



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at SciVerse ScienceDirect

Biological Control

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

Prey availability and abiotic requirements of immature stages of the aphid predator *Sphaerophoria rueppellii*

Rocco Amorós-Jiménez^{a,*}, Ana Pineda^a, Alberto Ferreres^b, M. Ángeles Marcos-García^a

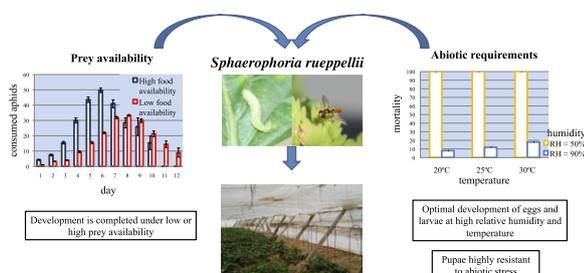
^a CIBIO (University of Alicante), Associated Unit IPAB CSIC-UA, Carretera San Vicente del Raspeig s/n, 03690 San Vicente del Raspeig, Alicante, Spain

^b ICA (CSIC), Associated Unit IPAB CSIC-UA, C/Serrano 115 dpdo., 28006 Madrid, Spain

HIGHLIGHTS

- ▶ *Sphaerophoria rueppellii*: an indigenous predatory hoverfly in the Mediterranean basin.
- ▶ Low relative humidity strongly impacts survival of larvae and eggs, but not of pupae.
- ▶ Development is completed at a wide range of temperatures, even at 30 °C.
- ▶ Survival of immature stages is not affected by aphid supply.
- ▶ *S. rueppellii* is a good candidate for classical biological control in warm climate.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 15 November 2011

Accepted 1 June 2012

Available online 12 June 2012

Keywords:

Syrphidae
Temperature
Relative humidity
Life cycle
Aphid supply
Greenhouse

ABSTRACT

Aphidophagous hoverflies (Diptera: Syrphidae) are natural enemies with a high potential as biological control agents. Nevertheless, there is only one commercially available species, *Episyrphus balteatus*, which despite naturally occurring in the Mediterranean basin, is not the best adapted to the conditions found in its agricultural areas. *Sphaerophoria rueppellii* is another common hoverfly species in the Mediterranean area both in outdoor and greenhouse crops. However, little information about the biology of this species is known and this is one of the main requirements for every control-based IPM program. In this work we assess the influence of different humidity and temperature combinations on the performance (mortality, developmental time and sublethal effects) of *S. rueppellii* under controlled conditions. We also study the effect of aphid supply during larval stage on mortality and developmental time of immature stages and on sublethal effects on adults. The results show that this species requires high environmental humidity (higher than 60%) to complete its development. Also, *S. rueppellii* is able to properly develop at a wide range of temperatures (20–30 °C). *S. rueppellii* reduces its voracity under low aphid density conditions, being able to adapt its feeding rate to the aphid availability. Mortality was not affected by food supply, while low prey availability led to longer developmental time and a decrease in larval and pupal weight and adult body size. These results show the suitability of this species as an aphid biological control agent under high humidity and temperature conditions, such as the ones inside Mediterranean greenhouses.

© 2012 Elsevier Inc. All rights reserved.

1. Introduction

The Mediterranean basin has the highest horticultural crop production of Europe (FAOSTAT, 2009), and the surface devoted to

organic and integrated production increases every year, particularly in protected (i.e. greenhouse) crops (Freier and Boller, 2009). Horticultural crops have several key pests, aphids (Hemiptera: Aphididae) being one of the most important. More

* Corresponding author. Fax: +34 965903780.

E-mail addresses: rocco.hoverfly@gmail.com, rocco@ua.es (R. Amorós-Jiménez).

specifically, polyphagous species such as *Aulacorthum solani* (Kaltenback), *Aphis gossypii* (Glover), *Macrosiphum euphorbiae* (Thomas) and *Myzus persicae* (Sulzer) are the most damaging aphids in protected crops (Blümel, 2004; Rabasse and Steenis, 2002).

Several species of predators and parasitoids have been used in greenhouse crops against aphids, providing unsatisfactory results that led to the use of compatible chemicals to control this pest (Ramakers, 2004). In addition, biological control of aphids has been based on the same species for more than two decades, and only recently new and more-effective natural enemies have started to be commercialized and released for aphid control (Sanchez et al., 2011). Several studies have proven that the extreme climate conditions inside greenhouse vegetable crops can influence the establishment and reproduction of natural enemies (Shipp and Van Houten, 1997; Zhang and Shipp, 1998) as well as the development and survival of their immature stages, preventing most of the species traditionally used from a proper performance. For these reasons, there is a strong demand for effective biological control strategies against aphids on protected horticultural crops (Sanchez et al., 2011). Specifically, there is a current trend to encourage the search and use of indigenous natural enemy species, that has already led to the replacement of several popular exotic biological control agents with indigenous species (van Lenteren, 2012).

Aphidophagous syrphids (Diptera: Syrphidae) are high potential agents in aphid biological control (Brewer and Elliott, 2004; Freier et al., 2007; Haenke et al., 2009; Tenhumberg and Poehling, 1995), being also compatible and complementary with the use of other biological control agents, such as parasitoid wasps (Pineda et al., 2007) or entomopathogenic fungi (Diaz et al., 2010). However, there is only one commercially available species, *Episyrphus balteatus* (De Geer). This species is particularly abundant and efficient on central and northern Europe (Tenhumberg, 1995), but it is not the most abundant in Mediterranean agricultural areas (Pineda and Marcos-García, 2008b). A high mortality rate when temperature is higher than 25 °C has been reported (Hart et al., 1997), a temperature condition which normally occurs in outdoor and indoor crops.

Sphaerophoria rueppellii (Wiedemann) is a predator hoverfly which usually occurs in Mediterranean crops (Pineda and Marcos-García, 2008b; Speight, 2005). This species seems to be the best adapted to the extreme climatic conditions of high temperature and humidity, such as the ones occurring in Mediterranean areas, and particularly those taking place in greenhouses from southeastern Iberian Peninsula (Pineda and Marcos-García, 2008b). In addition, previous work has shown that habitat management strategies such as providing additional floral resources (Pineda and Marcos-García, 2008c) and banker plants (Pineda and Marcos-García, 2008a) effectively enhance *S. rueppellii*'s populations in sweet-pepper Mediterranean greenhouses. Thus, this species has a high potential as an aphid biological control agent in protected crops, and it has been suggested to make this syrphid commercially available (Pineda and Marcos-García, 2008b). However, little information about the biology of this species is known to date.

One of the first steps before natural enemies can be used effectively as mass reared biological control agents is to obtain valid information about their biology and their interaction with herbivore insects (Wiedemann and Wilson, 1996). This work aims to provide information about some biotic and abiotic requirements of the aphidophagous syrphid *S. rueppellii*, one of the main requirements previous to rear this insect with commercial purposes. Our study system also consists of sweet-pepper [*Capsicum annuum* L. (Solanaceae)], a horticultural species largely extended in the Mediterranean area (FAOSTAT, 2009), and the aphid *M. persicae*, a species that causes severe economic losses in numerous crops worldwide (Blackman and Eastop, 2000; Minks and Harrewijn, 1989). We assess the influence of different humidity and temperature

combinations as well as of food supply during larval stage, on the performance of immature *S. rueppellii* stages under controlled conditions as well as on sublethal effects on the developed adults.

2. Materials and methods

2.1. Plant material, aphids and syrphids

Sweet-pepper plants (*C. annuum* var. California Wonder) were grown from seed in a climate room ($T = 25 \pm 1$ °C, $RH = 60 \pm 10\%$, Photoperiod = 14L:10D, average light intensity = 495 lux) in plastic pots (5 × 5 × 6 cm). These conditions were used throughout all of the rearing in this work. A stock colony of *M. persicae* was maintained on sweet-pepper plants in plastic boxes (30 × 30 × 60 cm) covered with a fine mesh on its upper part. The aphids were kept in a climate room with the same conditions as for plant growth. *S. rueppellii* cohorts were reared in plastic cages (30 × 30 × 60 cm), with a fine mesh on its upper part. The rearing cages contained bee granular pollen (© Sigma-Aldrich Co. LLC.), sugar provided as dry cubes, water (presented on a 100 ml plastic glass inverted on a Petri dish lid with a disc of filter paper) and a sweet-pepper plant infested with the aphid *M. persicae* to stimulate oviposition. Larvae were reared on *M. persicae* colonies on sweet-pepper plants.

2.2. Abiotic requirements

To assess the effect of environmental conditions on immature stages of this hoverfly, three different temperatures (20, 25, 30 ± 1 °C) and two relative humidity conditions (50%, $90 \pm 10\%$) were selected. Such conditions are common in both outdoor crops and greenhouses throughout spring and summer for a wide range of latitudes. Six treatments were established, representing all the possible combinations of those environmental conditions.

The temperature conditions needed were obtained by using three controlled FITOTRON cabinets, one for each temperature. Although this type of design mixes the effect of temperature and cabinet, it is a common problem among temperature cabinet studies and it is difficult to solve. The high humidity treatments were kept by using Petri dishes with a wet disk of paper inside and by sealing the dishes with Parafilm®. For low humidity treatments Petri dishes with a net on its upper part were used, so the humidity conditions inside the dish and that programmed on the rearing chamber were the same. Petri dish position was randomized and changed daily to compensate for any directional bias from the cabinet structure. Temperature and relative humidity inside the Petri dishes were checked by using Dataloggers (HOBO® U10-003). The Photoperiod throughout the experiment was 14:10 (L:D), and the average light intensity was 495 lux.

50 replicates were performed for each stage, consisting of a single egg, larva or pupa placed in a Petri dish (90 × 15 mm) with a piece of a sweet pepper leaf (1 cm²). Individuals from one assay were not re-used in other stage-assay. Eggs with the same age were obtained by placing an aphid-infested sweet-pepper plant in a rearing cage containing mature adults for two hours. Each egg was then removed from the plant by cutting off a small piece of plant tissue with the egg to avoid damage, and placed separately in a Petri dish. Mortality rate and time to egg hatching were recorded by checking each replicate every 24 h. Larval and egg mortality could be determined visually, whereas pupal mortality was scored when no adult emerged one week after the last adult emerged. A total of 50 eggs per treatment were observed.

Focusing on the larval stage, Ad libitum food supply (*M. persicae*) was provided throughout the larval cycle. Remaining aphids were removed daily and replaced with aphids from a rearing under controlled conditions, to avoid a negative effect in their quality due to

temperature and humidity conditions inside the Petri dishes. The piece of sweet pepper leaf was removed daily as well, to make sure that the aphids remained on it without spreading on the dish. Larval mortality and developmental time of larvae were assessed by checking each Petri dish every 24 h, from a total of 50 larvae per treatment.

Once larvae pupated, the pupae were kept under the conditions of the corresponding treatment. From the emerged adults, wing length was also determined, which is a good indicator of total body size in syrphids and other diptera and so, a good indicator of fitness (Stubbs and Falk, 1983). Specifically, the shortest length between the junction of the costal vein (C) with the humeral crossvein (h) and the junction of R4 + 5 with the medial vein (M) was measured (Dziocck, 2005). Due to differences between males and females, measurements were analyzed separately for each sex. Morphological measurements were always done using the left wing, to avoid any effect due to asymmetry.

To study the effects on pupal stage, syrphid eggs and larvae were reared under the standard rearing conditions described above. Then each pupa was placed separately in a Petri dish, on a piece of leaf where the pupation occurred to avoid manipulation. Mortality rate and time of development were determined, as well as wing length of the emerged adults. A total of 50 pupae per treatment were observed.

2.3. Biotic requirements

To assess the effect of food supply during larval stage on the performance of this hoverfly, two treatments were established: The “high food availability” treatment, where a high number of aphids (*M. persicae*) were provided throughout the larval stage, and the “low food availability” treatment, where we provided larvae with a limited amount of aphids, enough to allow the larval stage to complete. The daily amount of aphids for each treatment (see Table 1) was based on a preliminary experiment where the maximum and minimum number of aphids consumed by *S. rueppellii*'s larvae were determined (see Supplementary Table 1). We provided larvae from “high food availability” treatment with aphids according to the maximum daily aphid consumption data, while “low food availability” treatment was supplied with aphids according to the minimum daily aphid consumption obtained in this preliminary trial.

Each replicate consisted of a one-day old larva placed separately on its own Petri dish with a piece of sweet pepper leaf (1 cm²), a wet disk of paper and sealed with Parafilm®, to achieve 90% RH inside. Most of the aphids remained feeding on the leaf, so even first instar larvae, with a limited movement capacity (Chandler, 1968) were able to prey on the aphids that they needed. 60 replicates were performed for each treatment.

Every 24 h remaining aphids in the Petri dish were removed and counted. After that, new aphids from a rearing were provided. Only third and fourth instar-aphids were provided, to avoid underestimating the predation owing to the potential progeny production by aphid adults. Through observations every 24 h, daily and total aphid consumption rate throughout the larval stage were determined, as well as mortality rate and time of development of both larvae and pupae. Also, the third instar larvae and newly formed pupae were weighed using a precision weighing scale (Acculab ALC-110.4 Analytical Balance). Pupae were placed in two

30 × 30 × 60 cm plastic rearing cages according to the treatment, with a fine mesh on its upper part. Emergence rate and wing length of adults were measured. Experiments were carried out with the same environmental conditions explained above.

2.4. Statistical analysis

The normality of the data was tested with the Kolmogorov-Smirnov and Shapiro-Wilk tests. Data on mortality rate, developmental time and aphid consumption were not normally distributed and therefore were analysed with Generalized Linear Models (GENLIN) followed by LSD post hoc test for multiple pair-wise comparisons. The model was adjusted to a Poisson distribution with log link function for developmental time and aphid consumption, and to a binomial distribution with logit link function for mortality. Data on aphid consumption was analyzed with GENLIN for repeated measures (days). Data on wing length and weight were normally distributed and therefore were analyzed with a *t*-test or ANOVA, followed by Tukey post hoc test for multiple pair-wise comparisons. Wing length data from the larvae experiment were analysed with a one-way ANOVA to study the differences among temperatures, due to the fact that survival of larvae was 0% in the 50% RH treatments. Data on wing length from the pupae experiment were evaluated with a two-way ANOVA to determine effects of relative humidity and temperature. All data were analysed with the statistical packages SPSS V19.0 and Gen Stat 13.

3. Results

3.1. Abiotic requirements

Low humidity had a strong negative impact on the performance of *S. rueppellii*. Eggs (Fig. 1) and larvae (Fig. 2) were the most sensitive stages, with a higher mortality (egg: *df* = 1, 299; deviance ratio = 97.58; *P* < 0.001; larva: *df* = 1, 299; deviance ratio = 781.79; *P* < 0.001) and longer developmental time (egg: *df* = 1, 151; deviance ratio = 203.76; *P* < 0.001) when developing at 50%RH compared to 90%RH. Actually, larval mortality was 100% for all treatments when developing at low humidity, which made impossible to obtain data of their developmental time as well as pupa and adult parameters for these treatments. Interestingly, pupae were not affected by low humidity conditions (*df* = 1, 299; deviance ratio = 2.26; *P* > 0.05; Fig. 3).

The increase of temperature had no effect on egg and larva mortality (egg: *df* = 2, 299; deviance ratio = 2.13; *P* = 0.121; larvae: *df* = 2, 299; deviance ratio = 3.02; *P* = 0.051), whereas at 30 °C pupal mortality significantly increased compared with the other temperatures (*df* = 2, 299; deviance ratio = 5.81; *P* = 0.003; LSD: 20–30 °C *P* = 0.003, 25–30 °C *P* = 0.02). Interestingly, when larvae developed at 25 or 30 °C, the following pupal stage also had significantly higher mortality compared with larvae that developed at 20 °C (*df* = 2, 149; Wald statistic = 7.213; *P* = 0.03; LSD: 20–25 °C *P* = 0.026; 20–30 °C *P* = 0.008) (see Supplementary Fig. 1). In contrast, temperature had a positive effect on the developmental time of the three *S. rueppellii* stages, which showed a faster development as the temperature raised (egg: *df* = 1, 151; deviance ratio = 203.76; *P* < 0.001; larvae: *df* = 2, 130; Wald statistic = 194.5; *P* < 0.001; pupae: *df* = 2, 276; deviance ratio = 1293.58; *P* < 0.001; LSD, *P* < 0.001). However, the faster larval development had a negative consequence for the body size of the emerging adults, since the increase of temperature reduced wing length of males ($F_{2,20} = 31.46$; *P* < 0.001) and females ($F_{2,22} = 31.01$; *P* < 0.001 between 20 °C and 25–30 °C, *P* < 0.05 between 25 and 30 °C). Similarly, faster pupal development led to shorter wing length in both males (*df* = 2, 89; *F* = 44.85; *P* < 0.001) and females (*df* = 2, 89;

Table 1
Number of aphids provided daily on each treatment.

Treatment/Day	1	2	3	4	5	6	7	8	9	10	11
Ad libitum	10	20	30	50	60	65	65	70	70	70	70
Limited food	1	5	5	15	25	25	35	35	35	35	35

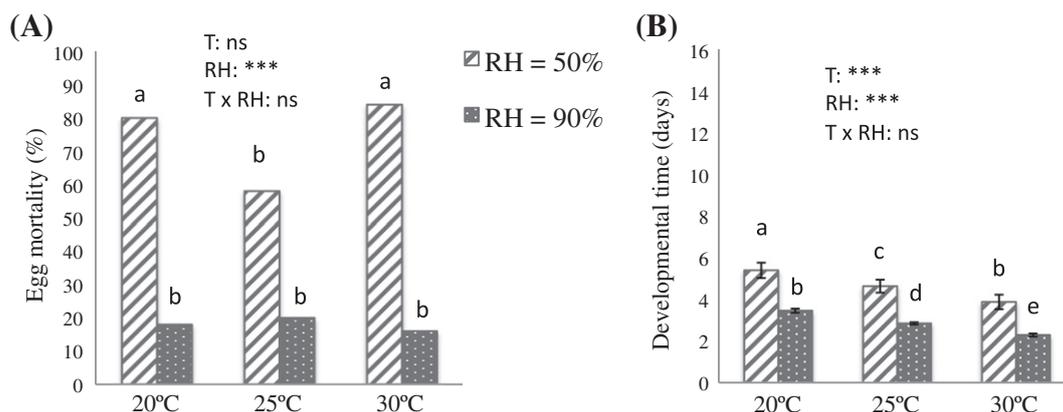


Fig. 1. Abiotic requirements for eggs. (A) Mortality rate (mean %). (B) Developmental time (mean + SEM). Different letters above bars indicate significant differences (GENLIN, LSD).

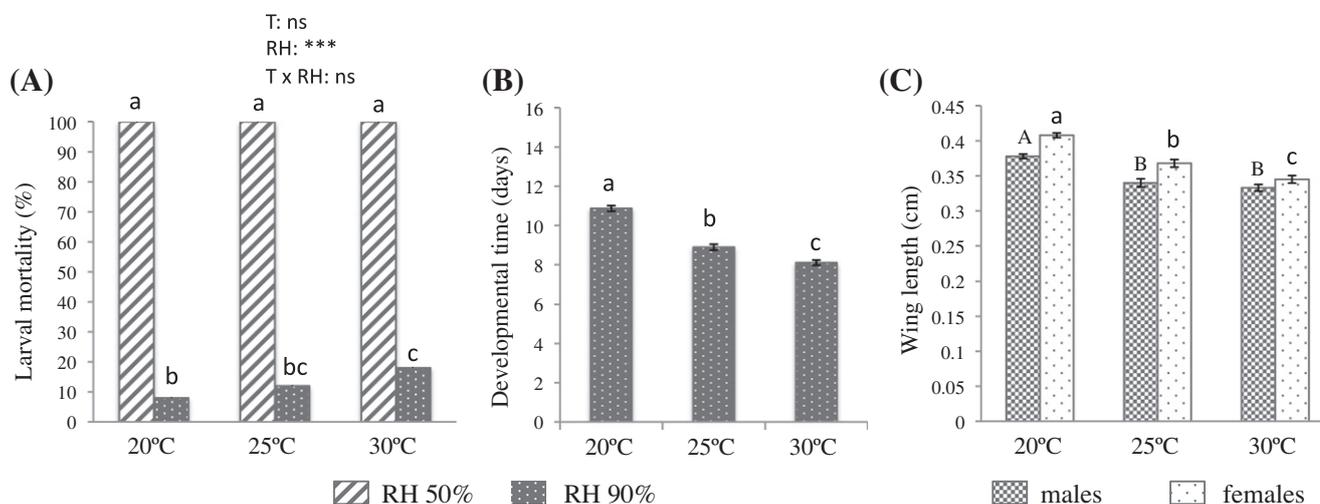


Fig. 2. Abiotic requirements for larvae. (A) Mortality rate (mean %). (B) Developmental time (mean + SEM). (C) Wing length of adults (mean + SEM). Different letters above bars indicate significant differences (GENLIN, LSD for mortality and developmental time, ANOVA and Turkey HSD for wing length).

$F = 48.48$; $P < 0.001$) suggesting that this reduction in body size is independent of a lower food intake.

3.2. Biotic requirements

The daily feeding rate of larvae (Fig. 4) was affected both by the level of food supply ($df = 1, 1115$; Wald statistic = 21.5; $P < 0.001$) and by the day of development ($df = 11, 1115$; Wald statistic = 7618.8; $P < 0.001$). The maximum aphid consumption was achieved 2 days later on the low food availability treatment, and the developmental time was also 2 days longer in this treatment (Fig. 4). A limited supply of aphids, had no impact on larval ($df = 1, 89$; Wald statistic = 0.0001; $P = 0.992$) nor pupal ($df = 1, 67$; Wald statistic = 1.323; $P = 0.254$) mortality of *S. rueppellii* (Fig. 5A). However, limited food supply increased the developmental time of larvae (Fig. 5B) compared with the high food availability treatment ($df = 1, 92$; Wald statistic = 140.7; $P < 0.001$), whereas pupal developmental time remained unaffected ($df = 1, 86$; Wald statistic = 0.192; $P < 0.663$). As we expected, limited food supply had a negative effect on the weight (Fig. 5C) of third instar larvae ($df = 53, t = 4.71, P < 0.001$), and newly formed pupae ($df = 68, t = 4.81, P < 0.001$). In the same way, the wing length of both adult females ($df = 17, t = 2.49, P = 0.023$) and males ($df = 15, t = 3.39, P = 0.004$) decreased with limited food supply during larval stage (Fig. 5D).

4. Discussion

4.1. Abiotic requirements

The results of this study show that abiotic conditions have a key role on the development of different immature stages of *S. rueppellii*. Pineda and Marcos-García (2008b) evaluated the composition and population dynamics of aphidophagous syrphids inside sweet-pepper greenhouses from southeastern Spain between 2004 and 2006. They found out that *S. rueppellii* was much more abundant than the rest of species in the years when drought periods happened earlier and lasted longer, suggesting that this species was the best adapted to the dry conditions occurring in Mediterranean areas compared with the other syrphid species identified, including *E. balteatus* and *Eupeodes corollae* (Fabricius). Additionally, such study showed that *S. rueppellii* appeared later in the season than the other syrphid species, when temperatures were higher. Based on that study, we expected that the performance of *S. rueppellii* would improve at high temperature and low humidity. In contrast to our initial expectations, our results do not support the hypothesis that *S. rueppellii* develops better under dry conditions. Specifically, this study shows that egg and larval stages are particularly susceptible to low relative humidity, whereas pupal stages are not affected by the humidity conditions (measured as developmental period, mortality rate and adult's wing length). However, the potential of this

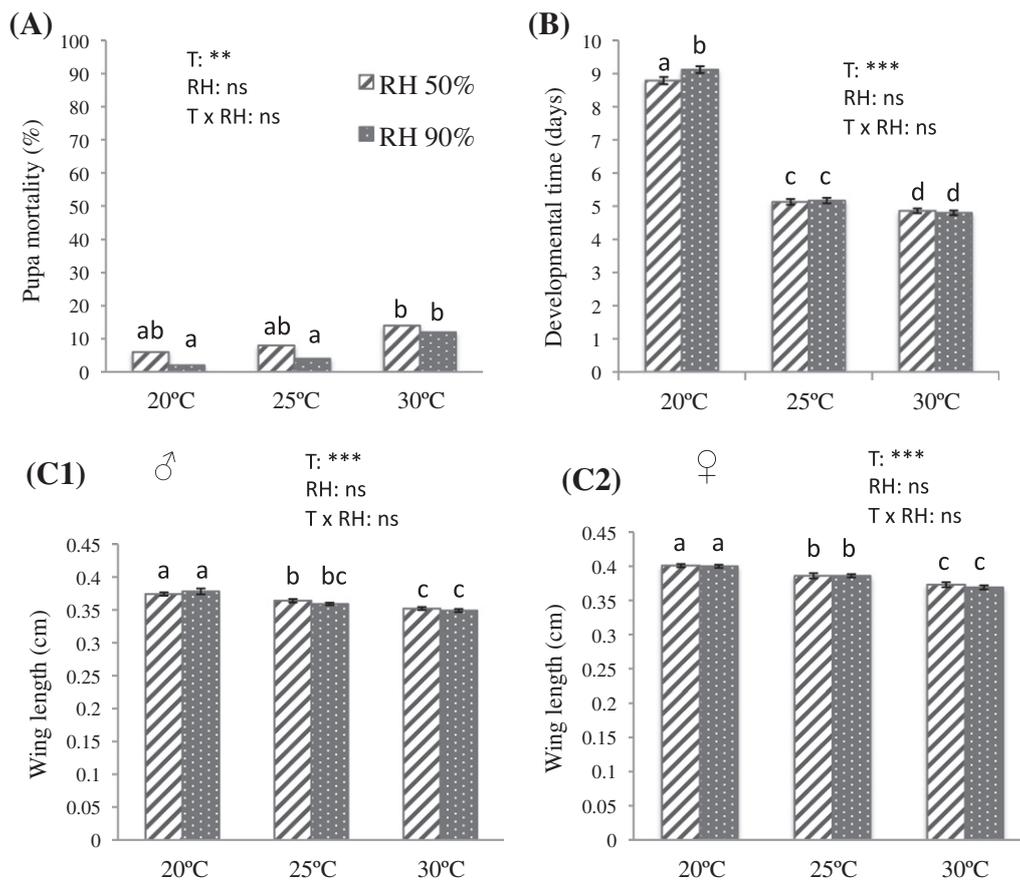


Fig. 3. Abiotic requirements for pupae. (A) Mortality rate (mean %). (B) Developmental time (mean + SEM), (C) Wing length of males and females (mean + SEM). Different letters above bars indicate significant differences (GENLIN, LSD for mortality and developmental time, two-way ANOVA and Turkey HSD for wing length).

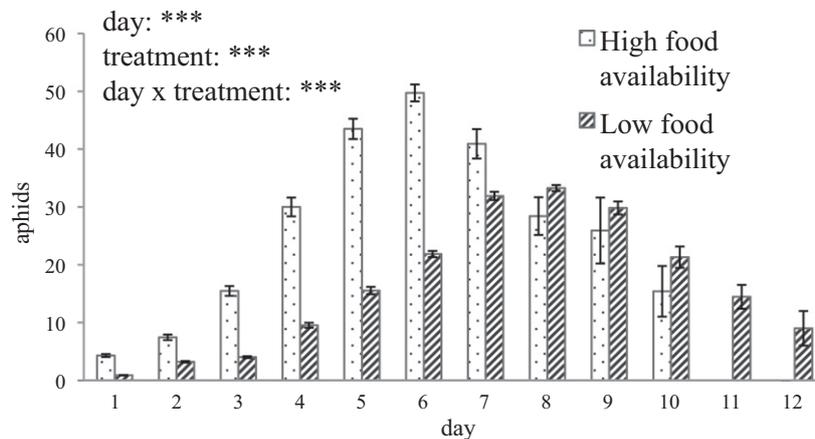


Fig. 4. Daily aphid consumption rate (mean + SEM) throughout larval stage on high and low food availability treatments. Data were analyzed with a GENLIN for repeated measures.

species to naturally establish on protected crops and efficiently control aphid populations would be favoured by the high humidity conditions occurring inside greenhouses.

Hoverflies may have several strategies to tolerate drought conditions in the field, such as the use of microhabitats or the adjustment of their activity schedules. Syrphid larvae are generally more active during the night than in daylight (Holmes, 1984; Vickerman and Sunderland, 1975), although we have observed in the field that *S. rueppellii* has also a voracious predatory activity during the day.

On the abaxial (lower) surface of leaves, which cannot be directly reached by light, a higher relative humidity and lower temperature occurs compared with the adaxial (upper) surface because of the higher stomata density (Gutschick, 1999). Personal observations both in laboratory and field conditions indicate that *S. rueppellii*'s females lay their eggs preferably on the reverse of leaves and larvae can normally be found here and on other areas of the plant where the humidity has been condensed. Regarding the pupal stage, almost all the pupation observed in controlled conditions

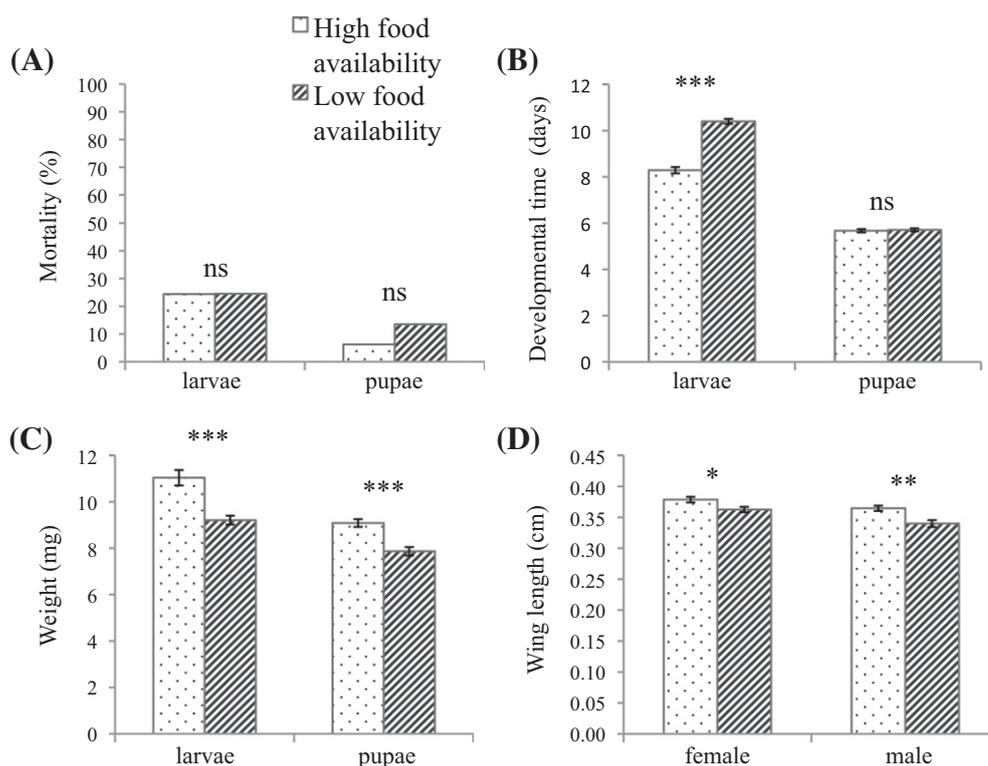


Fig. 5. Performance with different aphid supply. (A) Developmental time of larvae and pupae (mean + SEM). (B) Mortality rate of larvae and pupae (mean %). (C) Weight of larvae and pupae (mean + SEM). (D) Wing length of adults (mean + SEM). ns = not significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (GENLIN for developmental time and mortality, t -test for independent samples for body weight and wing length).

takes place in plant areas with a high condensation, such as the back of the leaves, places where a leaf is on top of the other, dead leaves or roots and fibres present on the substrate. These observations suggest that under low humidity conditions, like the ones occurring in outdoor crops or outside greenhouses, *S. rueppellii* could exploit these microhabitats where the optimal humidity and temperature conditions for its development and activity may be reached.

Pupa is the only stage for which mortality is affected by temperature independently of the relative humidity, increasing when the pupa is exposed to higher temperatures. This indicates that, although pupal developmental time and mortality are not affected by relative humidity, this immature stage is the most sensitive to the surrounding temperature. Development of all immature stages was completed faster when the temperature rose, with the shortest developmental period taking place at 30 °C. Honek and Kocourek (1988) and Saidov (1974) found this negative relation between temperature and developmental period in more than 20 species of aphidophagous insects, including syrphids such as *E. balteatus* and *Sphaerophoria scripta* (L.).

The relation between body size, fitness and temperature has been documented on a high number of animals, especially on insects (Atkinson, 1994), and it can be summarised in two rules. The first rule 'hotter is smaller' proposes that ectotherms that develop at higher temperatures will be relatively small as adults (Angilletta and Dunham, 2003; Atkinson, 1994), and our results on wing length support this pattern. The second rule 'Bigger is better' proposes that individuals with larger body size will tend to have greater performance and fitness than smaller individuals (Bonner, 2006; Peters, 1983) in the sense of a greater survival, fecundity and mating success (Kingsolver and Pfennig, 2004). According to this rule, our results of wing length suggest a negative effect of the temperature increase on *S. rueppellii* performance, as the mortality results also

show. Nevertheless, some authors (Frazier et al., 2006; Savage et al., 2004) suggest that there is another rule (*Hotter is better*), proposing that species that have adapted to high optimal temperature can also have enhanced fitness at high temperatures, through a shortened generation time (Roff, 2002). Interestingly, our results also support this hypothesis, since the three larval stages developed faster with increasing temperatures. Since *S. rueppellii* provides a case of a species that has evolutionarily adapted to warm climate, it will be an excellent candidate to evaluate whether the benefit of shorter developmental time caused by high temperatures overrides the fitness cost of the decrease in body size.

Immature stages of *E. balteatus*, the only syrphid species in commercial production, suffer a high mortality with temperatures over 25 °C (Hart et al., 1997). In previous studies, we monitored the temperature in several commercial greenhouses of southeastern Spain during two years, and temperatures in spring varied between 11 °C (during night) and 38 °C (in daytime). We believe that *S. rueppellii* is a high potential control agent on Mediterranean greenhouses, due to a better tolerance to the high temperatures present on these environments. Despite there are evidences that *S. rueppellii*'s performance decreases when developing at high temperatures, this is the most abundant species in Mediterranean greenhouses towards the end of spring, when the daily maximum temperature is over 25 °C, indicating that out of the species recorded, this hoverfly is the best adapted to the high temperature conditions present inside greenhouses (Pineda and Marcos-García, 2008b). Augmentative biological control is an important part of IPM programs, and the availability of several natural enemies that are effective under different abiotic conditions will contribute to the success of pest control under a changing climate. In addition, the use of native species and the high specificity of aphidophagous hoverflies ensures a lack of side effects to the environment and negative intraguild interactions with other natural enemies, which

is another key point for satisfactory results of biological control strategies.

4.2. Biotic requirements

Ovipositional preference by females has a profound effect on the performance of their offspring, ensuring the newly emerged larvae have enough food to develop (Sadegui and Gilbert, 2000). However, some indications imply that even small syrphid larvae must move between plants in search for new aphid colonies (Banks, 1968) as a single aphid colony may be insufficient to support larval development to maturity (Kan, 1988a, 1988b). *S. rueppellii* is able to complete its life cycle even under low aphid availability conditions, with survival of larvae not being affected by diet. This fact could allow the larvae to exploit small and developing aphid colonies, moving among different plants or areas within a plant, which is a very desirable feature on a biological control agent. Several authors state that aphid quantity and quality is a major factor influencing the development time of aphidophagous syrphids (Dziocck, 2005; Polak, 1980; Rojo et al., 1996). Limited food supply increases the developmental time of *S. rueppellii*'s larvae while, interestingly, the developmental period of pupal stage does not change in accordance with aphid's consumption throughout larval stage. This trend has also been observed on the hoverfly *E. corollae*, while in other species such as *E. balteatus*, pupal development shortens when larvae are provided with excess of aphids (Rojo et al., 1996). Nevertheless, a reduced weight of immature stages and wing length of adults is reached when aphid supply is not high enough. Consequently, larvae's diet has a major effect on body size of *S. rueppellii*, like has been reported on other hoverfly species like *E. corollae* and *E. balteatus* (Rojo et al., 1996). Body size is correlated with a large number of species' attributes that influence their fitness, including longevity, reproductive rate or resource use (Blackburn and Gaston, 1994; Harvey and Pagel, 1991).

Daily feeding rate under high food availability conditions reaches a peak once larvae have reached the third instar. Adams et al. (1987) and Soleyman-Nezhadiyan and Laughlin (1998) found that the last larval instar of syrphids is also the most voracious, been responsible of up to 90% of the total aphid consumption. Mean daily consumption under high food availability conditions was $26,11 \pm 4,89$ aphids/day, a slightly lower value than the one measured by Ming Hong and Quang Hung (2010) with the species *E. balteatus* feeding on *M. persicae* (31.4 ± 1.88 aphids/day). Under low food availability conditions, the maximum aphid consumption of *S. rueppellii*'s larvae is postponed two days, since third instar is reached later than in optimal food conditions. Our results agree with what has been exposed by several authors, which assure that the proportion of prey consumption during the first few days after eclosion is small (Adams et al., 1987; Barlow, 1979), and it decreases again towards the end of larval stage (Tenhumberg and Poehling, 1995).

Although the developmental period of the larvae is two days longer with limited aphid supply, the total aphid consumption is higher under high food availability conditions, being able to prey on nearly 220 aphids throughout this stage, a higher value than the one found by Hopper et al. (2011) with a species from the same genera, *Sphaerophoria sulphuripes* (Thomson) with a lifetime consumption of 194.44 third instar aphids. Even though aphid supply on the Low food availability treatment was below the optimal, *S. rueppellii*'s larvae hardly consumed all the aphids provided. The average number of non-preyed aphids that remained on the Petri dishes was 7.61 individuals (30% of the aphids supplied). A possible explanation to this may be that at very low aphid densities *S. rueppellii*'s larvae could be able to adapt their feeding rate according to the food availability conditions, as found by Tenhumberg and Poehling (1995) on some syrphids such as *E. balteatus* and *S. scripta*.

5. Conclusions

Because aphid populations grow exponentially, biological control strategies by using hoverflies should achieve a greater impact on aphid population during an early stage of the infestation (Tenhumberg and Poehling, 1995). Under low aphid density conditions, sublethal effects are observed on the *S. rueppellii* adults developed in such conditions, highlighting a reduced fitness in such conditions. According to this, the use of inoculative releases would not be effective, because under persistent low food availability conditions, the number of syrphids might not be sufficient to sustain a permanent population in the field and new releases would be needed in order to keep controlling the pest population. On the other hand, the fact that mortality rate of larvae does not increase even under low aphid density conditions, supports the potential use of this predator on augmentative control strategies through inundative releases. In addition, the fact that this species is adapted to the high humidity and temperature conditions similar to those occurring in Mediterranean greenhouses makes this species even more suitable for its use in these environments. However, estimating predatory efficiency of syrphid larvae based on laboratory estimates may lead to an overestimation on their actual impact on the pest in the field (Tenhumberg and Poehling, 1995). Additional factors may affect the efficacy and population dynamics of predators in field conditions, such as intraguild predation (Rosenheim et al., 1995), variation of environmental conditions and prey quality (Symondson et al., 2002), sublethal effects of pesticides (Desneux et al., 2007) or habitat management strategies (Landis et al., 2000), pointing out that field studies are needed in order to evaluate *S. rueppellii*'s effectiveness as an aphid control agent in commercial greenhouses.

Acknowledgments

We want to thank N. Estela, I. R. Steba and P. López for their help with insect cultures and experiments and E. Arcaya for her contribution with the preliminary bioassays. RAJ was supported by JAE Predoc CSIC scholarship (JAEPredoc_08_00457). The authors acknowledge the financial support from the Spanish Ministry of Science and Education (AGL2005-01449/AGR project).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biocontrol.2012.06.001>.

References

- Adams, T.H.L., Chambers, R.J., Dixon, A.F.G., 1987. Quantification of the impact of the hoverfly, *Metasyrphus corollae* on the cereal aphid, *Sitobion avenae*, in winter wheat – laboratory rates of kill. *Entomologia Experimentalis et Applicata* 43, 153–157.
- Angilletta, M.J., Dunham, A.E., 2003. The temperature-size rule in ectotherms: simple evolutionary explanations may not be general. *American Naturalist* 162, 332–342.
- Atkinson, D., 1994. Temperature and organism size – a biological law for ectotherms. *Advances in Ecological Research* 25, 1–58.
- Banks, C.J., 1968. Effects of insect predators on small populations of *Aphis fabae* in field. *Entomologia Experimentalis et Applicata* 11, 169–176.
- Barlow, C.A., 1979. Energy-utilization by larvae of a flower fly, *Syrphus corollae* (Diptera, Syrphidae). *Canadian Entomologist* 111, 897–904.
- Blackburn, T.M., Gaston, K.J., 1994. Animal body-size distributions – patterns, mechanisms and implications. *Trends in Ecology & Evolution* 9, 471–474.
- Blackman, R.L., Eastop, V.F., 2000. *Aphids on the World's Crops*. Wiley-Interscience, Chichester, UK.
- Blümel, S., 2004. Biological control of aphids on vegetable crops. In: Heinz, K.M., Driesche, V., Parella, M.P. (Eds.), *Biocontrol in Protected Culture*. Ball Publishing Batavia, IL, USA, pp. 297–312.
- Bonner, J.T., 2006. *Why Size Matters*. Princeton University Press, Princeton, NJ.

- Brewer, M.J., Elliott, N.C., 2004. Biological control of cereal aphids in North America and mediating effects of host plant and habitat manipulations. *Annual Review of Entomology* 49, 219–242.
- Chandler, A.E.F., 1968. Some factors influencing the occurrence and site of oviposition by aphidophagous Syrphidae (Diptera). *Annals of Applied Biology* 61, 435–446.
- Desneux, N., Decourtye, A., Delpuech, J.M., 2007. The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology* 52, 81–106.
- Díaz, B.M., Legarrea, S., Marcos-García, M.A., Fereres, A., 2010. The spatio-temporal relationships among aphids, the entomophthoran fungus, *Pandora neoaphidis*, and aphidophagous hoverflies in outdoor lettuce. *Biological Control* 53, 304–311.
- Dziocik, F., 2005. Evolution of prey specialization in aphidophagous syrphids of the genera *Melanostoma* and *Platycheirus* (Diptera: Syrphidae) – 1. Body size, development and prey traits. *European Journal of Entomology* 102, 413–421.
- Frazier, M., Huey, R.B., Berrigan, D., 2006. Thermodynamics constrains the evolution of insect population growth rates: 'warmer is better'. *The American Naturalist* 168, 512–520.
- Freier, B., Boller, E.F., 2009. Integrated pest management in Europe – History, policy, achievements and implementation. In: Peshin, R., Dhawan, A.K. (Eds.), *Integrated Pest Management: Dissemination and Impact*. Springer, Netherlands, pp. 435–454.
- Freier, B., Triltsch, H., Mowes, M., Moll, E., 2007. The potential of predators in natural control of aphids in wheat: results of a ten-year field study in two German landscapes. *Biocontrol* 52, 775–788.
- Food and Agriculture Organization of the United Nations. 2009. FAOSTAT Database. FAO, Rome, Italy.
- Gutschick, V.P., 1999. Biotic and abiotic consequences of differences in leaf structure. *New Phytologist* 143, 3–18.
- Haenke, S., Scheid, B., Schaefer, M., Tscharnkte, T., Thies, C., 2009. Increasing syrphid fly diversity and density in sown flower strips within simple vs. complex landscapes. *Journal of Applied Ecology* 46, 1106–1114.
- Hart, A.J., Bale, J.S., Fenlon, J.S., 1997. Developmental threshold, day-degree requirements and voltinism of the aphid predator *Episyrphus balteatus* (Diptera: Syrphidae). *Annals of Applied Biology* 130, 427–437.
- Harvey, P.H., Pagel, M.D., 1991. *The Comparative Method in Evolutionary Biology*. Oxford University Press.
- Holmes, P.R., 1984. A field study of the ecology of the grain aphid *Sitobion avenae* and its predators. *Bulletin of Entomological Research* 72, 623–631.
- Honek, A., Kocourek, F., 1988. Thermal Requirements for Development of Aphidophagous Coccinellidae (Coleoptera), Chrysopidae, Hemerobiidae (Neuroptera) and Syrphidae (Diptera) – Some General Trends. *Oecologia* 76, 455–460.
- Hopper, J.V., Nelson, E.H., Daane, K.M., Mills, N.J., 2011. Growth, development and consumption by four syrphid species associated with the lettuce aphid, *Nasonovia ribisnigri*, in California. *Biological Control* 58, 271–276.
- Kan, E., 1988a. Assessment of aphid colonies by hoverflies-II-Pea aphids and 3 Syrphid species, *Betasyrphus serarius* (Wiedemann), *Metasyrphus frequens* Matsumura and *Syrphus vitripennis* (Meigen) (Diptera, Syrphidae). *Journal of Ethology* 6, 135–142.
- Kan, E., 1988b. Assessment of aphid colonies by hoverflies-I-Maple aphids and *Episyrphus balteatus* (De Geer) (Diptera, Syrphidae). *Journal of Ethology* 6, 39–48.
- Kingsolver, J.G., Pfennig, D.W., 2004. Individual-level selection as a cause of Cope's rule of phyletic size increase. *Evolution* 58, 1608–1612.
- Landis, D.A., Wratten, S.D., Gurr, G.M., 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* 45, 175–201.
- Ming Hong, B., Quang Hung, H., 2010. Effect of Temperature and Diet on the Life Cycle and Predatory Capacity of *Episyrphus balteatus* (De Geer) (Syrphidae: Diptera) cultured on *Aphis Gossypii* (Glover). *International Society for Southeast Asian Agricultural Sciences* 16, 98–103.
- Minks, A.K., Harrewijn, P., 1989. *Aphids – Their biology, natural enemies and control*. Elsevier Science Publishers B.V., Amsterdam.
- Peters, R.H., 1983. *The Ecological Implications of Body Size*. Cambridge University Press, Cambridge, UK.
- Pineda, A., Marcos-García, M.A., 2008a. Introducing barley as aphid reservoir in sweet-pepper greenhouses: effects on native and released hoverflies (Diptera: Syrphidae). *European Journal of Entomology* 105, 531–535.
- Pineda, A., Marcos-García, M.A., 2008b. Seasonal abundance of aphidophagous hoverflies (Diptera: Syrphidae) and their population levels in and outside Mediterranean sweet pepper greenhouses. *Annals of the Entomological Society of America* 101, 384–391.
- Pineda, A., Marcos-García, M.A., 2008c. Use of selected flowering plants in greenhouses to enhance aphidophagous hoverfly populations (Diptera: Syrphidae). *Annales de la Societe Entomologique de France* 44, 487–492.
- Pineda, A., Morales, I., Marcos-García, M.A., Fereres, A., 2007. Oviposition avoidance of parasitized aphid colonies by the syrphid predator *Episyrphus balteatus* mediated by different cues. *Biological Control* 42, 274–280.
- Polak, B., 1980. The influence of food density and the size of food rations on the consumption and development of aphidophagous Syrphidae (Diptera). *Annals of Zoology* 35, 105–115.
- Rabasse, J.M., Steenis, M.J., 2002. Biological control of aphids. In: Albajes, R., Lodovica Gullino, M., Lenteren, J.C., Elad, Y. (Eds.), *Integrated Pest and Disease Management in Greenhouse Crops*. Springer, Netherlands, pp. 235–243.
- Ramakers, P.M.J., 2004. IPM program for sweet pepper. In: Heinz, K.M., Driesche, V., Parrella, M.P. (Eds.), *Biocontrol in Protected Culture*. Ball Publishing Batavia, IL, USA, pp. 439–455.
- Roff, D.A., 2002. *Life History Evolution*. Sinauer Associates, Sunderland, MA.
- Rojo, S., Hopper, K.R., Marcos-García, M.A., 1996. Fitness of the hoverflies *Episyrphus balteatus* and *Eupeodes corollae* faced with limited larval prey. *Entomologia Experimentalis Et Applicata* 81, 53–59.
- Rosenheim, J.A., Kaya, H.K., Ehler, L.E., Marois, J.J., Jaffee, B.A., 1995. Intraguild predation among biological control agents – theory and evidence. *Biological Control* 5, 303–335.
- Sadegui, H., Gilbert, F., 2000. Aphid suitability and its relationship to oviposition preference in predatory hoverflies. *Journal of Animal Ecology* 69, 771–784.
- Saidov, A.K., 1974. Effect of different factors on growth and development of syrphid larvae. *Uzbekskii Biologicheskii Zhurnal Armenii* 1, 47–49.
- Sanchez, J.A., La-Spina, M., Michelena, J.M., Lacasa, A., de Mendoza, A.H., 2011. Ecology of the aphid pests of protected pepper crops and their parasitoids. *Biocontrol Science and Technology* 21, 171–188.
- Savage, V.M., Gillooly, J.F., Brown, J.H., West, G.B., Charnov, E.L., 2004. Effects of body size and temperature on population growth. *American Naturalist* 163, 429–441.
- Shipp, J.L., Van Houten, Y.M., 1997. Influence of temperature and vapor pressure deficit on survival of the predatory mite *Amblyseius cucumeris* (Acari: Phytoseiidae). *Environmental Entomology* 26, 106–113.
- Soleyman-Nezhadiyan, E., Laughlin, R., 1998. Voracity of larvae, rate of development in eggs, larvae and pupae, and flight seasons of adults of the hoverflies *Melangyna viridiceps* Macquart and *Symosyrphus grandicornis* Macquart (Diptera: Syrphidae). *Australian Journal of Entomology* 37, 243–248.
- Speight, M.C.D., 2005. Species accounts of European Syrphidae (Diptera). In: Speight, M.C.D., Castella, E., Sarthou, J.-P., Monteil, C. (Eds.), *Syrph the Net, the Database of European Syrphidae*. Syrph the Net Publications, Dublin, Ireland.
- Stubbs, A.E., Falk, S.J., 1983. *British Hoverflies: An Illustrated Identification Guide*. British Entomological and Natural History Society.
- Symondson, W.O.C., Sunderland, K.D., Greenstone, M.H., 2002. Can generalist predators be effective biocontrol agents? *Annual Review of Entomology* 47, 561–594.
- Tenhuberg, B., 1995. Estimating predatory efficiency of *Episyrphus balteatus* (Diptera: Syrphidae) in cereal fields. *Environmental Entomology* 24, 685–691.
- Tenhuberg, B., Poehling, H.-M., 1995. Syrphids as natural enemies of cereal aphids in Germany: aspects of their biology and efficacy in different years and regions. *Agriculture, Ecosystems & Environment* 52, 39–43.
- van Lenteren, J., 2012. The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake. *BioControl* 57, 1–20.
- Vickerman, G.P., Sunderland, K.D., 1975. Arthropods in cereal crops – Nocturnal activity, vertical distribution and aphid predation. *Journal of Applied Ecology* 12, 755–766.
- Wiedemann, R.N., Wilson, L.T., 1996. Zoophytophagous Heteroptera summary and future research needs. In: Alomar, O., Wiedemann, R.N. (Eds.), *Zoophytophagous Heteroptera Implications for Life History and Integrated Pest Management*. Entomological Society of America, Lanham, MD.
- Zhang, Y., Shipp, J.L., 1998. Effect of temperature and vapor pressure deficit on the flight activity of *Orius insidiosus* (Hemiptera: Anthracoridae). *Environmental Entomology* 27, 736–742.