



RESEARCH ARTICLE

The golden native drone fly (*Eristalinus punctulatus*) is an effective hybrid carrot pollinator that lives within Australian crop agroecosystems

Abby E. Davis¹  | Lena A. Schmidt¹ | Karen C. B. S. Santos¹ | Lucie Martin¹ | Samantha Harrington² | Maurizio Rocchetti³ | Brad Hocking³ | Derek Wright³ | Cameron Spurr⁴ | David Cook⁵ | Romina Rader¹ 

¹Department of Environmental and Rural Science, University of New England, Armidale, New South Wales, Australia

²South Pacific Seeds, Griffith, New South Wales, Australia

³Costa Exchange Group, Corindi, New South Wales, Australia

⁴seedPurity Pty Ltd., Margate, Tasmania, Australia

⁵Department of Primary Industries and Regional Development, Kensington, Western Australia, Australia

Correspondence

Abby E. Davis

Email: aed236@cornell.edu

Funding information

Australian Research Council Future Fellowship, Grant/Award Number: FT210100851; Hort Innovation, Grant/Award Number: Managing Flies for Crop Pollination (PH16002)

Handling Editor: Marc Cadotte

Abstract

1. Native insect flower visitors can be important contributors to crop pollination, yet little is known of their pollination abilities and the resources (habitat) they need to be supported within crop agroecosystems.
2. Here, we compared the abundance and pollination abilities of the golden drone fly (*Eristalinus punctulatus*) to the European honey bee (*Apis mellifera*) in hybrid carrot crop fields known to produce variable seed yields in regional New South Wales, Australia. We further observed the egg-laying behaviours of female golden drone flies at a commercial berry orchard to provide insight into the habitat needs of this species.
3. In hybrid carrot crop fields, golden drone flies were far less abundant flower visitors than European honey bees; however, these flies deposited more carrot pollen grains on average (8.21 ± 3.04 SE) onto carrot flowers than European honey bees (3.45 ± 1.06 SE). Both insects also deposited pollen onto a similar number of carrot flowers (pollinated) per visit (about 2 out of 18).
4. Golden drone flies were observed laying eggs within masses of discarded red raspberry plant roots and soil (root balls) at a commercial berry orchard. The natural habitat utilised by these flies, as well as their egg-laying behaviours, were described for the first time.
5. Our results indicate that golden drone flies are effective pollinators of hybrid carrot crop plants. The habitat that these flies utilised to lay eggs (discarded plants and water) is cheap and commonly found in crop agroecosystems. Therefore, we recommend placing this low-cost habitat within, or nearby, crop fields as a potential management practice to support the lifecycle needs of golden drone flies and other non-bee pollinators.

KEYWORDS

Diptera, ecosystem services, honey bees, hover flies, non-floral habitat

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2023 The Authors. *Ecological Solutions and Evidence* published by John Wiley & Sons Ltd on behalf of British Ecological Society.

1 | INTRODUCTION

Flies are one of the most diverse and species-rich insect taxa found globally, accounting for every 1 in 10 species on Earth (Grimaldi & Engel, 2005; Wiegmann et al., 2011). While some flies are known to be pest insects, many are beneficial and play important roles in ecosystems as pollinators, predators and nutrient cyclers (Davis, Bickel, et al., 2023; Rader et al., 2020). Pollinating flies visit more than 100 cultivated cropping systems and over 550 wild plant species as adults (Larson et al., 2001), and this has led them to be the second most important pollinator taxon behind bees (Rader et al., 2016, 2020). As the demand for insect-pollinated agricultural commodities continues to increase (Aizen et al., 2008), and bees alone cannot be relied upon to provide consistent and reliable pollination services in the future (Aizen & Harder, 2009), flies are increasingly receiving attention as pollination service providers to agricultural cropping systems. However, few studies have tested if flies can transfer pollen grains (male gametes) to crop flower stigmas (pollinate) as effectively as bees (but see Howlett et al., 2011; Jauker et al., 2012; Rader et al., 2009).

Despite the increased research attention regarding flies as crop pollinators (Cook, Voss, et al., 2020; Doyle et al., 2020; Inouye et al., 2015; Orford et al., 2015; Rader et al., 2020; Raguso, 2020), quantitative measures of pollination success with this taxon are lacking in many cropping systems. Quantitative measures of pollination success, such as measuring and comparing pollen deposition and/or fruit set estimates after visits by potential pollinators, are useful metrics to compare the pollination ability of different species. For example, oilseed rape (*Brassica napus* subsp. *napus*; family Brassicaceae) crop flowers require an average of 160 pollen grains on each stigma for successful fertilisation to occur (Mesquida & Renard, 1984). Based on this knowledge, floral visitors that deposit more than 160 pollen grains per stigma are likely effective pollinators of this crop, which has been demonstrated in multiple studies (Howlett et al., 2011; Jauker et al., 2012; Phillips et al., 2018; Rader et al., 2009). The bulk of information collected on flies in pollination studies, however, typically includes visitation rates to flowers over a period (of time) or the amount of time a fly spends visiting a flower, which does not often demonstrate that successful pollination has occurred (Rader et al., 2020). Furthermore, flies are notoriously difficult to identify, so when they are observed visiting flowers they are commonly grouped by order (Diptera) or family and thus pollination success is rarely attributed to a single species. Nonetheless, there is evidence that certain species of flies in the families Syrphidae (hover flies) and Calliphoridae (blow flies) are effective pollinators of 11 different cropping systems: avocado (Perez-Balam et al., 2012), blueberry (Cook, Deyl, et al., 2020), carrot (Gaffney et al., 2011, 2018, 2019; Howlett, 2012; Spurr, 2003), celery (Sanchez Matos et al., 2021), fennel (Sanchez Matos et al., 2021), leek (Clement et al., 2007), mango (Saeed et al., 2016), onion (Currah & Ockendon, 1984; Faulkner & Hinton, 1980), oilseed rape (Howlett et al., 2011; Jauker & Wolters, 2008; Rader et al., 2009), strawberry (Hodgkiss

et al., 2018) and sweet pepper (capsicum; Dunn et al., 2020; Jarlan et al., 1997a, 1997b).

Flies are important taxa to support within agroecosystems, as natural populations of beneficial flies can provide critical ecosystem services to farm landscapes (Fijen et al., 2022; Orford et al., 2015); however, it is unlikely that current management schemes designed to support pollinators on farms are successfully benefitting fly reproduction and development (Davis, Bickel, et al., 2023). This is because most pollinator management recommendations involve planting a diverse array of flowering plants within or near crop fields (Albrecht et al., 2020; Decourtye et al., 2010; Lowe et al., 2021). While this has been shown to positively influence insect pollinator nutritional health and reproductive success (Ganser et al., 2021; Klaus et al., 2021; Rosanigo et al., 2020), many insect pollinators also require non-floral resources to use as nesting or oviposition (egg-laying) sites to support their immature life stages. For example, most crop flower-visiting fly species (99%; $n=242$) found to feed on floral resources (e.g. nectar and pollen) as adults did not feed on floral resources as immatures, instead the larvae of these species were mainly predators of small, soft bodied insects or detritivores (Davis, Bickel, et al., 2023). This suggests that crop-pollinating flies need both floral and non-floral resources to support their life cycle within agroecosystems, yet the non-floral resource needs of crop-pollinating flies is understudied (but see Davis, Bickel, et al., 2023; Davis, Schmidt, et al., 2023; Finch et al., 2023 for exceptions). It is therefore critical to document the basic life history needs (e.g. diet, habitat) of these beneficial flies to make informed recommendations to growers on how to support and conserve beneficial species within varied landscapes.

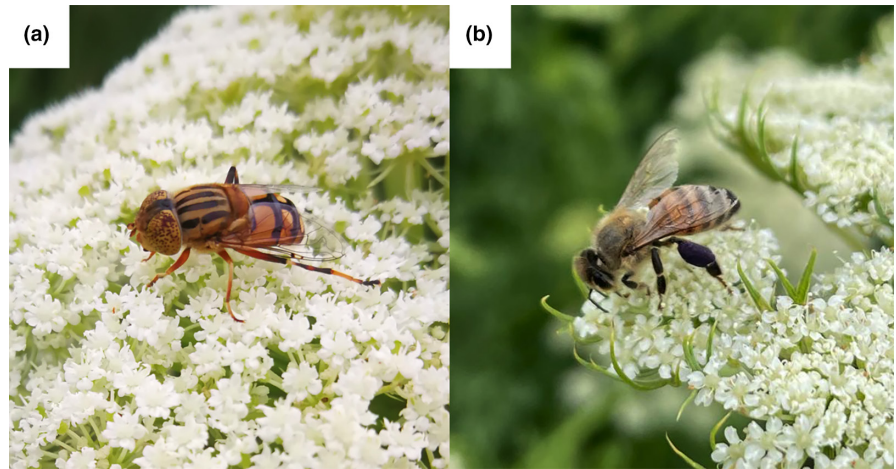
In this study, we investigated the abundance, pollination abilities (effectiveness), and oviposition needs of the golden native drone fly, *Eristalinus punctulatus* (Macquart, 1847), a black and yellow eristaline (Syrphidae) fly with large, spotted eyes, endemic to Australia (AU), New Caledonia and the Solomon Islands (Figure 1a; Thompson et al., 2017). We compared the number of flies seen visiting hybrid carrot (*Daucus carota* subsp. *sativus*; family: Apiaceae) umbels (abundance) as well as the effectiveness of *E. punctulatus* flies at depositing pollen onto hybrid carrot stigmas, to the European honey bee (*Apis mellifera* Linnaeus, 1758), the most used managed insect pollinator globally (Figure 1b). We also provide insights into *E. punctulatus* fly oviposition needs and behaviours from observations in red raspberry (*Rubus ideaus*; family: Rosaceae) plants located within a commercial berry farm.

2 | MATERIALS AND METHODS

2.1 | Study sites and cropping system

This study was conducted within the Riverina region of New South Wales (NSW), AU, during the austral summer (November to December) of 2021. The Riverina region is known to have fertile soils, therefore, many Australian agricultural cropping systems (e.g. grapes, rice and citrus) are grown here throughout the year. In the

FIGURE 1 Focal pollinator taxa foraging on hybrid carrot (*Daucus carota* subsp. *sativus*) flowers, (a) the golden (Australasian) native drone fly, *Eristalinus punctulatus* (Macquart, 1847), and (b) the European honey bee, *Apis mellifera* Linnaeus, 1758. The photo on the left was taken by Lena A. Schmidt and the photo on the right was taken by Karen C. S. B. Santos.



summer, the region is typically hot and dry and thus unfavourable for crop bloom, yet hybrid carrot is purposely grown to bloom in this season to avoid genetic contamination from wild carrot varieties, which can readily cross-pollinate with hybrid varieties. It is unfavourable for wild varieties to cross with hybrids because hybrid plants are specifically bred to display desirable traits, such as high yield and disease resistance, and the genetic material (pollen) from wild plants may disrupt future generations from inheriting these desirable traits (Hauser & Bjørn, 2001). Hence, the male fertile (pollen-producing) parent plants and the male sterile (seeding) parent plants are grown close together in fields, to best facilitate cross-pollination. As pollen from the male fertile line must be transferred to the male sterile flowers for successful pollination to occur, hybrid carrot is dependent on insect-mediated pollination.

Three field sites were located at large, commercial farms owned by third-party landowners and one field site was privately owned by the company South Pacific Seeds (Griffith, NSW, AU). The commercial sites produced between 5 to 14 hectares of hybrid carrot in monocultures, while the privately owned site grew a small plot (>1 ha) of hybrid carrot plants to trial different varieties. All sites were located between 20 to 40 km apart and grew separate male fertile and male sterile hybrid carrot parent lines. Permission to conduct fieldwork on all sites was granted by South Pacific Seeds, who managed all field sites used in this study.

2.2 | Floral visitation surveys

Based on preliminary floral visitation observations within hybrid carrot fields, both *E. punctulatus* flies and *A. mellifera* honey bees were seen visiting carrot umbels. We further noticed that a greater number of *A. mellifera* honey bees were visiting male fertile umbels compared to male sterile umbels, but we did not observe this with *E. punctulatus* flies. As crossing between parent lines is critical to facilitate pollen transfer from hybrid male fertile to male sterile parent lines, we conducted floral visitation abundance surveys on both hybrid parent lines of seed carrot umbels to evaluate the abundance of both species within fields.

To do this, we conducted floral visitation surveys at all field sites by walking 10 m transect lines between one row of hybrid male fertile plants and one row of hybrid male sterile plants. Two transect walks were conducted three times a week at each site from 22 November 2021 to 5 December 2021 during peak bloom (50% flowering). All transects were conducted walking slowly (1 m per minute when possible) and in the direction of the sun to avoid casting a shadow on the umbels. Surveys were carried out in variable weather conditions, but not when winds were stronger than a moderate breeze (<18 km/h, Beaufort 4) or in heavy rainfall. Both *E. punctulatus* flies and *A. mellifera* honey bees were identified by sight within the field, as these insects are morphologically distinctive from each other and other flower visitors in the region.

2.3 | Pollination effectiveness

To measure the number of carrot pollen grains *E. punctulatus* flies and *A. mellifera* bees deposited onto hybrid carrot flower stigmas, we conducted single-visit pollen deposition (SVD) trials. This was done by counting the number of pollen grains each taxon deposited onto virgin male fertile flower stigmas after one visit to an umbellet (a cluster of 20–30 carrot flowers), and also how many stigmas received carrot pollen grains. We bagged male sterile carrot umbels (clusters of 50–100 umbellets) that were still unreceptive to pollen (in bud) with insect-proof netting to prevent insect visitation to flowers (Figure 2a). Once receptive, we removed the bag and offered umbellets to taxa in natural field conditions. We offered one umbellet to one individual pollinator (*A. mellifera* bee or *E. punctulatus* fly), and if the pollinator visited the umbellet it was included as a replicate. For all taxa, we recorded the amount of time the pollinator spent visiting the umbellet (visit duration in seconds), and, once visited, we immediately placed the visited umbellet in an individual container over ice.

We successfully collected all SVD replicates from *A. mellifera* bees ($n=51$) in natural field conditions, but when we tried offering the umbellets to the *E. punctulatus* flies, our presence deterred the flies from visiting the umbellets; therefore, both *E. punctulatus* flies



FIGURE 2 Experimental design for single-visit pollen deposition trials in hybrid carrot (*Daucus carota* subsp. *sativus*) crop fields grown for seed production. (a) Male fertile umbels bagged with insect-proof netting to prevent insect visitation to flowers and (b) flight cages used to hold *Eristalinus punctulatus* (Macquart, 1857) flies to conduct pollination experiments. Photos taken by Abby E. Davis.



FIGURE 3 Image of a carrot (*Daucus carota* subsp. *sativus*) flower pistil (stained red in colour) from a hybrid male sterile parent plant mounted in fuchsine-stained glycerol gelatine as seen under a compound microscope at 40 \times magnification. The black arrows point to carrot pollen grains (stained purple in colour from the gelatine) adhered to the flower stigma after one visit from an *Eristalinus punctulatus* (Macquart, 1847) fly pollinator. Photo taken by Abby E. Davis.

and hybrid male fertile carrot plants were manipulated in the field using large cages (2m \times 2m \times 2m; $n=2$) to collect the SVD fly replicates only (Figure 2b). Wild *E. punctulatus* flies were caught with a hand-held net when visiting hybrid carrot umbels in the field, released within the cages, and left to acclimate for at least two hours before collecting SVD replicates. As the total area of each cage was 3m², the cages were large enough for extensive free flight. Once inside cages, the flies visited the offered umbellets in the same way as the bee taxa in field conditions. We further compared the two

insect pollinator treatments with a control treatment in which hybrid male sterile carrot umbels were bagged from bud until flowers were no longer receptive (no insect-mediated pollinator visitation) to test if pollen flow occurred in the system without insect-mediated pollination.

On the same day the SVD samples were collected, we then randomly selected a subset of 10 to 12 flowers from each umbellet replicate and mounted the flower pistils (the female reproductive part of the flower) in fuchsine-stained glycerol gelatine on a glass microscope slide (one replicate per microscope slide) using the methods described in Kearns and Inouye (1993). As each individual carrot flower has one to two pistils, we mounted between 10 to 24 pistils per replicate slide. We chose to mount a subset of flower pistils from the umbellet rather than all pistils because carrot flowers are small (<2–4 mm) in size and none of the observed focal taxa probed each individual carrot flower in an umbellet. Instead, *E. punctulatus* flies and *A. mellifera* honey bees probed flowers randomly while walking across the umbellet. We then used a compound microscope at 40 \times magnification to count the number of carrot pollen grains physically touching the surface of the mounted stigmas (Figure 3), as only one pollen grain is needed to successfully pollinate hybrid carrot (Hawthorn et al., 1956). We also counted the number of carrot pollen grains on the slide replicate not touching the flower stigmas, as these pollen grains may have been dislodged from the surface of the flower stigmas during the slide-mounting process.

2.4 | Observation of *E. punctulatus* oviposition

On 28 October 2022, while working at a commercial berry farm (30 $^{\circ}$ 00'12.5" S 153 $^{\circ}$ 08'51.7" E) in the Mid North Coast region of NSW, AU, we observed two *E. punctulatus* females hovering above stagnant water filled with partially submerged, decaying red raspberry plants (Figure 4a). The discarded plants were no longer in use by the commercial berry farm and were piled together to be composted. Permission to conduct fieldwork at this site was granted by Costa Exchange Group, which owned the field site where these observations were recorded.

FIGURE 4 The oviposition site of *Eristalinus punctulatus* (Macquart, 1847). (a) Location where the flies were seen hovering. (b) Female *E. punctulatus* ovipositing inside a discarded red raspberry (*Rubus idaeus* L.) root ball. (c) Location of eggs inside the red raspberry plant root ball as indicated by the white arrow. (d) Close-up of *E. punctulatus* eggs (white in colour) in between roots and soil. Egg oviposition occurred approximately 10 centimetres above the surface of stagnant water. Photos (a, b) were taken by Abby E. Davis and photos (c, d) taken by Lena A. Schmidt.



Following recent rain events, rainwater had accumulated at the base of the pile, forming a small, stagnant body of water. We noticed one *E. punctulatus* female landed on a damp mass of red raspberry roots and soil (root ball) and began walking around on the root ball. The female then stopped about 10 centimetres above the surface of the stagnant water and began probing with her ovipositor inside the soil and roots (Figure 4b). After about 5 min, the female flew away. When we checked the location where the female had probed her ovipositor along the boundary between the wet and decaying (dark brown) and dry (light brown) parts of the root ball (Figure 4c), we saw she had laid eggs inside the red raspberry plant root ball (Figure 4d). The oviposition behaviour was observed again shortly thereafter by another *E. punctulatus* female on a different red raspberry plant root ball. Throughout our observations, the female flies would hover around the stagnant water filled with discarded red raspberry plants, and land on dry red raspberry leaves hanging above the surface of the stagnant water or on the root balls.

2.5 | Statistical analyses

All statistical analyses were conducted using RStudio (2021). To assess the degree of dissimilarity (Euclidean abundance-based dissimilarity index) between the focal floral visitors of hybrid carrot (categorical: 'Apis mellifera' and 'Eristalinus punctulatus') based on two spatial scales (categorical: 'Site' and 'Plant line'), we constructed permutational multivariate analysis of variance (PERMANOVA) models using the *adonis* function in the *vegan* package (Oksanen et al., 2022). All PERMANOVA were fit against random permutations ($n=999$) of the original dataset. Indicator species analysis using the *indicspecies* package was then performed to see which species were specifically impacted by the significant factors in the PERMANOVA (Cáceres & Legendre, 2009).

3 | RESULTS

3.1 | Floral visitation surveys

In total, we conducted 208 floral visitation surveys (95 h) on hybrid carrot flowers, with 104 surveys on each parent line. Of the 4816 total focal insects observed, 99.8% ($n=4808$) were *A. mellifera* honey bees. Further, *A. mellifera* honey bees were seen in significantly higher numbers (abundance) visiting male fertile umbels compared to male sterile umbels, while the abundance of *E. punctulatus* flies did not significantly differ based on parent line (Figure 5). The hybrid carrot sites where sampling occurred did not significantly impact the abundance of the focal insect species observed ($\chi^2=1.81$, $df=3$, $p=0.62$).

3.2 | Pollination effectiveness

In total, we collected 153 hybrid carrot umbellet replicates which comprised 2822 floral pistils. From these umbellet samples, we counted an overall number of 1287 carrot pollen grains, with 618 carrot pollen grains physically touching the flower stigmas, and 669 carrot pollen grains not touching the stigmas but still mounted within the fuchsin-stained gelatine slide. The *E. punctulatus* flies transferred pollen on average to 12% of the total number of mounted hybrid male fertile carrot stigmas (average of 18 stigmas per replicate, $n=52$), followed by *A. mellifera* bees at 8.05% (average of 19 stigmas per replicate; $n=51$), and then the control treatment (bagged to prevent insect visitation) at 0.01% (average of 18 stigmas per replicate; $n=50$). Further, even though *E. punctulatus* flies spent one-third of the time *A. mellifera* bees spent visiting a single carrot umbellet, the flies deposited 238% more pollen grains on average onto hybrid male fertile carrot stigmas per visit compared to *A. mellifera* (Table 1).

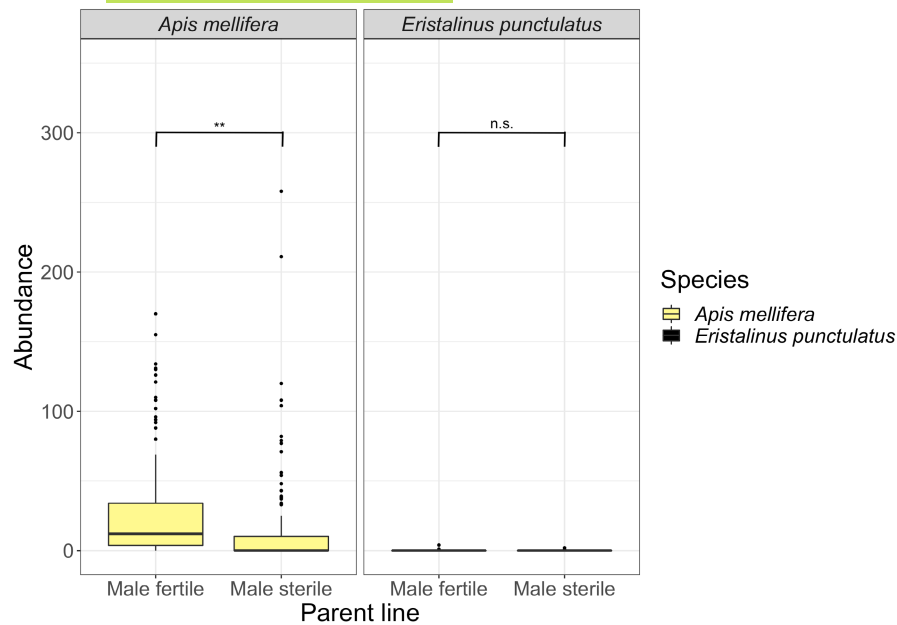


FIGURE 5 Abundance of *Eristalinus punctulatus* (Macquart, 1847) flies and *Apis mellifera* Linnaeus, 1758 honey bees on hybrid carrot parent lines (male fertile and male sterile) when conducting floral visitation surveys ($n=208$) across four field sites in the Riverina region of New South Wales, Australia. Species are differentiated by colour for clarity. Significant differences are between groups ($p < 0.01$) are indicated by asterisks (**), with 'n.s.' indicating no significant differences between groups. Lower to upper box boundaries indicate the inter-quartile range (IQR). Whiskers are extended to the furthest data point within $1.5 \times$ the IQR from each box end, and data points outside whiskers are outliers.

TABLE 1 Single-visit pollen deposition results for *Eristalinus punctulatus* (Macquart, 1847) (Diptera: Syrphidae) and *Apis mellifera* Linnaeus, 1758 (Hymenoptera: Apidae) pollinators in a commercial hybrid carrot cropping system grown for seed production. The bagged (no insect-mediated pollination) treatment prevented insect taxa from visiting carrot flowers. The column 'n' is the total number of umbellet replicates collected per treatment. The column 'Stigmas' is the average number of stigmas mounted per replicate (n). The column 'Stigmas with pollen per n' is the average (\pm SE) number of flower stigmas with pollen adhered to the surface of the stigma per replicate (n). The column 'Pollen grains per n' is the average (\pm SE) number of pollen grains per replicate (n). The column 'Pollen grains per stigma' is the average (\pm SE) number of pollen grains adhered to the surface of a flower stigma. Visit duration is the total amount of time (in seconds) each taxa spent visiting an umbellet.

Pollinator treatment	n	Stigmas	Stigmas with pollen per n	Pollen grains per n	Pollen grains per stigma	Visit duration (s)
<i>Eristalinus punctulatus</i> (Diptera: Syrphidae)	52	18	2.16 ± 0.51	15.3 ± 5.56	8.21 ± 3.04	4.29
<i>Apis mellifera</i> (Hymenoptera: Apidae)	51	19	1.53 ± 0.29	9.16 ± 2.89	3.45 ± 1.06	12.13
Bagged (no insect-mediated pollination)	50	18	0.24 ± 0.08	0.46 ± 0.14	0.3 ± 0.11	n/a

3.3 | Observation of *E. punctulatus* oviposition

In total, we observed two female *E. punctulatus* flies exhibiting oviposition behaviours (e.g. crawling on decaying root balls, laying eggs) within the partially submerged decaying red raspberry habitat for roughly 35 min. Upon observing *E. punctulatus* oviposition in the damp red raspberry roots and soil, we searched through the eight additional discarded red raspberry root balls partially submerged in rainwater. We found that five of the eight red raspberry root balls hosted additional *E. punctulatus* egg clutches (one egg clutch per root ball), as the size and shape of the eggs resembled *E. punctulatus* egg photos taken within Campoy et al. (2020). Further, *E. punctulatus* was the only species seen laying eggs at the observed location.

4 | DISCUSSION

Non-bee insect taxa are important contributors to global crop production (Rader et al., 2016, 2020). Here we found that *E.*

punctulatus flies deposited 238% more pollen grains on average onto hybrid male fertile carrot stigmas compared to *A. mellifera* honey bees, despite the flies visiting each umbellet for a shorter duration of time. This, coupled with the fact that both taxa pollinated roughly two stigmas (one to two flowers) per umbellet visit, implies that *E. punctulatus* flies are as effective as *A. mellifera* bees at transferring pollen between hybrid carrot parent lines in our region (Riverina, NSW, AU) of study. Moreover, only one pollen grain per stigma (two stigmas per flower) is needed to set seed in hybrid carrot production systems (Hawthorn et al., 1956), so the amount of pollen deposited by both taxa would be enough to produce seeds. To our knowledge, this is the first time the pollination ability of *E. punctulatus* has been tested in a commercial crop plant, and the second fly species in the genus *Eristalinus* to demonstrate effective pollination abilities in hybrid production systems (Sánchez et al., 2022).

While *E. punctulatus* flies were capable of effectively transferring pollen across hybrid carrot parent lines, they were infrequent floral visitors seen in low numbers across all field sites. Consequently, these flies are likely not abundant enough in this

system to provide broad-scale pollination services to hybrid carrot plants in our region of study. These low numbers of *E. punctulatus* flies sampled may reflect a lack of habitat for the immature stages of this species to successfully develop, as there was no shortage of flowers at all sites and thus the adult flies had plenty of floral resources (nectar and pollen) to feed on. Further, *A. mellifera* bees were typically seen in high numbers visiting umbels within fields but were more abundant visitors of male fertile umbels compared to male sterile umbels. This finding concurs with other studies that suggest that *A. mellifera* honey bees are generally inefficient pollinators of hybrid carrots as: (1) honey bees find hybrid male fertile carrot flowers unattractive and thus visit them less frequently than hybrid male sterile flowers (Broussard et al., 2017; Delaplane & Mayer, 2000; Gracie, 2011; Mas et al., 2018), and (2) honey bees rarely move pollen between hybrid parent lines, choosing to instead forage along parent lines (Erickson et al., 1979; Gaffney, 2011; Gaffney et al., 2011, 2019; Spurr, 2003). Therefore, future research is needed to identify if the carrot pollen deposited onto the flower stigmas by both taxa is viable, and to evaluate the foraging behaviours and activity patterns of *E. punctulatus* flies to see if they are successfully cross-pollinating parent lines.

Observations of *E. punctulatus* in commercial berry orchards indicate that decaying crop root balls are effective substrates for oviposition. The observation of *E. punctulatus* oviposition within decaying red raspberry plant root balls in the Mid North Coast (NSW, AU) is consistent with Campoy et al. (2020) and Davis, Schmidt, et al. (2023) and implies that decaying plant material is a suitable oviposition substrate of female *E. punctulatus* flies. At the time we performed the *E. punctulatus* pollination trial within hybrid carrot fields, the only known information about *E. punctulatus* reproduction in natural conditions was reported by Ferguson (1926), whereby the immature stages of *E. punctulatus* were found inside a rotting prickly pear (*Opuntia* spp.) and inside the drain of a hospital in Eidsvold, Queensland, AU. Additionally, Campoy et al. (2020) successfully reared *E. punctulatus* from soaked cereal grains in laboratory conditions, however, this was done by hand-netting wild female *E. punctulatus* in the field, as the authors did not find the eggs in natural conditions. Therefore, our observations on *E. punctulatus* oviposition within the decaying root balls of discarded red raspberry plants may be the first documented observation of the natural oviposition of this fly species.

The habitat in which we observed *E. punctulatus* fly oviposition can likely be recreated in other crop agroecosystems to support and encourage beneficial eristaline syrphid fly development. Deployment of resources, such as placing manure or carrion near flowering plants to attract pollinators, is common in Australian mango cropping systems (Finch et al., 2023; Pain, 2021), and has been demonstrated to benefit urban environments (Cusser et al., 2021). To support *E. punctulatus* oviposition, we recommend placing discarded plant material near fields before, or in between, periods of crop bloom to create a habitat for the immature stages of *E. punctulatus* to develop. This recommendation was trialled by Davis, Schmidt, et al. (2023), which demonstrated that placing small, portable pools filled with

habitat (water, decaying plant materials, soil) near carrot fields supported the oviposition and development of immature stages (eggs and larvae) of *E. punctulatus* flies. The deployed non-floral habitat further supported the development of *Eristalis tenax* (Linnaeus, 1758) flies, which are also effective pollinators in hybrid carrot crop systems (Gaffney et al., 2018). As discarded plant materials are common in agroecosystems, this habitat intervention will be low cost to growers. The deployment of non-floral resources such as decaying plant materials to benefit fly pollinators (see Finch et al., 2023 for another example) should be exercised with caution, however, as these substrates could also support the development of pest species like stable flies, *Stomoxys calcitrans* (Linnaeus, 1758), depending on the geographical location of the farm and features of the surrounding landscape (e.g. livestock facilities; Cook et al., 2011, 2018).

While we observed *E. punctulatus* oviposition within a commercial berry farm, the pollination ability of *E. punctulatus* within berry cropping systems is yet to be assessed. The commercial berry farm where we observed the natural oviposition of *E. punctulatus* flies was located nearby Coffs Harbour in the Mid North Coast region of AU, which, at the time this study was conducted, was experiencing an emergency biosecurity order due to the presence of the Varroa mite (*Varroa destructor* and *V. jacobsoni*; Kumar, 2022). As *A. mellifera* bees are negatively impacted by the Varroa mite yet the primary managed pollinators of berries and other crops within this region, supporting the needs of pollinating flies and other wild taxa naturally occurring within crop agroecosystems is an important management tool. Our observations call for new research to investigate the oviposition needs and pollination efficiency of other beneficial flies in agroecosystems, as berry cropping systems such as red raspberry could be supporting diverse insect communities that in return potentially provide additional free pollination services to growers.

AUTHOR CONTRIBUTIONS

Conceptualisation: Abby E. Davis, Lena A. Schmidt, Lucie Martin, Samantha Harrington, Cameron Spurr and Romina Rader. Investigation: Abby E. Davis, Lena A. Schmidt, Lucie Martin and Karen C. B. S. Santos. Photographers: Abby E. Davis, Lena A. Schmidt and Karen C. B. S. Santos. Writing—original draft preparation: Abby E. Davis. Writing—review and editing: Abby E. Davis, Lena A. Schmidt, Karen C. B. S. Santos, Lucie Martin, Samantha Harrington, Maurizio Rocchetti, Brad Hocking, Derek Wright, Cameron Spurr, David Cook and Romina Rader. Visualisation: Abby E. Davis. Supervision: Lena A. Schmidt, Samantha Harrington, Maurizio Rocchetti, Brad Hocking, Derek Wright, Cameron Spurr, David Cook and Romina Rader. Project administration: Romina Rader and Cameron Spurr.

ACKNOWLEDGEMENTS

We thank Mark Hancock, Mike Tarr and John Hall at South Pacific Seeds for discussion about the study and several anonymous reviewers for comments and suggestions that have improved the manuscript. We acknowledge the Wiradjuri people (Griffith, NSW, AU) and the Gumbaynggirr people (Coffs Harbour, NSW, AU) as the traditional owners of the land this research was conducted on and pay

respect to Wiradjuri Elders and Gumbaynggirr Elders past, present and future. The research was funded by the Horticulture Innovation Australia Limited Project titled “Managing Flies for Crop Pollination (PH16002)” and an Australian Research Council Future Fellowship (FT210100851) awarded to R. Rader. Open access publishing facilitated by University of New England, as part of the Wiley - University of New England agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

Samantha Harrington was employed by the company South Pacific Seeds. Maurizio Rocchetti, Brad Hocking and Derek Wright were employed by the company Costa Exchange Group. Cameron Spurr was employed by the company seedPurity Pty Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.12290>.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within [Figure 5](#) and [Table 1](#) of this article.

STATEMENT ON INCLUSION

Our study brings together authors from academia, industry and the government, all of which were based in the country where the study was carried out (Australia). The distinct perspectives and skill sets of all parties improved productivity, increased knowledge, and facilitated innovative solutions to ensure the appropriate interpretation of data and results.

ORCID

Abby E. Davis  <https://orcid.org/0000-0002-0942-8439>

Romina Rader  <https://orcid.org/0000-0001-9056-9118>

REFERENCES

- Aizen, M., Garibaldi, L., Cunningham, S., & Klein, A. (2008). Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. *Current Biology*, *18*, 1572–1575.
- Aizen, M. A., & Harder, L. D. (2009). The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. *Current Biology*, *19*, 915–918.
- Albrecht, M., Kleijn, D., Williams, N. M., Tschumi, M., Blaauw, B. R., Bommarco, R., Campbell, A. J., Dainese, M., Drummond, F. A., & Entling, M. H. (2020). The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: A quantitative synthesis. *Ecology Letters*, *23*, 1488–1498.
- Broussard, M. A., Mas, F., Howlett, B., Pattemore, D., & Tylanakis, J. M. (2017). Possible mechanisms of pollination failure in hybrid carrot seed and implications for industry in a changing climate. *PLoS ONE*, *12*, e0180215.
- Cáceres, M. D., & Legendre, P. (2009). Associations between species and groups of sites: Indices and statistical inference. *Ecology*, *90*, 3566–3574.
- Campoy, A., Pérez-Bañón, C., Aznar, D., & Rojo, S. (2020). Description of the preimaginal stages of the golden native dronefly from Australia, *Eristalinus punctulatus* (Macquart, 1847) (Diptera: Syrphidae). *Austral Entomology*, *59*, 784–793.
- Clement, S. L., Hellier, B. C., Elberson, L. R., Staska, R. T., & Evans, M. A. (2007). Flies (Diptera: Muscidae: Calliphoridae) are efficient pollinators of *Allium ampeloprasum* L. (Alliaceae) in field cages. *Journal of Economic Entomology*, *100*, 131–135.
- Cook, D., Voss, S., Finch, J., Rader, R., Cook, J., & Spurr, C. (2020). The role of flies as pollinators of horticultural crops: An Australian case study with worldwide relevance. *Insects*, *11*, 1–31.
- Cook, D. F., Dadour, I. R., & Voss, S. C. (2011). Management of stable fly and other nuisance flies breeding in rotting vegetable matter associated with horticultural crop production. *International Journal of Pest Management*, *57*, 315–320.
- Cook, D. F., Deyl, R. A., Mickan, B. S., & Howse, E. T. (2020). Yield of southern highbush blueberry (*Vaccinium corymbosum*) using the fly *Calliphora albifrontalis* (Diptera: Calliphoridae) as a pollinator. *Austral Entomology*, *59*, 345–352.
- Cook, D. F., Telfer, D. V., Lindsey, J. B., & Deyl, R. A. (2018). Substrates across horticultural and livestock industries that support the development of stable fly, *Stomoxys calcitrans* (Diptera: Muscidae). *Austral Entomology*, *57*, 344–348.
- Currah, L., & Ockendon, D. J. (1984). Pollination activity by blowflies and honeybees on onions in breeders' cages. *Annals of Applied Biology*, *105*, 167–176.
- Cusser, S., Pechal, J., & Haddad, N. (2021). Carrion increases pollination service across an urban gradient. *Urban Ecosystems*, *24*, 243–250.
- Davis, A. E., Bickel, D. J., Saunders, M. E., & Rader, R. (2023). Crop-pollinating Diptera have diverse diets and habitat needs in both larval and adult stages. *Ecological Applications*, *33*, e2859.
- Davis, A. E., Schmidt, L. A., Harrington, S., Spurr, C., & Rader, R. (2023). Provisioning Australian seed carrot agroecosystems with non-floral habitat provides oviposition sites for crop-pollinating Diptera. *Insects*, *14*, 439.
- Decourtye, A., Mader, E., & Desneux, N. (2010). Landscape enhancement of floral resources for honey bees in agro-ecosystems. *Apidologie*, *41*, 264–277.
- Delaplane, K. S., & Mayer, D. F. (2000). *Crop pollination by bees*. CABI.
- Doyle, T., Hawkes, W., Massy, R., Powney, G., Menz, M., & Wotton, K. (2020). Pollination by hoverflies in the Anthropocene. *Proceedings of the Royal Society B-Biological Sciences*, *287*, e20200508.
- Dunn, L., Lequerica, M., Reid, C. R., & Latty, T. (2020). Dual ecosystem services of syrphid flies (Diptera: Syrphidae): Pollinators and biological control agents. *Pest Management Science*, *76*, 1973–1979.
- Erickson, E. H., Peterson, C. E., & Werner, P. (1979). Honey bee foraging and resultant seed set among male-fertile and cytoplasmically male-sterile carrot inbreds and hybrid seed Parents1, 2. *Journal of the American Society for Horticultural Science*, *104*, 635–638.
- Faulkner, G. J., & Hinton, W. L. (1980). F1 hybrid brussels sprout seed: An assessment of production methods and their economic viability. *Horticultural Research*, *20*, 49–59.
- Ferguson, E. (1926). Revision of Australian Syrphidae (Diptera). Part II. *Proceedings of the Linnean Society of New South Wales*, *51*, 137–183.
- Fijen, T. P. M., Read, S. F. J., Walker, M. K., Gee, M., Nelson, W. R., & Howlett, B. G. (2022). Different landscape features within a simplified agroecosystem support diverse pollinators and their service to crop plants. *Landscape Ecology*, *37*, 1787–1799.

- Finch, J., Gilpin, A.-M., & Cook, J. (2023). Fishing for flies: Testing the efficacy of "stink stations" for promoting blow flies as pollinators in mango orchards. *Journal of Pollination Ecology*, 32, 79–100.
- Gaffney, A. (2011). *Insect floral visitors and their behaviour in hybrid carrot seed crops in Tasmania*. University of Tasmania.
- Gaffney, A., Allen, G., & Brown, P. (2011). Insect visitation to flowering hybrid carrot seed crops. *New Zealand Journal of Crop and Horticultural Science*, 39, 79–93.
- Gaffney, A., Bohman, B., Quarrell, S., Brown, P., & Allen, G. (2019). Limited cross plant movement and non-crop preferences reduce the efficiency of honey bees as pollinators of hybrid carrot seed crops. *Insects*, 10, 34.
- Gaffney, A., Bohman, B., Quarrell, S. R., Brown, P. H., & Allen, G. R. (2018). Frequent insect visitors are not always pollen carriers in hybrid carrot pollination. *Insects*, 9, 61.
- Ganser, D., Albrecht, M., & Knop, E. (2021). Wildflower strips enhance wild bee reproductive success. *Journal of Applied Ecology*, 58, 486–495.
- Gracie, A. (2011). *Improving reliability of flowering in bolting resistant carrot seed crops*. Horticulture Australia.
- Grimaldi, D., & Engel, M. S. (2005). *Evolution of the insects*. Cambridge University Press.
- Hauser, T. P., & Björn, G. K. (2001). Hybrids between wild and cultivated carrots in Danish carrotfields. *Genetic Resources and Crop Evolution*, 48, 499–506.
- Hawthorn, L., Bohart, G., & Toole, E. (1956). Carrot seed yield and germination as affected by different levels of insect pollination. *Proceedings of the American Society for Horticultural Science*, 67, 384–389.
- Hodgkiss, D., Brown, M. J. F., & Fountain, M. T. (2018). Syrphine hoverflies are effective pollinators of commercial strawberry. *Journal of Pollination Ecology*, 22, 49–54.
- Howlett, B. G. (2012). Hybrid carrot seed crop pollination by the fly *Calliphora vicina* (Diptera: Calliphoridae). *Journal of Applied Entomology*, 136, 421–430.
- Howlett, B. G., Walker, M. K., Rader, R., Butler, R. C., Newstrom-Lloyd, L. E., & Teulon, D. A. J. (2011). Can insect body pollen counts be used to estimate pollen deposition on pak choi stigmas? *New Zealand Plant Protection*, 64, 25–31.
- Inouye, D. W., Larson, B. M., Szymank, A., & Kevan, P. G. (2015). Flies and flowers III: Ecology of foraging and pollination. *Journal of Pollination Ecology*, 16, 115–133.
- Jarlan, A., De Oliveira, D., & Gingras, J. (1997a). Effects of *Eristalis tenax* (Diptera: Syrphidae) pollination on characteristics of greenhouse sweet pepper fruits. *Journal of Economic Entomology*, 90, 1650–1654.
- Jarlan, A., De Oliveira, D., & Gingras, J. (1997b). Pollination by *Eristalis tenax* (Diptera: Syrphidae) and seed set of greenhouse sweet pepper. *Journal of Economic Entomology*, 90, 1646–1649.
- Jauker, F., Bondarenko, B., Becker, H. C., & Steffan-Dewenter, I. (2012). Pollination efficiency of wild bees and hoverflies provided to oilseed rape. *Agricultural and Forest Entomology*, 14, 81–87.
- Jauker, F., & Wolters, V. (2008). Hover flies are efficient pollinators of oilseed rape. *Oecologia*, 156, 819–823.
- Kearns, C. A., & Inouye, D. W. (1993). *Techniques for pollination biologists*. University Press of Colorado.
- Klaus, F., Tschamtkke, T., Bischoff, G., & Grass, I. (2021). Floral resource diversification promotes solitary bee reproduction and may offset insecticide effects—evidence from a semi-field experiment. *Ecology Letters*, 24, 668–675.
- Kumar, S. (2022). *Biosecurity (Varroa mite) emergency order*. New South Wales Government, Department of Primary Industries.
- Larson, B., Kevan, P., & Inouye, D. (2001). Flies and flowers: Taxonomic diversity of anthophiles and pollinators. *Canadian Entomologist*, 133, 439–465.
- Lowe, E. B., Groves, R., & Gratton, C. (2021). Impacts of field-edge flower plantings on pollinator conservation and ecosystem service delivery—A meta-analysis. *Agriculture, Ecosystems & Environment*, 310, 107290.
- Mas, F., Harper, A., Horner, R., Welsh, T., Jaksons, P., & Suckling, D. M. (2018). The importance of key floral bioactive compounds to honey bees for the detection and attraction of hybrid vegetable crops and increased seed yield. *Journal of the Science of Food and Agriculture*, 98, 4445–4453.
- Mesquida, J., & Renard, M. (1984). *Etude des quantites de pollen deposees sur les stigmates dans differentes conditions de pollinisation: influence sur la production de graines chez le Colza d'hiver male-fertile*. Colloques de l'INRA.
- Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., Oara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B. M., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., ... Weedon, J. (2022). *vegan: Community ecology package*. CRAN R-project, R package version 2.6-2. The Comprehensive R Archive Network.
- Orford, K. A., Vaughan, I. P., & Memmott, J. (2015). The forgotten flies: The importance of non-syrphid Diptera as pollinators. *Proceedings of the Royal Society B-Biological Sciences*, 282, e20142934.
- Pain, S. (2021). *The essential fly*. Knowable Mag.
- Perez-Balam, J., Quezada-Euan, J. J., Alfaro-Bates, R., Medina, S., McKendrick, L., Soro, A., & Paxton, R. J. (2012). The contribution of honey bees, flies and wasps to avocado (*Persea americana*) pollination in southern Mexico. *Journal of Pollination Ecology*, 8, 42–47.
- Phillips, B. B., Williams, A., Osborne, J. L., & Shaw, R. F. (2018). Shared traits make flies and bees effective pollinators of oilseed rape (*Brassica napus* L.). *Basic and Applied Ecology*, 32, 66–76.
- Rader, R., Bartomeus, I., Garibaldi, L., Garratt, M., Howlett, B., Winfree, R., Cunningham, S., Mayfield, M., Arthur, A., Andersson, G., Bommarco, R., Brittain, C., Carvalheiro, L., Chacoff, N., Entling, M., Foully, B., Freitas, B., Gemmill-Herren, B., Ghazoul, J., ... Woyciechowski, M. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences of the United States of America*, 113, 146–151.
- Rader, R., Cunningham, S., Howlett, B., Inouye, D., & Douglas, A. (2020). Non-bee insects as visitors and pollinators of crops: Biology, ecology, and management. *Annual Review of Entomology*, 65(65), 391–407.
- Rader, R., Howlett, B. G., Cunningham, S. A., Westcott, D. A., Newstrom-Lloyd, L. E., Walker, M. K., Teulon, D. A. J., & Edwards, W. (2009). Alternative pollinator taxa are equally efficient but not as effective as the honeybee in a mass flowering crop. *Journal of Applied Ecology*, 46, 1080–1087.
- Raguso, R. A. (2020). Don't forget the flies: Dipteran diversity and its consequences for floral ecology and evolution. *Applied Entomology and Zoology*, 55, 7.
- Rosanigo, M. P., Marrero, H. J., & Torretta, J. P. (2020). Limiting resources on the reproductive success of a cavity-nesting bee species in a grassland agroecosystem. *Journal of Apicultural Research*, 59, 583–591.
- RStudio. (2021). *RStudio: Integrated development environment for R*. RStudio, PBC.
- Saeed, S., Naqqash, M. N., Jaleel, W., Saeed, Q., & Ghouri, F. (2016). The effect of blow flies (Diptera: Calliphoridae) on the size and weight of mangos (*Mangifera indica* L.). *PeerJ*, 4, e2076.
- Sánchez, M., Belliure, B., Montserrat, M., Gil, J., & Velásquez, Y. (2022). Pollination by the hoverfly *Eristalinus aeneus* (Diptera: Syrphidae) in two hybrid seed crops: Celery and fennel (Apiaceae). *The Journal of Agricultural Science*, 160, 194–206.
- Sanchez Matos, J., Barberino, A. T. M. S., de Araujo, L. P., Lôbo, I. P., & de Almeida Neto, J. A. (2021). Potentials and limitations of the bio-conversion of animal manure using fly larvae. *Waste and Biomass Valorization*, 12, 3497–3520.
- Spurr, C. (2003). *Identification and management of factors limiting hybrid carrot seed production in Australia*. University of Tasmania.

- Thompson, F. C., Ximo, M., Young, A. D., & Skevington, J. H. (2017). Flower flies (Diptera: Syrphidae) of Philippines, Solomon Islands, Wallacea and New Guinea. *The Entomological Society of Latvia*, 3, 501–524.
- Wiegmann, B. M., Trautwein, M. D., Winkler, I. S., Barr, N. B., Kim, J.-W., Lambkin, C., Bertone, M. A., Cassel, B. K., Bayless, K. M., Heimberg, A. M., Wheeler, B. M., Peterson, K. J., Pape, T., Sinclair, B. J., Skevington, J. H., Blagoderov, V., Caravas, J., Kutty, S. N., Schmidt-Ott, U., ... Yeates, D. K. (2011). Episodic radiations in the fly tree of life. *Proceedings of the National Academy of Sciences of the United States of America*, 108, 56–95.

How to cite this article: Davis, A. E., Schmidt, L. A., Santos, K. C. B. S., Martin, L., Harrington, S., Rocchetti, M., Hocking, B., Wright, D., Spurr, C., Cook, D., & Rader, R. (2023). The golden native drone fly (*Eristalinus punctulatus*) is an effective hybrid carrot pollinator that lives within Australian crop agroecosystems. *Ecological Solutions and Evidence*, 4, e12290. <https://doi.org/10.1002/2688-8319.12290>