii* was better than with *N. cucumeris* and *Amblyseius andersoni* (Chant) and as good as with *Iphiseius degenerans* (Berlese) (both Acari: Phytoseiidae) under Dutch summer conditions (van Houten et al. 2005). At the same time a mass-rearing system based on the use of the factitious prey *Carpoglyphus lactis* (L.) (Acari: Carpoglyphidae), a stored-product mite that is easy to rear, was developed and patented (Bolckmans and van Houten 2006).

Despite the impressive data, the uptake of *A. swirskii* by Dutch growers initially started slowly. Many of the sweet pepper growers were content with the combination of *N. cucumeris* and *Orius laevigatus* Fieber (Hemiptera: Anthocoridae) they were using for thrips control. Whiteflies were not a big problem in Dutch sweet pepper greenhouses. An additional disadvantage was that, in contrast to *N. cucumeris*, no slow-release sachets were available for *A. swirskii*.

The success of *Amblyseius swirskii* in Spain

In the early 2000s there were increasing problems with *F. occidentalis* and *B. tabaci* control in protected sweet pepper crops in south-eastern Spain. The growers still largely relied on synthetic insecticides to control these pests and were caught in a vicious circle: increasing resistance of both pests to insecticides (e.g. Espinosa et al. 2002; Fernández et al. 2009) and pest resurgence (i.e. pesticide-induced pest outbreaks) led to increasing application frequencies and dose rates, and ultimately to the use of illegal pesticides. This, in turn, caused even more pest problems, increasing residue levels and environmental impact, and decreasing food safety. Biocontrol companies had tried to introduce IPM in greenhouse vegetable production in southern Spain for several years without success, mainly because they initially tried to copy the strategies used in The Netherlands, based on the use of *E. formosa* and *E. eremicus* for whitefly control and *N. cucumeris* and *O. laevigatus* for thrips control. However, the climate and greenhouse technology in southern Spain was different from that in The Netherlands—the Dutch solutions did not work sufficiently under these conditions, leading to poor establishment of beneficials, and they were too expensive. Later attempts to adapt these methods to local conditions resulted in the replacement of the parasitoids by the indigenous parasitoid *E. mundus*, which was more effective in *B. tabaci* control than the above-mentioned parasitoids in southern Spain (Stansly et al. 2004, 2005). However, results were still disappointing, especially in summer plantings and thus, growers continued to rely on chemical control. In 2005, initial semi-field experiments demonstrated that biological control of *B. tabaci* on sweet pepper with *A. swirskii* was possible in southern Spain and promising results were also obtained for control of *F. occidentalis* (Hoogerbrugge et al. 2005; Belda and Calvo 2006). However, it was still difficult to convince the growers that biocontrol could work in practice.

In 2006 this situation changed. Greenpeace Germany had sent sweet pepper from German supermarkets to a laboratory for residue analysis. The results were dramatic. Residues of isofenphos-methyl were detected in 60 % of the samples from Spain. This active ingredient was and is not registered in the European Union; in 40 % of the samples the isofenphos-methyl values were above the maximum residue level. In samples of other origins (Turkey, The Netherlands, Morocco) isofenphos-methyl was not detected (CVUA Stuttgart 2007). Greenpeace published these results widely (see e.g. Krautter 2007) and German consumers largely stopped buying Spanish sweet peppers. The major market for the Spanish growers collapsed, and suddenly their interest in biocontrol re-emerged.

The positive results obtained in semi-field trials in Spain mentioned above were confirmed in further experiments. Releases of *A. swirskii* in combination with *E. mundus* significantly improved control of *B. tabaci* compared to using the parasitoid only in protected sweet pepper (Calvo and Belda 2007; Calvo et al. 2009), which was later confirmed in commercial greenhouses (Calvo et al. 2012). Releases of *A. swirskii* significantly reduced *F. occidentalis* densities in sweet pepper, but the thrips was not sufficiently controlled in sweet pepper flowers to mitigate the risk of Tomato-spotted wilt virus infections (Belda and Calvo 2006). As in The Netherlands, the mite therefore needed to be combined with *O. laevigatus* (Weintraub et al. 2011; Calvo et al. 2012). Overall, biological control of both pests with the system based on *A. swirskii* was not only more efficient, but also cheaper than the previously used strategy consisting of parasitoids for whitefly control and *N. cucumeris* and *O. laevigatus* for thrips control (Calvo et al. 2012). *A. swirskii* also provided excellent control of *B. tabaci* and *F. occidentalis* in cucumber, eggplant, melon and courgette in southern Spain (Calvo et al. 2008, 2011).

Within 3 years, nearly all sweet pepper growers switched from chemical control to biological control of both pests (van der Blom 2005; Merino-Pacheco 2007; van der Blom et al. 2008). The area of sweet pepper under biological control increased from a mere 200 ha in the season of 2005–2006 to about 6,000 ha in 2008–2009; Fig. 1). At the same time, the percentage of sweet pepper samples with pesticide residues decreased from

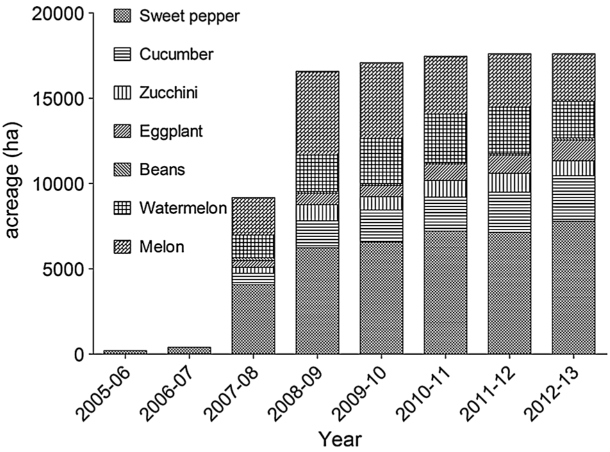

Fig. 1 Greenhouse area (ha) by crop in Spain under biological control-based integrated pest management programmes based on the use of *Amblyseius swirskii* (Frutas y Hortalizas 2014). *Amblyseius swirskii* was first commercially released in 2006–2007 in sweet pepper

33.3 % in January 2007 to <1 % throughout the season 2007–2008 (Glass and Gonzalez 2012). In 2012–2013, the total greenhouse area in Spain under IPM in which *A. swirskii* was released was around 18,000 ha, including more than 2,100 ha cucumber, more than 950 ha eggplant, around 1,100 ha zucchini and about 6,000 ha of other crops (Fig. 1).

Further characteristics of *Amblyseius swirskii* making it a successful biocontrol agent

Wide range of application: host plants and temperature

In addition to various wild plants (see section Origin, distribution and early research), *A. swirskii* is able to establish in many vegetable crops, including peppers, cucumber or eggplants as well as in ornamentals and fruit trees (Calvo and Belda 2007; Calvo et al. 2012; Gerson and Weintraub 2012; Juan-Blasco et al. 2012). In life-table studies with *Typha latifolia* pollen as food source in the laboratory, no development occurred at 13 °C and the r_m was negative at 15 °C. The highest r_m (0.160) was recorded at 32 °C; the estimated lower threshold for population growth was 15.5 °C and the estimated upper threshold 37.0 °C. This implies that populations should grow quickly between 20 and 32 °C, a temperature range common in many agro-systems, but population growth could be slow below 20 °C (Lee and Gillespie 2011).

Feeding on other pests and non-prey food

Amblyseius swirskii is a generalist predatory mite feeding on many different small insects and mites (Table 1) as well as on pollen from many plants (Ragusa and Swirski 1975; Goleva and Zebitz 2013) and other non-prey food, including eggs of the Mediterranean flour moth *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae), decapsulated dry cysts of the brine shrimp *Artemia franciscana* Kellogg, mango powdery mildew *Oidium mangiferae* Berthet and various artificial diets (Abou-Awad et al. 2011; Nguyen et al. 2013, 2014a, b). Its ability to feed on pollen greatly helps to establish in high numbers in flowering plants, for instance in sweet pepper, even before pests are present (Bolckmans et al. 2005). This ability to build up populations on pepper pollen makes it also possible to use ornamental peppers as banker plants for *A. swirskii* in ornamental greenhouses to increase predatory mite densities (Xiao et al. 2012a; Avery et al. 2014; Buitenhuis et al. 2015). As a generalist, *A. swirskii* can be used for the control of different pests simultaneously. Although the presence of whitefly can lead to a short-term escape of thrips from predation (van Maanen et al. 2012), thrips control is not negatively affected by the presence of *B. tabaci* or *T. vaporariorum*, or vice versa, in greenhouses (Messelink et al. 2008; Calvo et al. 2011). To the contrary, Messelink et al. (2008), (2010) observed that the presence of thrips and spider mites enhanced *T. vaporariorum* control by *A. swirskii* by increasing predator densities, because the generalist *A. swirskii* performs better on a mixed pest diet.

Amblyseius swirskii can also feed and reproduce on *T. urticae* (El-Laithy and Fouly 1992; Xiao et al. 2012b); however, it has a clear preference for *F. occidentalis* (Xu and Enkegaard 2010). It is not able to control spider mites in the absence of other pests on greenhouse cucumbers, mainly because the predatory mites cannot enter dense spider mite webbing and therefore can only feed on spider mites outside or near the edges of the webbing (van Houten et al. 2007a; Messelink et al. 2010). However, spider mite damage was much lower in the presence than in the absence of *F. occidentalis* and/or *T.*

vaporariorum, probably due to the strong numerical response of the predator when these pests were present (Messelink et al. 2010).

Good results have been achieved with *A. swirskii* in the control of broad mites, *Polyphagotarsonemus latus* (Banks) (Acari: Tarsonemidae), in sweet pepper, hot pepper, eggplant and gboma eggplant (*Solanum macrocarpon*) (Tal et al. 2007; Stansly and Castillo 2009; van Maanen et al. 2010; Onzo et al. 2012; Abou-Awad et al. 2014a, b). Preliminary experiments have indicated that *A. swirskii* could play an important role in the control of the invasive red palm mite, *Raoiella indica* Hirst (Acari: Tenuipalpidae) (Peña et al. 2009). In phalaenopsis (Orchidaceae), *Brevipalpus* sp. (Acari: Tenuipalpidae) has been controlled with releases of *A. swirskii* (H. Nennmann, Pflanzenschutzdienst Nordrhein Westfalen, pers. comm.). The chilli thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), can also be controlled by *A. swirskii* in pepper (Arthurs et al. 2009; Dogramaci et al. 2011).

More recent research has shown that *A. swirskii* can also feed on citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae), and significantly reduce citrus psyllid populations on isolated plants in a greenhouse (Juan-Blasco et al. 2012). It still remains to be investigated whether *A. swirskii* can contribute to the control of citrus psyllid in the field. It is important to note that the ability to feed and reproduce on a specific pest in laboratory trials does not guarantee successful control of this pest. *Amblyseius swirskii* develops and reproduces very well on the tomato russet mite, *Aculops lycopersici* (Massee) (Acari: Eriophyidae), on leaf discs in Petri dishes (Park et al. 2010, 2011); however, it cannot control this pest on tomato due to the glandular trichomes on stems and leaves of tomato plants, which impair the movement of the predatory mite (van Houten et al. 2013).

Combination with other control agents

Amblyseius swirskii has been combined with other biocontrol agents in various crops, with no detrimental effects on biological control of whitefly, thrips, spider mites and other pests (van Houten et al. 2007b; Chow et al. 2010; Messelink et al. 2010; Calvo et al. 2012), with one known exception. When it is combined with the aphidophagous gall midge *Aphidoletes aphidimyza* (Rondani) (Diptera: Cecidomyiidae), predation of the predatory mite on the eggs of the gall midge can disrupt biological control of aphids (Messelink et al. 2011). In addition, there are many pesticides that are compatible with *A. swirskii* (Calvo et al. 2007; Gradish et al. 2011), which allows the simultaneous control of pests and diseases that cannot be controlled biologically.

Release systems

Good coverage and dispersal of predatory mites is important for biological control, especially in ornamentals, where the pest levels that can be tolerated are lower than in vegetables. Therefore, patches of prey can be sparsely distributed and there is often not enough prey to maintain a predator population (Skirvin and Fenlon 2003; Van Driesche and Heinz 2004; Buitenhuis et al. 2010, 2015). To achieve this, various release methods have been developed for *A. swirskii* since its introduction. Initially, the predatory mites were only available in bottles with wheat bran as carrier material, and needed to be distributed by hand. Later, release systems based on mechanical blowers were developed, which distribute the mites more uniformly and reduce labour cost (Opit et al. 2005; Pezzi et al. 2015; see also http://www.koppert.com/products/distribution-appliances/). Another release method is the 'slow release', using breeding sachets. These sachets contain a carrier material such as wheat bran, and a food source for the factitious prey mites. The predatory mites feed and multiply in the sachet and can leave through a small hole that is punched into the sachets and disperse into the crop for several weeks (Midthassel et al. 2014). Sachets are therefore a valuable option in systems where no alternative food in form of pollen is available and preventive releases help to keep pest levels low (Midthassel et al. 2014). For *A. swirskii*, commercial slow-release sachets can contain the factitious prey *C. lactis*, *Suidasia medanensis* (Oudemans) (Acari: Suidasiidae) or *Thyreophagus entomophagus* (Laboulbène and Robin) (Acari: Acaridae) (Bolckmans and van Houten 2006; Fidgett and Stinson 2008; Baxter et al. 2011; Midthassel et al. 2013; Nguyen et al. 2013). Recently, a slow-release sachet containing two prey mites, *C. lactis* and *Lepidoglyphus destructor* (Schrank) (Acari: Glycyphagidae), was developed—this combination increases the lifetime of the breeding sachet significantly from 3–4 to 6–8 weeks (Bolckmans et al. 2013).

Conclusions

The pathway for uptake of innovations in pest management is often envisaged as a linear process of (1) basic research, (2) laboratory trials, (3) greenhouse research trials, (4) commercial trials, and (5) adoption (Murphy 2014). The development of *A. swirskii* into a successful biocontrol agent largely followed this pathway. Initial laboratory experiments were carried out at the University of Amsterdam, greenhouse trials at the Glasshouse Horticulture Division of Applied Plant Research in The Netherlands (now WUR Glasshouse Horticulture). Based on the results of these trials, *A. swirskii* caught the attention of Koppert Biological Systems, and more semi-field experiments and commercial trials were conducted by this company, both in The Netherlands and Spain. As shown above, adoption was initially largely driven by external factors, i.e. pesticide resistance and residue problems. After the initial successes in Spain, biocontrol strategies based on *A. swirskii* were quickly adopted by many growers of vegetable and ornamental crops in various parts of the world. This, in turn, stimulated further research and the development of better rearing and release systems, which again opened further possibilities for using this predatory mite.

Amblyseius swirskii was put on the market in 2005. In 2009 it was already used in more than 20 countries (Cock et al. 2010) and more than 18,000 ha of protected crops in Spain (Fig. 1) and in 2014 it is sold in more than 50 countries. The large-scale success of *A. swirskii* would have never been possible without the enthusiasm and expertise of advisors and consultants both from private companies and government agencies, such as universities and research stations, and last but not least, motivated and knowledgeable growers. Growers are the last link in the chain and how they use natural enemies will ultimately determine their success.

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