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Predatory gall midges on mealybug pests – Diversity, life history, and feeding behavior in diverse agricultural settings

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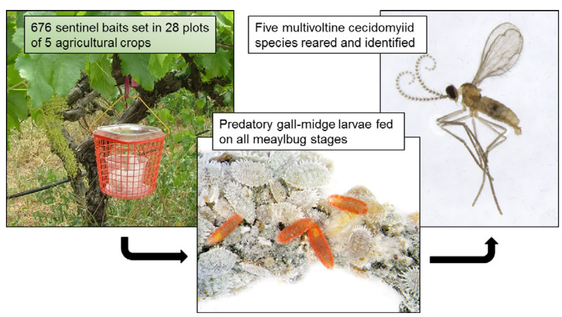
HIGHLIGHTS

- Five gall-midge species occurred in mealybug colonies exposed in five crops.
- Each was reared from at least two mealybug species belonging to different genera.
- Larvae feed on all mealybug stages and may subsist on a single individual.
- The predators are multivoltine and complete twice as many generations as their prey.
- No preference for distinct prey genera was found in laboratory trials.

GRAPHICAL ABSTRACT



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ABSTRACT

Predatory gall midges (Diptera: Cecidomyiidae) are some of the most common natural enemies associated with mealybugs. However, the generally poor knowledge on their life history and taxonomy has obscured their role in the biological-control of these pests. A comprehensive survey in vineyards and in banana, citrus, persimmon and pomegranate orchards throughout Israel, using more than 670 sentinel baits, revealed five species of gall midges. All species fed in the laboratory on *Planococcus citri* (Risso) and *Phenacoccus solani* Ferris, and in trials with *Diadiplosis multifila* (Felt) no preference for either of these mealybug species was found. Larvae fed on all stages of the mealybugs, and the gall midges completed their life cycle within 10–20 days. Adult peak activity of the five studied species was in summer, with low numbers obtained from baits in winter and fall. No difference in overall numbers of gall midges was found among crops, and differences in species composition among sites are attributed to geographic and climatic conditions.

1. Introduction

Mealybugs (Hemiptera: Pseudococcidae) are serious pests of diverse agricultural crops worldwide, whose effective control is impeded by a combination of factors, including their cryptic behavior, clumped distribution pattern, protective wax secretion, and the development of resistance to widely used insecticides (Franco et al., 2009; Daane et al., 2012). Spread by international trade has made a major contribution to the invasiveness status of many multivoltine mealybug species, which are able to develop on a wide range of host plants (Ben-Dov, 1994; Miller et al., 2002; Franco et al., 2009; Daane et al., 2012). Well known examples include the vine mealybug, *Planococcus Ficus* (Signoret) (Daane et al., 2012), the Hibiscus mealybug, *Maconellicoccus*

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hirsutus (Green) (Franco et al., 2009), the Solanum mealybug, *Phenacoccus solani* Ferris (Ben-Dov, 2005), and more recently the mealybugs *Planococcus minor* (Maskell) (Francis et al., 2012), *Phenacoccus peruvianus* Granara de Willink (Beltrà et al., 2010) and *Phenacoccus solenopsis* Tinsley (Fand and Suroshe, 2015). While chemical control is still the most common practice against mealybug infestations, increased awareness of its negative effects on the environment and the development of insecticide resistance favor the use of biological control and other sustainable strategies against these pests (Franco et al., 2004, 2009; Charles et al., 2010; Daane et al., 2012). Because the majority of serious mealybug pests are invasive alien species, classical biological control has been the leading practice, relying mainly on a combination of parasitoid wasps and the predatory coccinellid beetle *Cryptolemus montrouzieri* Mulsant, often with high degrees of success (Moore, 1988; ScaleNet, 2011). Similarly, augmentation biocontrol has been limited to wasps of the family Encyrtidae and to *C. montrouzieri*, although lacewings (Neuroptera: Hemerobiidae) and predacious gall midges (Diptera: Cecidomyiidae) are also commonly associated with mealybug colonies (Franco et al., 2004, 2009). In fact, comprehensive systematic studies in New Zealand (Charles, 1993) and in Israel (Z. Mendel, unpublished data) have demonstrated that cecidomyiids are the most common predators reared from mealybug colonies, but the impact of these natural enemies on mealybug populations has hardly been evaluated.

The gall midges include more than 6200 described and many undescribed species, the majority of which are phytophagous or mycetophagous in the larval stage (Gagné and Jaschhof, 2014). The family is best known for the phytophagous species because most are gall inducers and some are major or minor pests of cultivated plants, with important impact in agriculture, and forestry. Nevertheless, the family also contains hundreds of species whose larvae are predatory on insects and other invertebrates (adults do not feed). The life history of most predatory gall midges is unknown, and many of them have never been associated with any prey, having been described from adults caught in flight. The recognition of such species as predators relies on the fact that they belong to genera in which predation is known, and while this assumption is most probably true in general, it reflects our poor knowledge on the diversity, abundance and life history of most predatory cecidomyiids. An added challenge is the difficult taxonomy of predatory gall midges, and the need for study of all life stages for proper species identification. Predation has probably evolved several times in the evolution of the Cecidomyiidae and is currently known in 33 genera, the best known being *Lestodiplosis* Kieffer, *Arthrocnodax* Rübsaamen, *Diadiplosis* Felt, *Dicrodiplosis* Kieffer and *Trisopsis* Kieffer (Gagné and Jaschhof, 2014). General reviews on predatory gall midges were provided by Nijveldt (1969), and more recently by Harris (2004), and Gagné (1994) provided detailed information on their taxonomy. The larvae of most predatory species whose biology is known were recorded to feed on various Coccoidea (Hemiptera) (Harris, 1968, 1990, 1997), whereas others are known to feed on aphids (Harris, 1973), mites (Gagné, 1995; Gagné and Jaschhof, 2014), other cecidomyiids, and occasionally other invertebrates. The best known predatory cecidomyiids are *Aphidoletes aphidimyza* (Rondani) and *Feltiella acarisuga* (Vallot), which are produced commercially for use against aphids and tetranychid spider mites, respectively. Extensive information on the biology and ecology of these two species comes from numerous studies (e.g., Gillespie et al., 2000; Mo and Liu, 2006; Jandricic et al., 2013; Madahi et al., 2015), which point to the potential of predatory gall midges as biocontrol agents.

Knowledge about the food range of predacious gall midges is scarce; if specialization on a certain type of prey exists, then this is a generic trait, while individual species may be polyphagous or at least oligophagous within that type. Thus, for example, species of *Arthrocnodax* feed on eriophyoid mites and those of *Feltiella* Rübsaamen feed on tetranychid mites; *Aphidoletes* Kieffer species are restricted to aphids, and species of *Diadiplosis* and *Dicrodiplosis* Kieffer specialize on mealybugs (Harris, 2004; Gagné and Jaschhof, 2014). By contrast, *Lestodiplosis* and *Trisopsis* appear to be polyphagous at the generic level, as species in these genera have been recorded to feed on diverse types of invertebrate prey (Cole and Harris, 2002; Harris, 2004; Gagné and Jaschhof, 2014).

Four genera of gall midges, namely *Diadiplosis*, *Dicrodiplosis*, *Triommata* Barnes and *Megommata* Barnes, are considered to be specialized mealybug predators, although actual predation has been recorded for only half of the approximately 50 species included in them (Gagné and Jaschhof, 2014). The two *Triommata* and six *Megommata* species are restricted to the Afrotropical and Oriental Regions, whereas *Diadiplosis* and *Dicrodiplosis* are larger, cosmopolitan genera. The only other gall midges in which mealybug predation has been recorded are the apparently polyphagous *Trisopsis incisa* Felt and *T. walkeriana* Felt, which were recorded from various insects and mites (Gagné and Jaschhof, 2014). Gall midges are some of the most abundant mealybug predators and have sometimes been judged to be the most efficient ones (Smith and Compere, 1928; Carter, 1944); nevertheless, they have rarely been considered in biological control schemes. Moore (1988) lists four *Diadiplosis* and one *Dicrodiplosis* species that were used in classical biological control programs, of which only *Diadiplosis pseudococci* Felt was considered to be successful when introduced from Mexico into Hawaii against the pineapple mealybug *Dysmicoccus brevipes* (Cockerell) (Carter, 1944). The other four species mentioned by Moore (1988) have either established, failed, or have not been evaluated following their introduction, including *Diadiplosis koebelei* (Koebele), which was regarded as a promising agent against *Pseudococcus longispinus* (Targioni-Tozzetti) in New Zealand (Charles, 1985). We found no records on the use of mealybug-preying gall midges in augmentation or conservation biological control programs.

The role of predatory gall midges in the natural control of mealybug populations deserves to be studied. We suggest that the poor knowledge of their biology or even taxonomic identity precludes their incorporation into actual management programs. Indeed, the statement made by Harris (1968) in his revision of Coccoidea-preying gall midges that "a great deal still remains to be learned about the biology of even the commonest known species", still holds true almost 50 years later. In the present study we conducted a methodical survey of mealybug-preying gall midges in diverse agricultural crops that are susceptible to mealybug infestations throughout Israel in order to determine their (1) identity and relative abundance, (2) life history and seasonal activity, and (3) prey range and predation behavior. We further discuss the limitations and possible advantages of predatory gall midges as mealybug natural-enemies under natural conditions.

2. Material and methods

2.1. Study sites and collection methods

Collecting was done from 28 agricultural plots throughout Israel, from the temperate Golan Heights in the North to the arid Arava valley in the south (Fig. 1). Sampling included citrus, pomegranate, banana, grapevine and persimmon plots, all of which suffer mealybug damage. Sampling was confined to organic plots in order to avoid the expected adverse effects of pesticides on the insect populations. To avoid difficulties in locating small and patchy mealybug colonies and in particular to ascertain that the gall midges are associated with the studied mealybugs, we used 'sentinel traps' as described by Francis et al. (2012). The traps were