Volatile Semiochemicals Increase Trap Catch of Green Lacewings (Neuroptera: Chrysopidae) and Flower Flies (Diptera: Syrphidae) in Corn and Soybean Plots

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Abstract

This study reports on the attractiveness of volatile chemicals to green lacewings (Neuroptera: Chrysopidae) and flower flies (Diptera: Syrphidae) as measured by catch on yellow sticky traps within corn [Zea mays L. (Cyperales: Poaceae)] and soybean [Glycine max (L.) Merr. (Fabales: Fabaceae)] plots. Green lacewings were attracted to eugenol-baited traps in two tests in soybean plots. Follow-up testing in corn showed that catch of green lacewings was enhanced when traps were baited with eugenol, its structural analog isoeugenol, or 2-phenylethanol; trap catch of green lacewings was greater with these compounds than with structural analog, 4-allylanisole. In a follow-up test in soybean, more green lacewings were caught on traps baited with isoeugenol than with 4-allylanisole. Catch did not differ among traps baited with eugenol, isoeugenol, or 2-phenylethanol or among those baited with eugenol, 2-phenylethanol, or the ethanol control. In a 6-wk experiment in soybean, green lacewings were attracted to eugenol-baited traps in 5 of 6 wks but to traps baited with structural analog methyl eugenol in only 1 wk. Flower flies were attracted to 2-phenylethanol in initial tests in corn and soybean plots. Subsequent testing in soybeans with 2-phenylethanol and structural analogs confirmed attraction to 2-phenylethanol and also showed attractancy of 2-phenylacetaldehyde but not benzylamine. A 6-wk test in soybean found that flower flies were also attracted to traps baited with either eugenol or methyl eugenol. This is the first report of green lacewing attraction to eugenol and isoeugenol and first report of flower fly attraction to eugenol. Structure-activity relationships among attractants and practical aspects of their use are discussed.

Key words: chemical ecology, 2-phenylethanol, eugenol, beneficial insect

Knowledge about the responsiveness of beneficial insects to plant-produced, volatile semiochemicals may improve understanding of insect ecology (Knudsen et al. 1993, Breitkreuz et al. 2015, Jones et al. 2015b) and also lead to practical means of recruiting them to enhance ecosystem services within various settings, e.g., agricultural habitats (Agelopolous et al. 1999, James and Price 2004, Turlings and Ton 2006, Khan et al. 2008). Several means of enhancing beneficial insect performance have been proposed, including exploitation of volatile semiochemicals that natural enemies use in locating food sources such as floral resources and prey (Sabelis et al. 1999, Hatano et al. 2008, Kaplan 2012, Heil 2014, Kelly et al. 2014). Theoretically, such chemicals may be deployed to attract and retain beneficial insects within crop fields, such that searching behavior of insect natural enemies is prolonged and probability of them encountering prey increased (Sabelis et al. 1999, James and Price 2004, Hatano et al. 2008, Kelly et al. 2014).

A large pool of candidate compounds has been identified that includes constitutive compounds such as floral and “green-leaf” volatiles and compounds whose production is induced by herbivore feeding, with responsiveness among a wide spectrum of beneficial insects (Hunter 2002, Turlings and Ton 2006, Khan et al. 2008, Heil 2014). However, until recently, field testing of such volatiles has typically lagged far behind their testing in the laboratory (Hunter 2002, Khan et al. 2008, Kaplan 2012), but if the practical potential of such compounds is to be realized for pest management, additional field studies are needed (Hunter 2002; James 2003, 2005).

Ideally, systematic testing of these volatile chemicals should be conducted in the field against a diversity of natural enemies from various geographic regions to determine the spectrum and degree of activity and to determine whether they can eventually be exploited to improve pest management with natural enemies (Hunter 2002, Kaplan 2012, Heil 2014). Field crops have a diverse assemblage of generalist and specialist natural enemies (Flint and Dreistadt 1998, Michaud et al. 2008), such as damsel bugs and insidious flower bugs (Hemiptera: Nabidae and Anthocoridae, respectively), green lacewings, and brown lacewings (Neuroptera: Chrysopidae and Hemerobiidae, respectively), lady beetles (Coleoptera: Coccinellidae), flower (or hover) flies (Diptera: Syrphidae), and...
vocans. However, testing of natural enemies’ responsiveness to volatile semiochemicals has been relatively limited in field crops compared to perennial cropping systems (James 2005, Turlings and Ton 2006, Maeda et al. 2015). Thus, field crops remain researchable settings for testing the responsiveness of insect natural enemies to volatile semiochemicals, and this paper reports on experiments involving responses of various natural enemies to volatile semiochemicals in field crop plots.

Materials and Methods

Field tests of the responsiveness of beneficial insects to volatile chemicals were conducted during the summers of 2004 through 2007 in 0.5-1.5-ha plots of corn [Zea mays L. (Cyperales: Poaceae)] and soybean [Glycine max (L.) Merr. (Fabales: Fabaceae)] at the Eastern South Dakota Soil and Water Research Farm near Brookings, South Dakota (44°19’ N, 96°46’ W, 500 m elevation). These crops were used because they regularly contain a diverse assemblage of beneficial insects such as aphidophagous predators that could be tested each year (Kieckhefer et al. 1992, Elliott et al. 2002, Hesler 2014). The plots were maintained with tillage consisting of fall chisel plow and spring surface cultivation, a combination of 2-3 preplant and postemergent herbicide applications at maximum labeled rates, and variable nitrogen fertilization commensurate with yield goals for corn and soybean in the region (Pikul et al. 2005, Hesler 2014). No insecticide was applied to plots from the planting through sampling period each year.

The volatile chemicals tested were based mainly on activity to various beneficial insects in the previous laboratory and limited field tests (Table 1). Altogether, eight field trials were conducted (Table 2). The first three trials screened candidate compounds for activity with beneficial insects, and the fourth was designed to confirm attractancy of eugenol to green lacewings. The last four trials were follow-up tests that compared attractancy of structural analogs of active compounds identified in the screening trials.

Two types of dispensers were used to disperse attractants. The first six trials were conducted in 2004 and 2005 with volatile chemicals dispensed from cotton wicks (3.8 cm long; Patterson, St. Paul, MN). The chemicals were applied to the wicks by pipette at 100 mg per compound as either stock or solvent-based (camphor only; ethanol = solvent) solutions. Wicks were prepared in the morning and deployed in the field on traps immediately afterward for 48 hour. The remaining two field trials were run with volatile compounds dispensed via controlled-release, plastic sachets containing 2 g per chemical (ChemTica International, Heredia, Costa Rica). These two trials were run for 6 and 8 wk in 2006 and 2007, respectively, to also assess temporal trends in attractancy. Ethanol was chosen as the non-attractant control in all trials because of its use as a solvent for camphor and the absence of published studies of attractancy to beneficial insects.

Treatment wicks or sachets were attached to the top of the non-adhesive side of a yellow Pherocon AM sticky trap (23 × 28 cm, Trécé Inc., Salinas, CA). Baited traps were folded lengthwise with the sticky surface exposed, and they were clipped on to 1-m tall stakes and placed 10–30 m apart to avoid interference among treatments. Stakes were placed between plant rows, with traps set just above the canopy (≈0.7 m high.) in soybean plots and 1 m high in corn plots. Treatments were randomly assigned to traps within individual crop rows, which were considered as replicate blocks. From 4 to 10 replicates were used per study (Table 2). Traps were retrieved from the field plots, and beneficial insects were identified to family level and counted. The counts were subjected to separate analysis of variance (PROC GLIMMIX; SAS Institute 2012) by the family for each test. Treatment means were separated by the LSMEANS feature with Tukey–Kramer adjustment. However, a Kruskal–Wallis non-parametric test was used when relatively low or zero counts for some compounds rendered them inapt for parametric analysis. Significant outcomes of Kruskal–Wallis tests were followed by a Nemenyi post hoc procedure for mean separation (Zar 2010, Elliott and Hynan 2011).

Results

Overview

Several kinds of beneficial insects were captured on the traps in relatively large numbers, but only the capture of green lacewings (Neuroptera: Chrysopidae) and flower flies (Diptera: Syrphidae) varied significantly (P < 0.05) among the attractant-baited traps. Captures of green lacewings varied significantly among volatile-baited traps in tests 2, 4, 5, 6, 7, and 8; flower fly captures varied significantly among baited traps in tests 1, 3, 7, and 8 (Table 2). Results for each of these two groups are reported separately by test below.

Green Lacewings

Capture of green lacewings varied among volatile attractants screened in soybean plots in 2004 (F = 9.14; df = 2, 15; P = 0.0025), as traps captured more green lacewings when their wicks were impregnated with eugenol compared with either methyl salicylate or ethanol (Fig. 1). In a follow-up test in soybean in 2004, trap catch varied by treatment (F = 5.86; df = 1, 18; P = 0.0026), with about twice as many green lacewings captured on eugenol traps (x ± SE = 3.2 ± 0.7) as on ethanol traps (1.5 ± 0.3).

Trap catch of green lacewings varied among structural analogs of eugenol in both soybean (F = 7.94; df = 4, 20; P < 0.001) and corn (F = 7.03; df = 4, 30; P < 0.001) in 2005. In soybean (Fig. 2), more green lacewings responded to isoeugenol than to 4-allylansiol or ethanol, but the response did not differ statistically from that to eugenol or 2-phenylethanol. The response of green lacewings did not differ between eugenol and ethanol or among 2-phenylethanol, 4-allylansiol, and ethanol. In corn (Fig. 3), the response of green lacewings did not differ among eugenol, 2-phenylethanol, and isoeugenol, but more green lacewings responded to these compounds than to ethanol or 4-allylansiol; response did not differ between ethanol and 4-allylansiol.

During the 6-wk experiment in 2006, response of green lacewings in soybean varied by volatile (F = 44.96; df = 3, 40; P < 0.001), week (F = 5.83; df = 5, 30; P < 0.001) and the volatile-by-week interaction (F = 2.14; df = 15, 90; P = 0.015). A significant interaction indicated that green lacewing response to volatiles was not consistent over individual weeks of the trapping period, with trap catch differing in each of the first 5 wks but not in week 6 (Fig. 4). Specifically, more green lacewings were captured on eugenol traps compared with ethanol traps in each of the first 5 weeks. More green lacewings were captured on eugenol-baited than on octanal-baited traps in weeks 1, 2, 3, and 5. More green lacewings were captured on eugenol-baited than on methyl eugenol-baited traps in weeks 1 and 5. Capture of green lacewings was greater on methyl eugenol-baited traps than on traps baited with octanal or ethanol in week 3. Trap catch never differed significantly between octanal and ethanol.
| Volatile chemical                      | Abbreviation | Alternate chemical name                        | Dosage, dispenser | Supplier                        | References                                      |
|---------------------------------------|--------------|----------------------------------------------|-------------------|---------------------------------|------------------------------------------------|
| Year 2004                             |              |                                              |                   |                                 |                                                 |
| Camphor                               | CAM          | 1,7,7-trimethylbicyclo[2.2.1]heptan-2-one    | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     | Riddick et al. 2000                             |
| Ethanol (non-attractant control)      | ETOH         | 1-phenyl-1-propanol                          | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     |                                                 |
| Eugenol                               | EUG          | 3-(3-methoxy-4-hydroxyphenyl)prop-1-ene      | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     |                                                 |
| 2-Isopropyl-3-methoxypyrazine         | IMP          | 2-isopropyl-3-methoxypyrazine                | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     |                                                 |
| Methyl salicylate                     | MSAL         | Methyl 2-hydroxybenzoate                     | 100 mg, cotton roll | Sigma-Aldrich, Milwaukee, WI     |                                                 |
| 2-Phenylethanol                       | 2PE          | 2-phenethanol                                | 100 mg, cotton roll | Sigma-Aldrich, Milwaukee, WI     |                                                 |
| Terpineol (mixed isomers)             | TERP         | 2-(4-methyl-1-cyclohex-3-enyl)propan-2-ol    | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     |                                                 |
| trans-Caryophyllene                   | TC           | trans-(1R,9S)-8-methylene-4,11,              | 100 mg, cotton roll | Spectrum Chemical, Gardena, CA   |                                                 |
| Year 2005                             |              | 11-trimethylbicyclo-undec-4-ene             |                   |                                 |                                                 |
| 4-Allylanisole                        | 4AA          | 1-methoxy-4-(2-prophenyl)benzene             | 100 mg, cotton roll | Sigma-Aldrich, Milwaukee, WI     |                                                 |
| Ethanol (non-attractant control)      | ETOH         | 1-phenyl-1-propanol                          | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     |                                                 |
| Eugenol                               | EUG          | 3-(3-methoxy-4-hydroxyphenyl)prop-1-ene      | 100 mg, cotton roll | Sigma-Aldrich, St. Louis, MO     |                                                 |
| Isoeugenol                            | ISO          | 3-(3-methoxy-4-hydroxyphenyl)prop-2-ene      | 100 mg, cotton roll | Spectrum Chemical, Gardena, CA   |                                                 |
| 2-Phenylethanol                       | 2PE          | 2-phenethanol                                | 100 mg, cotton roll | Sigma-Aldrich, Milwaukee, WI     |                                                 |
| Years 2006–2007                       |              |                                              |                   |                                 |                                                 |
| 4-Allylanisole                        | 4AA          | 1-methoxy-4-(2-prophenyl)benzene             | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| 2-Benzylamine                         | BA           | phenylmethanamine                            | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| Eugenol                               | EUG          | 3-(3-methoxy-4-hydroxyphenyl)prop-1-ene      | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| Isoeugenol                            | ISO          | 3-(3-methoxy-4-hydroxyphenyl)prop-2-ene      | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| Methyl eugenol                        | MET          | 3-(3,4-dimethoxyphenyl)prop-1-ene            | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| Octanal                               | OCT          | octylaldehyde                                | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| 2-Phenylacetaldehyde                  | PAA          | 2-phenylethanal                              | 2 g, sachet       | ChemTica International, Heredia, Costa Rica |                                                 |
| 2-Phenylethanol                       | 2PE          | 2-phenethanol                                | 2 g, sachet       | Predalure, AgBio, Westminster, CO |                                                 |
Flower Flies

Trap catch of flower flies varied by volatile attractant in two-day screening tests in corn ($F = 24.21; df = 5, 54; P < 0.001$) and soybean plots ($\chi^2 = 13.3, df = 4, P = 0.001$) in 2004. In corn, more flower flies were caught on traps baited with 2-phenylethanol than on those with other attractants (Fig. 5). In soybean, traps baited with 2-phenylethanol caught a mean ($\pm$ SE) of 1.5 $\pm$ 0.6 flower flies per trap, whereas traps baited with other attractant caught no flower flies.

Trap catch of flower flies also varied in a follow-up trial with 2-phenylethanol and its structural analogs. In an 8-wk trial in 2007, trap catch of flower flies varied by volatile attractant ($F = 59.45; df = 3, 120; P < 0.001$), week ($F = 18.66; df = 7, 40; P < 0.001$), and the attractant-by-week interaction ($F = 2.36; df = 21, 120; P = 0.002$). Figure 6 illustrates the complexity of flower fly response to volatiles over the 8 wks of this trial. Trap catch was greater with 2-phenylethanol than with benzylamine and ethanol each week except week 6, and greater with 2-phenylethanol than with 2-phenylacetaldehyde during weeks 2, 3, and 4. Traps with 2-phenylacetaldehyde captured more flower flies than those with benzylamine and ethanol during weeks 1, 7, and 8, and more than with benzylamine during week 5. Trap catch of flower flies did not differ between benzylamine and ethanol in any week.

Finally, during a 6-wk trial in soybean in 2006 involving eugenol, methyl eugenol, and octanal, flower fly response varied by volatile ($F = 4.10; df = 3, 90; P = 0.009$) and by week ($F = 3.01; df = 5, 20; P = 0.026$) but not by the volatile-by-week interaction ($F = 0.45; df = 15, 90; P = 0.51$). More flower flies responded to methyl eugenol and eugenol than to octanal and ethanol (Fig. 7).

### Table 2. Tests of the attractancy of volatile chemicals to beneficial insects in agricultural plots near Brookings, SD

| Test no. | Crop   | Date            | Volatiles tested* | n† | Insects evaluated           |
|----------|--------|-----------------|-------------------|----|-----------------------------|
| 1        | Corn   | 2–4 Aug. 2004   | CAM, IMP, 2PE, TC, TERP, ETOH | 10 | Flower flies                |
| 2        | Soybean| 13–15 Aug. 2004 | EUG, MSAL, ETOH   | 6  | Green lacewings             |
| 3        | Soybean| 17–19 Aug. 2004 | IMP, 2PE, TC, TERP, ETOH | 4  | Flower flies                |
| 4        | Soybean| 24–26 Aug. 2004 | EUG, ETOH         | 10 | Green lacewings             |
| 5        | Soybean| 20–22 Jul. 2005 | 4AA, EUG, ISO, 2PE, ETOH | 5  | Green lacewings             |
| 6        | Corn   | 20–22 Jul. 2005 | EUG, MET, OCT, ETOH | 7  | Green lacewings             |
| 7        | Soybean| 3 Jul.–14 Aug. 2006 | (traps replaced weekly; lures replaced after 3 wks) | 6  | Green lacewings, flower flies |
| 8        | Soybean| 20 Jun.–15 Aug. 2007 | (traps replaced weekly; lures replaced after 4 wks) | 6  | Flower flies                |

*See Table 1 for names of abbreviated volatiles tested.
†Sample size.

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**Fig. 1.** Chemical structures and name abbreviations of test compounds.
Fig. 2. Mean number of green lacewings (GLW) per sticky trap (± SE) baited with 100 mg of one of three volatile compounds (ETOH = ethanol, MSAL = methyl salicylate, and EUG = eugenol) from 13 – 15 August 2004 in a soybean plot near Brookings, SD.

Fig. 3. Mean number of green lacewings (GLW) per sticky trap (± SE) baited with 2 g of 2-phenylethanol or eugenol or one of its structural analogs from 20 to 22 July 2005 in a soybean plot near Brookings, SD. ETOH = ethanol (control), 4AA = 4-allylanisole, 2PE = 2-phenylethanol, EUG = eugenol, and ISO = isoeugenol.

Fig. 4. Mean number of green lacewings (GLW) per sticky trap (± SE) baited with 2 g of 2-phenylethanol or eugenol or one of its structural analogs from 20 – 22 July 2005 in a corn plot near Brookings, SD. ETOH = ethanol (control), 4AA = 4-allylanisole, ISO = isoeugenol, 2PE = 2-phenylethanol, EUG = eugenol.

Fig. 5. Mean number of green lacewings (GLW) per week on sticky traps (± SE) baited with 2 g volatile chemicals from 3 July – 14 August 2006 in a soybean plot near Brookings, SD. See Tables 1 and 2 for treatments. Columns of letters denote significant differences among treatments for each week; NS = not significant. ETOH = ●, EUG = ○, MET = ▽, OCT = △.

Fig. 6. Mean number of flower flies per sticky trap (± SE) baited with 100 mg volatile chemicals from 2 – 4 August 2004 in a corn plot near Brookings, SD. CAM = camphor, ETOH = ethanol (control), IMP = 2-methoxy-3-isopropylpyrazine, 2PE = 2-phenylethanol, CARY = trans-caryophyllene, TERP = terpineol.

Fig. 7. Mean number of flower flies per week on sticky traps (± SE) baited with volatile chemicals from 20 June – 15 August 2007 in a soybean plot near Brookings, SD. See Tables 1 and 2 for treatment details. Columns of letters denote significant differences among treatments for each week; NS = not significant. ETOH = △, 2PE = ▽, BA = ●, 2PAA = ○.
The response did not differ between eugenol and methyl eugenol, between eugenol and octanal, or between octanal and ethanol.

Discussion

Results of this study showed that green lacewings and flower flies responded significantly to particular volatile compounds within corn and soybean field plots. Green lacewings were attracted to point sources of eugenol and two of its structural isomers, isoeugenol, and methyl eugenol; however, 4-allylanisole, another structural analog of eugenol, did not elicit a significant response. In addition, green lacewings responded to 2-phenylethanol in one test. Flower flies were also significantly attracted to 2-phenylethanol and its structural analog, 2-phenylacetaldehyde, but not to the analog, 2-benzylalcohol. In one test, flower flies were also attracted to traps baited with eugenol and methyl eugenol.

Yellow sticky traps are biased toward sampling actively flying insects, and baiting with volatile compounds may heighten active movements of insects toward such traps (Zou et al. 2012). Accordingly, this study successfully used yellow sticky traps in corn and soybean fields to measure the differential responses to several volatile compounds by two types of actively flying insects, namely adult green lacewings and adult flower flies. These two types of insects are part a suite of actively flying natural enemies that inhabit corn and soybean fields in the upper Midwestern U.S. (Bhatti et al. 2005, Schmidt et al. 2008). There are several other kinds of non-flying, arthropod natural enemies that inhabit these fields (Schmidt et al. 2008, Hesler 2014), and different methods would be needed to determine whether they also respond to the volatile compounds (Zou et al. 2012). Future studies should use alternate sampling methods to assess whether compounds (e.g., 2-phenylethanol and eugenol) that were active in the present study might also be attractive to non-flying natural enemies in corn and soybean fields.

Studies evaluating natural enemy responses to volatile chemicals indicate that responses were often context-dependent on factors such species, environment (e.g., crop habitat), and time of year (Rodriguez-Saona et al. 2011, Jones et al. 2015b). As with my study, many studies have evaluated responsive natural enemies at the family level, especially when volatile compounds are tested across the general arthropod community (Rodriguez-Saona et al. 2011, Braasch et al. 2012). Thus, some variation in responsiveness within and among studies could be due to the presence or absence of individual species at a given time of year within a particular crop (Rodriguez-Saona et al. 2011). Follow-up studies with active compounds in my study (e.g., 2-phenylethanol and eugenol) should identify the individual species of green lacewings and flower flies that respond to them and account for factors such as time of year, crop, and crop phenology.

Results of the tests in my study indicate that responsiveness of green lacewings and flower flies appears to be related to the chemical structure of volatile compounds, based on a differential catch on traps baited with structural analogs. For instance, eugenol, isoeugenol, methyl eugenol, and 4-allylanisole are each composed of a benzene ring with an allyl and a methoxy group attached (Fig. 8). Greater response of green lacewings to eugenol, isoeugenol, and methyl eugenol than to 4-allylanisole suggests that response may depend on either 1) placement of the methoxy group on the benzyl ring at the second (rather than third) position away from the allyl moiety or 2) the presence of hydroxy or methoxy groups at both the second and third positions from the allyl moiety.

Similarly, benzylamine, 2-phenylethanol, and 2-phenylacetaldehyde each consist of a benzene ring with a relatively short carbon chain containing a single functional group (Fig. 8). Of these, 2-phenylethanol and 2-phenylacetaldehyde were attractive to flower flies. The chain of these three compounds consists of two or three carbons, whereas the chain of benzylamine contains a single carbon. This suggests that number of carbon atoms, and not a functional group, of the chain substituent is important in attracting flower flies. Töth et al. (2006) also showed attractiveness of 2-phenylacetaldehyde to green lacewings (Chrysoperla carnea S.l.) in Hungary. However, Zhu et al. (2005) found that trap catch of green lacewings (Chrysoperla carnea (Say)) in alfalfa fields in Iowa, U.S.A., was increased by 2-phenylethanol, but not by 2-phenylacetate, an analog with a two-carbon chain.

Although green lacewings were typically attracted to eugenol and its analogs and flower flies to 2-phenylethanol and its analogs, green lacewings also responded significantly to 2-phenylethanol and flower flies responded significantly to eugenol and methyl eugenol in one experiment each. In the case of 2-phenylethanol, it is not clear why the attraction to green lacewings was limited to only one of five experiments with this compound. I hypothesize that factors such as crop phenology, the seasonal activity of green lacewings, or both may have influenced its sporadic activity. Regardless, crossover activity of 2-phenylethanol and methyl eugenol to green lacewings and flower flies suggests that a mixture of the compounds might be advantageous in helping to ensure attraction of these insects. Mixtures of volatile semiochemicals often elicit stronger responses in natural enemies than individual compounds (Töth et al. 2009, Jones et al. 2015a, Maeda et al. 2015) and may be used strategically to encompass a greater range of natural enemies and cover a broader period of applicability (Jones et al. 2015a).

Previous studies have shown green lacewings respond to some of the same volatile compounds that were attractive in this study. For instance, studies have shown that green lacewings are attracted to methyl eugenol (Suda and Cunningham 1970, Umeya and Hirao 1975, Pai et al. 2004), but my study appears to be the first report of green lacewings attracted to its analogs, eugenol, and isoeugenol. Other studies have also shown that green lacewings respond to 2-phenylethanol (Zhu et al. 1999, 2005; Jones et al. 2015a) and to 2-phenylacetaldehyde (Töth et al. 2006). Testing with additional
analogs is needed to delineate exact structure-activity relationships between volatile compounds and green lacewings.

Similarly, previous studies have also shown that flower flies respond to some volatile chemicals that were attractive in my study. For instance, Jones et al. (2015a) showed that three species of flower flies were attracted to 2-phenylethanol, but I did not find previous reports regarding flower fly response to the analog 2-phenylacetaldehyde, as in one of my tests. Further testing of these compounds with other flower fly populations is recommended to confirm my results.

The attraction of flower flies to eugenol in one experiment of my study appears to be novel. Although Dowell (2015) reported that significant numbers of flower flies were captured in traps baited with methyl eugenol, flower flies were not attracted to that compound in my study. The disparity between Dowell’s (2015) results and mine may indicate that structure-activity relations among isolomers differ among populations or species of flower flies and suggests that more research on these relationships is needed.

Compounds that were active in this study (i.e., eugenol, isoeugenol, methyl eugenol, 2-phenylethanol, and 2-phenylacetaldehyde) are all naturally occurring, plant-derived (and often flower-based), volatile chemicals (Knudsen et al. 1993, Zhu et al. 1999, Tan and Nishida 2012). Thus, their attractiveness to green lacewings and flower flies raises basic questions about their role in the chemical ecology between plants and these insects. As such, these attractants may be utilized as tools to study various ecological aspects of green lacewings and flower flies, such as their interactions with plants (Knudsen et al. 1993), aggregation, and mating behaviors (Breitkreuz et al. 2015), diurnal activity patterns, and seasonal phenology (Jones et al. 2015b).

Volatile attractants may also be applied to recruit green lacewings and flower flies into crop fields to enhance the potential for biological control services (Turlings and Ton 2006, Kaplan 2012). Although some species of green lacewings are predacious as adults, predation occurs primarily by larvae with green lacewings and exclusively by larvae with flower flies (Flint and Dreistadt 1998). Thus, a sequence of additional steps is needed to move from mere attraction of adult green lacewings and flower flies to point sources of volatiles in crop plots to the actual enhancement of biological pest control by these predators in agricultural fields (Braasch and Kaplan 2012, Heil 2014). In addition, research is needed to determine the impact of drawing natural enemies such as green lacewings and flower flies into particular crop fields and away from other agricultural habitats and from natural and seminatural settings (Braasch and Kaplan 2012, Kelly et al. 2014). Nonetheless, results of this study have identified several candidate compounds that may be used in future basic and applied studies on the chemical ecology of green lacewings and flower flies.

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