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# One stone; two birds: concurrent pest control and pollination services provided by aphidophagous hoverflies

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ABSTRACT

Biological pest control and pollination are vital ecosystem services that are usually studied in isolation, given that they are typically provided by different guilds of arthropods. Hoverflies are an exception, as larvae of many aphidophagous species prey upon agriculturally important aphid pests, while the adults feed on floral nectar and pollen and can be effective pollinators of important agricultural crops. While this is widely known, the concurrent provisioning of pest control and pollination by aphidophagous hoverflies has never been studied. Here, we compared the potential of two aphidophagous hoverflies, *Eupeodes corollae* and *Sphaerophoria rueppellii* to concurrently control the aphid *Myzus persicae* and improve pollination (measured as seed set and fruit weight) in sweet pepper (*Capsicum annuum*). In a first semi-field experiment, aphid populations were reduced by 71 and 64% in the *E. corollae* and *S. rueppellii* treatments, respectively, compared to the control. In a second experiment, the aphid population reduction was 80 and 84% for *E. corollae* and *S. rueppellii*, respectively. Fruit yield in aphid-infested plants, was significantly increased by 88 and 62% for *E. corollae* and *S. rueppellii*, respectively, as compared to the control. In a separate trial, where the plants were not infested with aphids, yield increased by 29 and 11% for *E. corollae* and *S. rueppellii*, respectively, even though these differences were not statistically significant. The increase in seed set in the hoverfly treatments was statistically significant in both pollination experiments, i.e. independently of the presence of aphids. These results demonstrate, for the first time, that aphidophagous hoverflies can concurrently provide pest control and pollination services.

## 1. Introduction

Biological pest control and pollination are vital services provided by insects in natural and managed ecosystems (Egan et al., 2020; EU, 2015). Both of these ecosystem services can have a crucial impact on crop productivity with the additional sustainability gain deriving from controlling pests naturally without the need to use environmentally harmful pesticides (Power, 2010). Despite the fact that biological control and pollination may interact in affecting crop productivity, they are studied in isolation given that, usually, each ecosystem service is provided by different guilds of arthropods. In a recent study, Gagic et al., (2019) examined the interaction of biological pest control and pollination in cotton, however, in this study as well, these services were provided by different species of arthropods. In practice, the provisioning of biological pest control and pollination can be supported via habitat management; by selecting/promoting the suitable plants that provide specific floral resources catering to either natural enemies or pollinators (Campbell et al., 2012; Tschumi et al., 2016; van Rijn and Wäckers, 2016; Wäckers and van Rijn, 2012; Winqvist et al., 2011). From the point of view of sustainable crop management, it would be of great interest to have concurrent provisioning of pollination and biological pest control services by the same insect species. Hoverflies (Diptera: Syrphidae) hold great promise for providing dual ecosystem services (Doyle et al., 2020; Dunn et al., 2020; Wotton et al., 2019), however, to our knowledge, the concurrent provisioning of biological control and pollination by the same hoverfly species has never been studied.

The dipteran family Syrphidae includes more than 6.000 species, known as hoverflies or flower flies (Dunn et al., 2020). The adults of the majority of the hoverfly species depend on flowers to obtain nectar as an energy source and pollen for egg maturation (Almohamad et al., 2009; van Rijn and Wäckers, 2016). As such, they may contribute to the pollination of many plant species including economically important crops (Jauker and Wolters, 2008; Rader et al., 2016, 2009). The larvae of approximately one third of the hoverfly species are voracious predators of mainly aphids (Bellefeuille et al., 2019; Hodgkiss et al., 2018; Hopper et al., 2011) as well as some other agriculturally important pests, such as, thrips and spider mites (Dunn et al., 2020). Despite the

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vast number of aphidophagous hoverfly species, with potential applied interest for aphid control, to date, only two species are commercially available, namely *Episyrphus balteatus* (De Geer) (Katzbiotech, 2020) and more recently *Sphaerophoria rueppellii* (Wiedemann) (Amorós-Jiménez et al., 2014, 2012). Both species are migratory and very common in Europe with *E. balteatus* being more abundant in central and northern Europe while *S. rueppellii* more abundant in southern Europe (Gómez-Polo et al., 2014; Pineda and Marcos-García, 2008; Speight, 2011). Interestingly, several studies have demonstrated the potential of *E. balteatus* to pollinate a number of crops (Hodgkiss et al., 2018; Jauker and Wolters, 2008) but there are no pollination studies yet for *S. rueppellii*. Similarly, to our knowledge, only two species of non-aphidophagous hoverflies, *Eristalis tenax* (L.) and *Eristalinus aeneus* (Scopoli), are commercially available for pollination in Europe (Polyfly, 2020). While the adults of both species are honeybee mimics and are effective pollinators, their larvae are saprophagous, feeding on decaying plant material, rather than being pest predators (Jarlan et al., 1997a; Rader et al., 2009). Despite the proven efficacy for aphid control, on the one hand, and pollination on the other, the use of aphidophagous hoverflies in biological control and Integrated Pest Management (IPM) programs is relatively limited as compared to other aphid arthropod natural enemies. According to Dunn et al., 2020, this is due to serious knowledge gaps about the performance of hoverflies in semi-field and field conditions and due to the lack of cost-efficient and reliable mass-rearing systems. Thus, selecting promising hoverfly species for testing their performance in (semi-) field conditions could help address these knowledge gaps.

The hoverfly genus *Eupeodes* comprises highly migratory species with a great potential for aphid biological control due to the voracity of their larvae. The species *Eupeodes corollae* (F.) for instance, consumes up to 1000 aphids to complete larval development (Pu et al., 2019; Whittingham, 1991). *Eupeodes corollae* is one of the most abundant hoverfly species in Europe with an extremely wide distribution spanning from Iceland in the north to South Africa in the south and from the Azores in the east up to China in the west (Rojo et al., 1997; Speight, 2011). *Eupeodes corollae* has been reported to be one of the most abundant aphidophagous hoverfly species occurring naturally in vegetable greenhouse crops in southern Spain (Gómez-Polo et al., 2014; Pineda and Marcos-García, 2008). In the Americas, the species *E. fumipennis* (Thomson) consumed more than double the biomass of lettuce aphids when compared to three other aphidophagous hoverflies (Hopper et al., 2011). Furthermore, the American species *E. americanus* maintained adult egg laying and larval voracity at temperature as low as 12 °C (Bellefeuille et al., 2019). Finally, the European species *Eupeodes latifasciatus* (Macquart) has been found to be an effective pollinator of commercial strawberry, and crucially, showed enhanced pollination efficacy when compared to the hoverfly *E. balteatus* (Hodgkiss et al., 2018). Despite the high potential of the *Eupeodes* species, and *E. corollae* in particular, these species have never been tested as dual providers of aphid control and pollination.

Greenhouse sweet pepper *Capsicum annuum* L., is a high value crop where aphids, especially the green peach aphid *Myzus persicae* (Sulzer) (Hemiptera: Aphididae), are major pests (van der Ent et al., 2017). Aphid biological control in sweet-pepper is usually based on preventative and/or curative releases of several natural enemies to cope with the exponential growth of the aphid populations (Beltrà et al., 2018; Boulanger et al., 2018; Brenard et al., 2020; Fratoni et al., 2020; Jandricic et al., 2016; Messelink et al., 2012). While sweet-pepper has hermaphrodite, self-pollinating flowers, the use of pollinating insects such as bumblebees results in increased seed set (number of seeds per fruit) and fruit weight (Roldán Serrano and Guerra-Sanz, 2006). As is the case in many plant species, variables of plant reproductive success, such as, seed set and fruit weight can serve as an index of pollination efficacy given that both parameters are correlated with pollen load (Roldán Serrano and Guerra-Sanz, 2006). The use of hoverflies, especially species with high aphid killing rates, such as *E. corollae*, offer a great opportunity to test for concurrent provisioning of aphid control and pollination in sweet pepper. Recently we managed to develop a cost-efficient and reliable mass-rearing system for *E. corollae* (Pekas, A. unpublished). We also include *S. rueppellii* in our study because it is a commercially available species increasingly employed for aphid biocontrol during the last years in Europe. Thus, in the present greenhouse study we firstly, sought to evaluate the potential of *E. corollae* and *S. rueppellii* in providing concurrently pest control and pollination services to sweet pepper. Secondly, we compared *E. corollae* and *S. rueppellii* performance as pest controllers and pollinators of sweet peppers.

## 2. Materials & methods

### 2.1. Plants and insects

All experiments were carried out in a greenhouse at the GreenLab facilities of Biobest N.V. in Westerlo (Belgium). Temperature and humidity in the greenhouse were recorded automatically (Temperature humidity sensor, 30 MHz, The Netherlands). Sweet pepper plants, cultivar IDS (Rijk Zwaan), were grown from seeds sown in tray cells and subsequently transplanted in plastic pots (30 cm diameter) filled with potting soil (50% black + 50% white peat) (Greenyard, The Netherlands). *Sphaerophoria rueppellii* and *E. corollae* used in the experiments were reared for multiple generations on an *ad libitum* supply of *M. persicae* on sweet pepper plants at Biobest Belgium. Aphid colonies were also reared on the same sweet pepper variety for multiple generations.

### 2.2. Aphid control experiments

#### 2.2.1. Experiment A

This experiment was conducted from June 5th until June 24th 2019. The average temperature and relative humidity (RH) were (mean ± SE) 24.04 ± 0.04 °C (min 14.6 °C; max 39.6 °C) and 69.36% ± 0.06% RH (min 44.4%; max 89.4%), respectively. Ten sweet pepper plants (approximately 0.5 m high, all bearing flowers) were placed at a 0.5 × 0.5 m grid in a walk-in cage (1.8 m wide 2.5 m long 2 m high), covered with thrips proof screen net and with double door sealed with a zipper. The number of flowers per plant was counted and fruitlets already set before introduction of insects (see later) were removed from the plants. Each plant was infested with five adults of *M. persicae*. The aphids were transferred with a fine hairbrush on a marked leaf in the middle of the plant. Four cages (=replicates) were used to release adults of *E. corollae* and another four cages to release adults of *S. rueppellii.* As a control, we used four additional cages containing sweet-pepper plants infested with five aphids per plant, receiving no hoverflies. Two days after the introduction of the aphids, and subsequently weekly during four consecutive weeks, 20 adult hoverflies (<24 h old; 1:1 sex ratio) from each species were collected from the rearing and released in each experimental cage. Experimental cages were aligned in two rows, of eight and four cages respectively. Treatments were alternated in the order *E. corollae*, *S. rueppellii*, and control. We assessed the aphid populations on the release leaf and three randomly selected leaves from the lower (n = 1), middle (n = 1) and upper (n = 1) part of each plant. Assessments took place repeatedly at intervals of three to five days following the release of the hoverflies. In addition, the number of hoverfly eggs or larvae present on each sampled leaf and hoverfly adults per cage was recorded. All assessments took place between 10:00 and 14:00 h.

#### 2.2.2. Experiment B

This experiment was conducted from September 24th until October 24th, 2019. The average temperature and relative humidity were 20.73 ± 0.02 °C (min 13.7 °C; max 41.1 °C) and 64 ± 0.06% (min 35.5; max 87.3%), respectively. The experimental protocol was identical as in the first experiment with the exception that eight sweet pepper plants were introduced per cage and that we used six experimental cages for the release of each hoverfly species and two cages as control. Assessments of the aphid and hoverfly abundance were performed twice a week between 10:00 and 14:00 h.

### 2.3. Pollination experiments

#### 2.3.1. With aphids

After the end of the assessments of the first experiment above, plants were kept until July 24th 2019 to allow fruits to grow. Subsequently, all fruits were collected from the plants and weighed individually while ten of the heaviest fruits per cage were cut open in order to count the number of seeds.

#### 2.3.2. Without aphids

In a separate experiment, we assessed the contribution of the hoverflies to pollination without the presence of aphids on the plants. This experiment was conducted from August 16th until October 8th, 2019. We used four experimental cages, containing ten plants each (sweet pepper cultivar IDS, Rijk Zwaan), to release *S. rueppellii* and another four cages to release *E. corollae* adults (<24 h old; 20 adults per cage weekly at a 1:1 sex ratio, during the first four weeks). Four additional cages served as control, i.e. without releasing any hoverflies. The number of flowers per plant was counted and the fruitlets already set before the release of the hoverflies were removed from the plants.

In this experiment, fruits were collected twice, at 31 days and 53 days after the release of the hoverflies. All fruits were collected from the plants and weighed individually while ten of the heaviest fruits per cage were cut open in order to count the number of seeds.

### 2.4. Statistical analyses

We used generalized linear models (GLM) assuming quasi-Poisson error distribution to compare the number of flowers (dependent variable) among treatments (explanatory variable), at the beginning of the experiments, before the introduction of the insects.

Linear mixed effects models using the *lme* function from the *nlme* package (Pinheiro et al., 2018) were constructed to compare the number (sum from all replicates per treatment) of aphids, eggs, larvae and adults of hoverflies (dependent variables) among treatments. Treatment was the fixed factor and replicate nested within assessment date the random factor. The same approach was employed to compare the number of seeds per fruit in the pollination experiment without aphids where fruits were collected in two dates (replicate nested within assessment date as the random factor). In Experiment A (one harvest date), the number of seeds per fruit was compared among treatments with a model with replicate as random factor.

A linear mixed effects model with yield (total fruit weight per treatment) as dependent variable, treatment as fixed factor and replicate as random factor was used to compare yield among treatments. The sum of fruit yield from both harvest dates was used as the dependent variable in the pollination experiment without aphids.

Validation of the linear mixed effects models was done visually by plotting the residuals versus the fitted values. In all analyses, when significant effects were found the *glht* function from the *multcomp* package was used to perform Tukey HSD tests for post-hoc pairwise comparisons (Hothorn et al., 2008). All statistical analyses were carried out in R v.3.5.1 (R Core Team, 2018).

## 3. Results

### 3.1. Aphid control experiments

Aphid numbers differed significantly among treatments in both experiments (Experiment A: $F_{2,9} = 5.12$, $P = 0.032$; Experiment B: $F_{2,11} = 46.76$, $P < 0.0001$) (Fig. 1A). At the end of Experiment A, aphid numbers were 71% and 64% lower in the *E. corollae* and *S. rueppellii* treatments, respectively, compared to the control. In the Experiment B, aphid populations were reduced by 80% and 84% in the *E. corollae* and *S. rueppellii* treatments, respectively, compared to the control. No significant differences were found regarding aphid suppression between hoverfly species for both experiments (Tukey post-hoc tests $P = 0.957$ and $P = 0.819$).

In Experiment A, the number of hoverfly eggs and larvae was similar for both hoverfly species (eggs: $F_{1,6} = 0.012$, $P = 0.914$; larvae: $F_{1,6} = 0.118$, $P = 0.742$) (Fig. 1B & C). Regarding adult abundance we found no significant differences either ($F_{1,6} = 0.028$, $P = 0.872$) (Fig. 1D).

In Experiment B, the number of hoverfly eggs was not statistically different between treatments ($F_{1,10} = 1.61$, $P = 0.232$). The abundance of larvae was significantly higher in the *S. rueppellii* than in the *E. corollae* treatment ($F_{1,10} = 11.41$, $P = 0.007$). The number of *S. rueppellii* adults was significantly higher compared to *E. corollae* ($F_{1,10} = 13.46$, $P = 0.004$).

### 3.2. Pollination experiments

#### 3.2.1. With aphids

The number of flowers was not significantly different among treatments (GLM: $F_{2,9} = 0.148$; $P = 0.864$). Adults of both hoverfly species were seen regularly visiting the sweet pepper flowers.

Fruit yield differed significantly among treatments ($F_{2,9} = 23.11$; $P < 0.0001$) (Fig. 2). The experimental cages were *E. corollae* (3175 ± 178 g; mean ± SE) and *S. rueppellii* (2746 ± 178 g) were released provided a significantly higher fruit yield compared to the control (1692 ± 111 g). This was equivalent to an increase of 87.6% and 62.2% in yield for *E. corollae* and *S. rueppellii*, respectively, as compared to the control. No significant difference in fruit yield was found between hoverfly species ($P = 0.136$).

Seed set was significantly higher in the hoverfly treatments as compared to the control ($F_{2,9} = 25.01$; $P < 0.0001$; *E. corollae*: 299 ± 15.17 seeds per fruit; (mean ± SE); *S. rueppellii*: 217 ± 15.90; control 145 ± 15.14) (Fig. 3). Seed set was significantly higher (37.8%) in the cages where *E. corollae* was released compared to the fruits collected from the cages where *S. rueppellii* was released ($P < 0.001$).

#### 3.2.2. Without aphids

The number of flowers per treatment was not significantly different among treatments (GLM: $F_{2,9} = 0.05$; $P = 0.947$). Although fruit yield was increased in the hoverfly treatments as compared to the control (*E. corollae*: 4190 ± 313 g; increase by 29.28%; *S. rueppellii*: 3600 ± 613 g; increase by 11.08%; control: 3241 ± 334 g), the differences were not statistically significant ($F_{2,9} = 1.17$; $P = 0.351$) (Fig. 4).

Seed set was significantly higher in the hoverfly treatments compared to the control ($F_{2,9} = 5.26$; $P = 0.03$; *E. corollae*: 174 ± 15.59 seeds per fruit; (mean ± SE); *S. rueppellii*: 148 ± 16.78; control 91 ± 10.81) (Fig. 5). No significant differences were found in seed set between *E. corollae* and *S. rueppellii* ($P = 0.705$).

## 4. Discussion

Our results show that the aphidophagous hoverflies *E. corollae* and *S. rueppellii* can concurrently provide biological pest control and pollination in greenhouse sweet pepper. Both species significantly reduced the aphid populations on the sweet pepper plants under experimental conditions, while concurrently increasing seed set and fruit yield compared to the control. To our knowledge, this is the first study to demonstrate and quantify the concurrent delivery of both ecosystem services provided by hoverflies. Moreover, our study provides the first data on the performance of *E. corollae*, a potentially new aphid biocontrol agent, in a greenhouse experiment. Overall, these results have important practical implications, both for the sustainable management

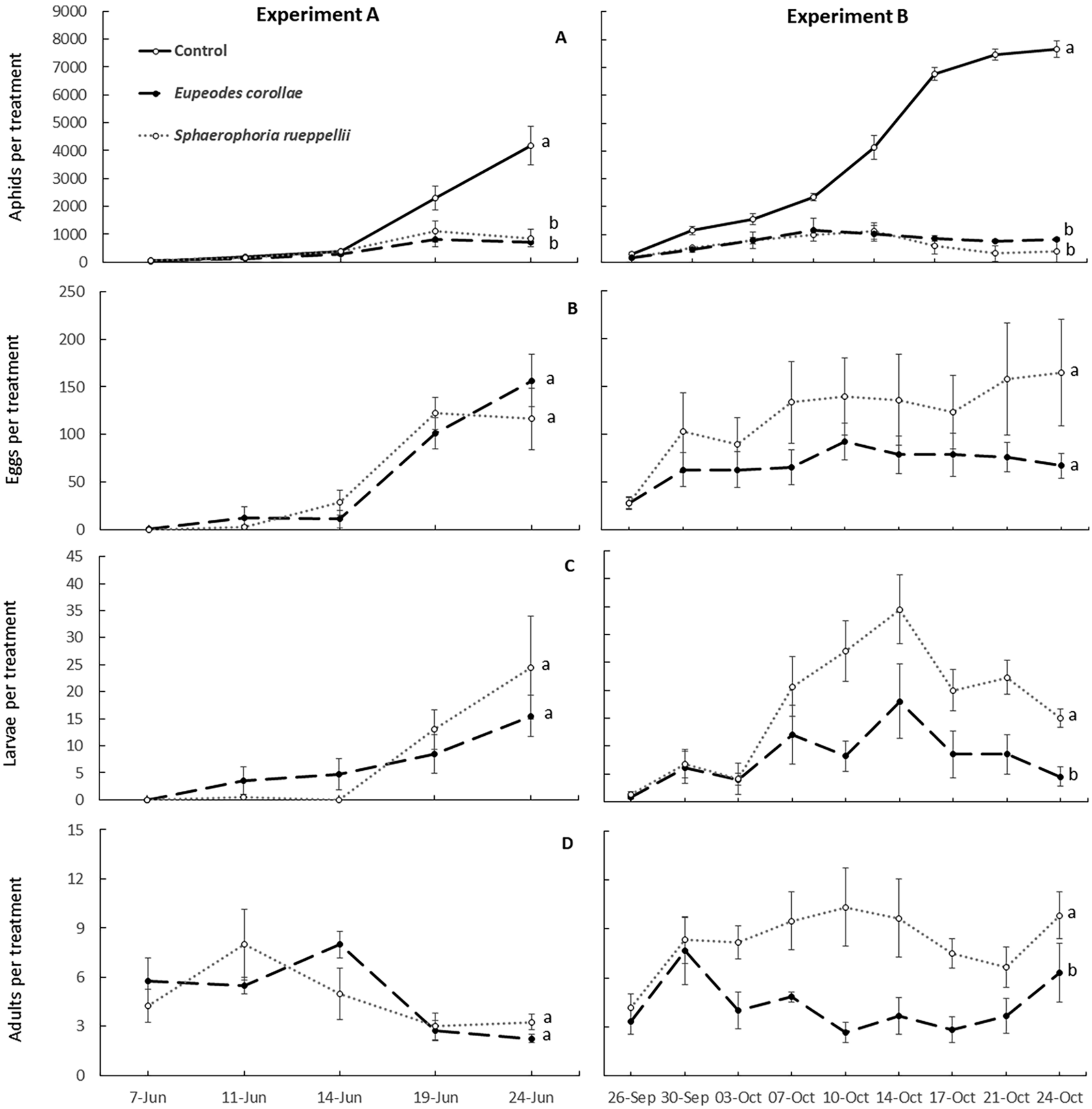


**Fig. 1.** Mean (±SE) number of A) aphids and B) hoverfly eggs, C) hoverfly larvae and D) hoverfly adults per treatment in two greenhouse experiments. Treatments include the release of either *Eupeodes corollae* or *Sphaerophoria rueppellii* or no release of hoverflies (control) in experimental cages containing plants infested with the aphid *Myzus persicae*. Different letters denote statistically significant differences at $P < 0.05$.

of greenhouse crops, such as sweet pepper, and for the management of ecosystem services in natural ecosystems.

### 4.1. Aphid control

*Sphaerophoria rueppellii* has already been employed successfully in biocontrol programs against aphids in sweet pepper and other crops in the Mediterranean and norther Europe (Vaello et al., 2019). In our experiments, *E. corollae* and *S. rueppellii* had a similar performance in controlling the aphid populations on the sweet-pepper plants. *E. corollae* was not applied in biological control programs up to date because it was not commercially available. Thus, our findings are interesting from an applied point of view in the sense that *E. corollae* looks like a promising new species for aphid biological control.

Previous studies suggested that *E. corollae* has some very interesting attributes for aphid biocontrol, such as high larval voracity and relatively higher tolerance to low temperatures. *E. corollae* is reported to consume up to 1000 aphids (*Aphis craccivora* Koch) to complete larval development or on average 126 aphids/day (Pu et al., 2019). In comparison, *S. rueppellii* consumes up to approximately 200 aphids (*M. persicae*) to complete larval development (26.11 aphids/day) (Amorós-Jiménez et al., 2012). The other commercially available hoverfly, *E. balteatus,* consumes 232 aphids (*M. persicae*) to complete larval development (31.4/day) (Hong and Hung, 2010). Other commercially

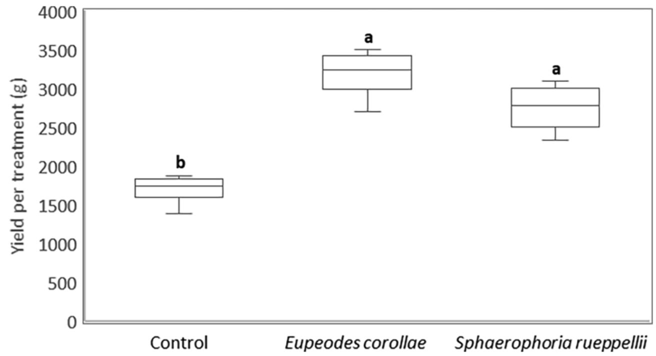


**Fig. 2.** Fruit yield (g) from experimental cages with sweet pepper plants visited by the hoverflies *Eupeodes corollae* or *Sphaerophoria rueppellii* or control cages where plants were not visited by hoverflies. Plants in all treatments were originally infested with the aphid *Myzus persicae*. Different letters denote statistically significant differences at $P < 0.05$.

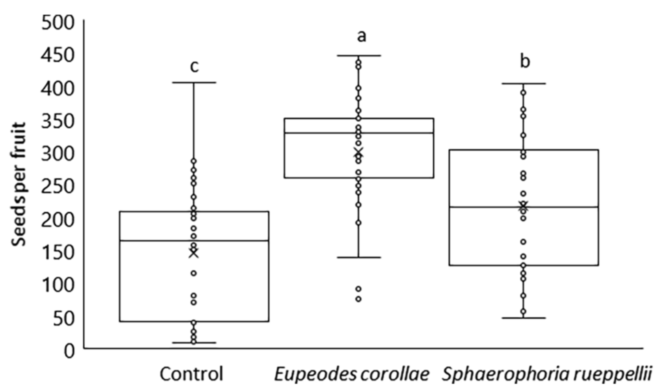


**Fig. 3.** Number of seeds per fruit collected from experimental cages with sweet pepper plants visited by the hoverflies *Eupeodes corollae* or *Sphaerophoria rueppellii* or control cages where plants were not visited by hoverflies. In all treatments, sweet pepper plants were initially infested with the aphid *Myzus persicae*. Different letters denote statistically significant differences at $P < 0.05$.

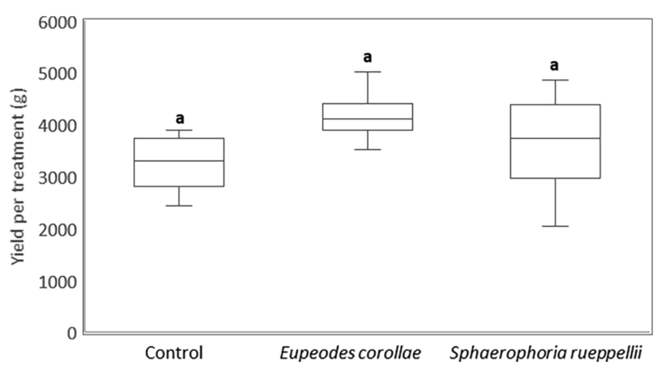


**Fig. 4.** Fruit yield (g) from experimental cages with sweet pepper plants visited by the hoverflies *Eupeodes corollae* or *Sphaerophoria rueppellii* or control cages where plants were not visited by hoverflies. Plants in all treatments were not infested with aphids. Boxplots sharing the same letter do not differ significantly at $P > 0.05$.

available aphid predators, such as the gall midge *Aphidoletes aphidimyza* (Rondani) (Diptera: Cecidomyiidae) or the ladybird *Adalia bipunctata* (L.) (Coleoptera: Coccinelidae) consume on average approximately 30 (Boulanger et al., 2018) and 343 (Beltrà et al., 2018) aphids, respectively, to complete larva development. The larvae of the green lacewing *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae), that also used extensively in biological control programs consume approximately 300

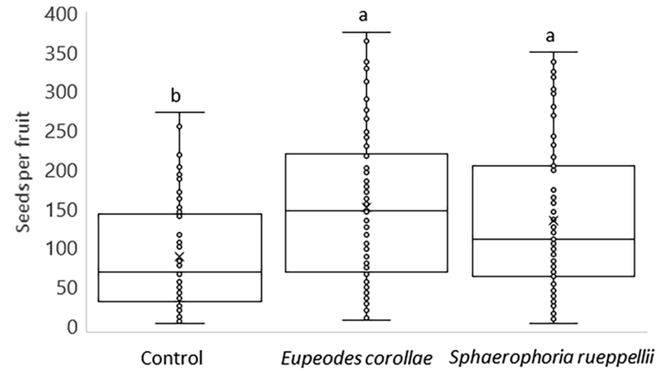


**Fig. 5.** Number of seeds per fruit collected from experimental cages with sweet pepper plants visited by the hoverflies *Eupeodes corollae* or *Sphaerophoria rueppellii* or control cages where plants were not visited by hoverflies. Plants were not originally infested with aphids. Different letters denote statistically significant differences at $P < 0.05$.

aphids to complete development (Liu and Chen, 2001). Obviously, the conditions in the studies above vary greatly, which means that direct comparisons among species have to be performed; however, the above results strongly suggest that *E corollae* larvae are much more voracious than the larvae of *S. rueppellii* and *E. balteatus* and apparently more voracious than other aphid predators. In principle, this can be an advantage, especially in situations with higher prey densities. However, when aphid densities are lower, being more voracious might hamper larval development and hence restrict pest control over successive generations. In a previous study comparing *E. corollae* and *E. balteatus* under conditions of limited prey, larval and pupal survival was reduced for the former hoverfly species (Rojo et al., 1996). The same study also reported prolonged larva development for *E. corollae* with limited access to prey. Thus, the ability of a hoverfly (or any aphid predator) to develop and persist at early and low aphid infestations can be crucial for efficient aphid control (see Beltrà et al. 2018). Longer-term experiments, comparing the two hoverfly species tested here in field conditions, would be necessary to shed light onto this issue.

Other factors can also interfere with and determine the efficacy of the hoverflies in the field, such as the capacity of the adults and larvae to locate the aphid colonies and their performance under different abiotic conditions. According to Pineda and Marcos-García (2008), who studied the seasonal pattern in the abundance of naturally occurring aphidophagous hoverflies in sweet-pepper screen houses in southern Spain, *S. rueppellii* seems to be better adapted to high temperatures while *E. corollae* performs better under lower temperatures. *E. corollae* was shown to be the most abundant species earlier in the season when temperatures were low while *S. rueppellii* abundance peaked later in the season coinciding with the higher temperatures (Pineda and Marcos-García, 2008). Additional evidence about the tolerance of the *Eupeodes* species to low temperatures comes from another study showing that *E. americanus* adults maintained flight activity and oviposition and larvae continued preying upon aphids at temperatures as low as 12° C (Bellefeuille et al., 2019). From an applied perspective, both species have potential advantages for aphid control under certain climatic conditions. Alternatively, releasing a mix of both hoverfly species can be also considered. From our experiments in commercial sweet pepper screen houses in southern Spain, we have seen that both hoverfly species often co-occur. When releasing pupae from the two species concurrently in similar numbers, both species established in the crop, with the abundance of adults observed in the field being in our experiments always higher for *E. corollae* than *S. rueppellii* (Robledo, A. unpublished). More field experiments will be required in order to draw definitive conclusions regarding field performance under defined climatic conditions.

### 4.2. Pollination

Fruit yield was significantly higher in cages with hoverflies (increased by 87.6% and 62.2% by *E. corollae* and *S. rueppellii*, respectively) compared to control cages only when the plants were infested with aphids. Although the increase in yield in the experiment without aphids was less pronounced (increase of 29.28% for *E. corollae* and 11.08% for *S. rueppellii*) and not statistically significant, it followed the same pattern as in the experiment with aphids. The fact that yield effects were more pronounced in the experiment with aphids was to be expected, given that here the hoverflies affected yield mainly through aphid control; aphids are known to impose a significant cost on plant physiology (Goggin, 2007). In a commercial sweet pepper greenhouse, plants are likely to suffer some level of aphid infestation although. While the aphid pressure will be typically lower than in our experiments. Interestingly, the increase in seed set in the hoverfly treatments was statistically significant independently of the presence of aphids. Overall, these results show that both hoverfly species tested in our study, in addition to controlling aphid infestations, act as pollinators of sweet pepper.

Our results also suggest that *E. corollae* might be more effective as a pollinator than *S. rueppellii* in sweet pepper. This was supported by the fact that the number of seeds per fruit was consistently higher in the *E. corollae* treatment. In a previous study in strawberry, another species of the genus *Eupeodes*, namely *E. latifasciatus*, proved to be superior as a pollinator to *E. balteatus* (Hodgkiss et al., 2018). Differences in pollination efficacy among species may be attributable to various factors, such as, differences in size, morphology i.e. number of body hair, and/or differences in activity and behaviour (Willmer and Finlayson, 2014). Although *E. corollae* is slightly bigger than *S. rueppellii* it is difficult to say if this difference in size could explain our results. Future studies should focus on the flower visitation frequency, behaviour and pollen load of both species during flower foraging to draw definitive conclusions about pollination efficacy in sweet pepper or other crops.

It would be interesting to know how the benefit towards pollination derived from *E. corollae* and *S. rueppellii* compares to pollination by other effective pollinators of sweet pepper, such as, bumblebees, honeybees and non-aphidophagous hoverflies (Valverde et al., 2019). Dag and Kammer, (2001) reported increased yield by 30 and 36% in experimental plots visited by the honeybee *Apis mellifera* L. or the bumblebee *Bombus terrestris* L. (both Hymenoptera: Apidae) in comparison with the control plots. Similarly, in a greenhouse experiment, Roldán Serrano and Guerra-Sanz, (2006) found a significant increase ranging between 60 and 140% between years, in fruit yield/m$^2$, in experimental plots with bumblebees compared to control plots. Finally, sweet pepper fruits visited by the non-aphidophagous hoverfly *E. tenax* had significantly more seeds (19.3%) compared to the non-visited control whereas the increase in the yield was not statistically significant (12.8%) (Jarlan et al., 1997a, 1997b). Again, it is not possible to directly compare the efficacy of hoverflies with other pollinator taxa based on the results from the previous studies; this would require detailed studies addressing the impact of a single flower visit. Hoverflies might have an advantage over bumblebees for pollination in enclosed environments, for example, in indoor vertical farming crops where bumblebees are not always efficient due to over-pollination effects, i.e. decreasing crop quality from repeated visits of pollinators to the flower (Martin et al., 2019). Despite the fact that hoverflies may have limitations as pollinators relative to the more specialized pollen collectors, such as bees (Jauker and Wolters, 2008; Rader et al., 2009), our study shows that aphidophagous hoverflies can combine pollination and pest control benefits and thus contribute substantially to the reproductive fitness of the plants they visit. This is an obvious advantage especially when compared to the non-aphidophagous hoverflies.

We are also aware that the amount of hoverflies released per cage in our experiments was relatively high for a commercial sweet pepper greenhouse. Nevertheless, one of the objectives of our study was the comparison of the two hoverfly species and in that sense, our results are valid. In addition, it has to be considered that our experiments represent peppers grown in closed-off conditions. In open tunnels or in the open field, hoverflies may be distracted away from the sweet pepper flowers if more attractive flower species were available in the surroundings of the crop. In a choice experiment Amorós et al., (2014) reported that adult males and females of *S. rueppellii* preferred flowers of sweet alyssum (*Lobularia maritima* L.) over flowers of coriander (*Coriandrum sativum* L.) while the sweet pepper flowers were the least preferred. This is especially relevant for the semi-open screen house structures in sweet pepper crops in the Mediterranean where the adult hoverflies can move freely from the crop to visit more attractive flowers in the surroundings of the greenhouses (Pineda and Marcos-García, 2008). It may also be an issue in situations where banker plants are employed to enhance biological control (Jandricic et al., 2014). A means to attract and retain the populations of the hoverflies is by selecting the suitable plant diversity in the surroundings of the greenhouses; subsequently the hoverflies (and potentially other natural enemies and pollinators) can disperse from the surrounding vegetation to the greenhouse to provide biocontrol and pollination services (Messelink et al., 2014; Sánchez et al., 2020).

## 5. Conclusion

We have shown that the aphidophagous hoverflies *E. corollae* and *S. rueppellii* can simultaneously control the aphid infestation and enhance variables of reproductive success that are linked to pollination in sweet pepper plants, such as the number of seeds per fruit and yield. The contribution towards pollination was more pronounced when the plants were originally infested with aphids. In our experiments, *E. corollae* was at least as efficient as *S. rueppellii* for *M. persicae* control, while our results suggest that it might be a more effective pollinator than *S. rueppellii*. Thus, *E. corollae* seems a promising species for use in biological control and IPM programs. To our knowledge, this is the first time that biological control and pollination services are demonstrated concurrently for the same species of hoverfly. Our results also show that both ecosystem services act together in terms of enhancing yield. The concurrent dual provisioning of ecosystem services by aphidophagous hoverflies is of great practical relevance for the management of biological control and pollination in natural and managed ecosystems.

## CRediT authorship contribution statement

**Apostolos Pekas:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing. **Ines De Craecker:** Methodology. **Sten Boonen:** Methodology. **Felix L. Wäckers:** Writing - review & editing. **Rob Moerkens:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2020.104328.

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