Floral Scent of Canada Thistle and Its Potential as a Generic Insect Attractant

A. M. EL-SAYED,[1,2] J. A. BYERS,[3] L. M. MANNING,[1] A. JÜRGENS,[1] V. J. MITCHELL,[1] AND D. M. SUCKLING[1]

J. Econ. Entomol. 101(3): 720–727 (2008)

ABSTRACT The flowers of Canada thistle, *Cirsium arvense* (L.), attract a wide range of insects, including pollinators and herbivorous species. This attraction is primarily mediated by floral odor, which offers potential for developing generic insect attractants based on odor. In this study, we have analyzed the chemical composition of the volatiles produced by Canada thistle flowers. Nineteen floral compounds were identified in the headspace, including phenylacetaldehyde (55%), methyl salicylate (14%), dimethyl salicylate (8%), pyranoid linalool oxide (4.5%), and benzaldehyde (3.5%). Other minor compounds include benzyl alcohol, methylbenzoate, linalool, phenylethyl alcohol, furanoid linalool oxide, *p*-anisaldehyde, 2,6-dimethyl-1,3,5,7-octatetraene, benzylacetate, benzyl tiglate, (E,E)-α-farnesene, benzyl benzoate, isopropyl myristate, and 2-phenylethyl ester benzoic acid. The relative attractiveness of various doses of the main floral volatile compound phenylacetaldehyde (i.e., 10, 100, 200, and 400 mg) was tested for insect attraction. Both the total catch and the biodiversity of insect species trapped increased as the loading of phenylacetaldehyde increased. Volatiles were chosen from the odors from the flowers of Canada thistle and formulated and tested in the field. An 11-component blend was the most attractive of several floral blends tested. These findings indicate that chemical components of flower odors of Canada thistle can serve as a generic insect attractant for monitoring of invasive pest species.

KEY WORDS kairomone, invasive species, floral volatiles, Canada thistle, *Cirsium arvense*

During the last half-century, pheromones have been used extensively for monitoring and controlling economically important agricultural pests. For example, sex pheromones of moths produced by females are used to attract conspecific males, whereas aggregation pheromones produced by one or both sexes are used to attract both males and females of the same species. Pheromones are species specific, and this selectivity is considered an advantage because nontarget beneficial species (i.e., parasitoids and predators) are unharmed in an integrated pest management or invasive pest surveillance program. However, sex pheromones cannot be used in monitoring of invasive species, especially when the identity and arrival of the pest species is unknown and unpredictable, i.e., a new incursion of invasive species (Suckling et al. 2005) or when it is necessary to monitor many species simultaneously (Suckling and Gibb 2003).

The risk of transport of non-native pest species is increasing due to significant increases in global trade and intercontinental travel of people. Invasive species can become serious pests once they are established, causing enormous damage to valued indigenous and productive species (Pimentel et al. 2000). Early detection and tracking of these unwanted invaders is essential for preventing their establishment and population buildup. This can entail the deployment of traps around entry ports and cargo facilities as an early warning system for the arrival of an array of unwanted species (Brockerhoff et al. 2006). In this case, sex pheromones are difficult to deploy because the identity of the invasive species is not known beforehand, and the sex pheromone may not be readily available. In this regard, generic attractants that can attract a broad range of insect species could be more useful than species-specific sex or aggregation pheromones, because continuous monitoring and a rapid response are essential to successful detection and eradication.

Several generic insect attractants have been reported in the literature (Creighton et al. 1973; Cantelo and Jacobson 1979; Meagher 2001a, 2001b; Meagher 2002). These generic attractants are usually floral volatile compounds or fermented sweet baits, or synthetic compounds produced by these fermented media (Meagher 2002; Landolt and Hammond 2001; El-Sayed et al. 2005). For example, the combination of 3-methyl butanol and acetic acid, produced during the fermentation process of sweet baits, attracts a wide range of insect species (Landolt and Hammond 2001, El-Sayed et al. 2005, Meagher and Mislevy 2005). In addition, many insects are attracted to flowers by

[1] HortResearch, Canterbury Research Centre, Lincoln 8152, New Zealand.
[2] Corresponding author, e-mail: ael-sayed@hortresearch.co.nz.
[3] U.S. Arid-Land Agricultural Research Center, USDA–ARS, 21881 North Cardon Lane, Maricopa, AZ 85238.

0022-0493/08/0720–0727$04.00/0 © 2008 Entomological Society of America

either floral odors or by visual cues or a combination of both (Pombal and Morellato 2000, Balkenius et al. 2006). Phenylacetaldehyde, which is produced by many flowers, is attractive to a wide range of insect species (Creighton et al. 1973, Maini and Burgio 1990, Meagher 2002).

The flowers of Canada thistle, *Cirsium arvense* (L.) Scop (Asteraceae), have been reported to attract a wide range of insects (Proctor et al. 1996). In addition, we have observed the attraction of many insects, including moths, bees, wasps, and beetles, to the flowers of Canada thistle. Plepys et al. (2002) reported the attraction of the moth, *Autographa gamma* (L.), to flowers of *C. arvense* in a wind tunnel. Floral scent was considered the primary cue in the attraction of this species to the flowers (Plepys et al. 2002). The chemistry of Canada thistle volatiles has been previously investigated (Connick and French 1991, Plepys et al. 2002, Andersson et al. 2002). Theis (2006) identified individual compounds in the headspace of *C. arvense* that attracted a wide range of insects in the field, but no blend combinations were tested in that study.

We have analyzed the volatiles produced by Canada thistle flowers, and then we formulated and field tested several floral blends to determine the best blend composition to attract a wide range of insect species in significant numbers. We have conducted these field trails in several locations worldwide, including Australia, the United States, and Europe. In this work, we present the data obtained from the field trails conducted in Arizona. We anticipate that the results of these field tests might provide a potential floral volatile blend that can be used as a generic attractant to monitor the arrival of unwanted insects However, this work is the first study to investigate in greater detail, the attraction of various insect species to floral blends based on the volatiles of Canada thistles in field trapping experiments.

Materials and Methods

Plants. Canada thistles were individually grown from seeds that were field collected on site at the Lincoln campus in 2006; seeds were planted in 16.5-cm-diameter pots that contained South-Hort potting mix (Southern Horticultural Products, Christchurch, New Zealand), and fertilized with Osmocote (Scotts Miracle-Gro, Marysville, OH). Plants were kept in a greenhouse at 22°C ± 4°C, and they were 110 cm in height during volatile collection.

Volatile Collection and Chemical Analysis. Volatile collections from Canada thistle flowers were made in the laboratory by using two different methods: 1) a dynamic headspace collection method followed by sorbent extraction, and 2) a semidynamic headspace collection followed by thermodesorption. Collection of volatiles was conducted under natural light conditions and room temperature.

In the dynamic headspace collection 1, the intact flower head was housed in a glass container (4.0 cm i.d., 6.0 cm in height). The glass container consisted of two parts that tightly closed together using ground glass fittings and a rubber band. One part had a narrow slot (2 mm in width by 17 mm in length) to allow insertion of the flower into the glass container without damaging the stem. A charcoal–filtered airstream was pulled over the flower and the headspace was collected on an adsorbent trap containing 50 mg of Tenax-GR 35/60 (Alltech Associates Inc., Deerfield, IL) in a 15-mm-long by 10-mm-diameter glass tube. Tenax traps were thermally conditioned at 200°C under a stream of nitrogen before use. The airflow in the headspace collection system was 2 liters/min, and each collection session lasted for 1.2 h. The charcoal filter used to clean the incoming air was thermally activated before use in an oven at 200°C. Control samples were collected from the above-mentioned system but without flowers to distinguish between floral compounds and ambient contaminants. Immediately after volatile collection, Tenax traps were extracted with 1 ml of hexane (5 × 200-μl aliquots, *n*-hexane analaR, BDH, Laboratory Supplies, Poole, England). Quantification of compounds in the extracts was conducted using external standard methods. Sample volumes were reduced to 10 μl at ambient temperature under a stream of argon. Samples were sealed and stored at −80°C until used.

For the collection of volatiles using the semidynamic headspace method 2, single flower heads were enclosed in polyethylene oven bags (Toppits) for 20 min, and the emitted volatiles were trapped for 10 min in an adsorbent tube by using a membrane pump (ASF Thomas, Inc., Puchheim, Germany). The flow rate was adjusted to ≈200 ml/min by using a 9-V battery. ChromatoProbe quartz microvials (15 mm in length, 2 mm i.d.; Varian, Inc., Palo Alto, CA) were used as adsorbent tubes after cutting the closed end and filling them with a mixture (1:1) of 3 mg of Tenax-GR (mesh 35–60). Adsorbents were fixed in the tubes with glass wool. Control samples were collected from the surrounding air to distinguish between floral compounds and ambient contaminants.

Gas Chromatography-Mass Spectrometry analysis (GC-MS). The concentrated extracts of headspace from flowers were analyzed using a Saturn 2200 GC-MS (Varian, Inc.). The GC-MS system was equipped with a 30 m by 0.25 mm i.d. by 0.25 μm, VF5-MS capillary column (Varian, Inc.). Helium was used as the carrier gas. The spectra were recorded at an ionization voltage of 70 eV over a mass range m/z 20–499. The transfer line and the trap were held at 250°C and 180°C, respectively. Compounds were identified by comparing their mass spectra with authentic standards and the NIST MS library, and by coincidences for Kovats retention indices published in the literature (El-Sayed 2007).

For liquid samples the oven was programmed from 40°C (held for 2 min) to 240°C at 4°C/min. Samples were injected in splitless mode and the temperature of the injector was maintained at 220°C. For MicroSPE samples the 1079 injector was fitted with the ChromatoProbe kit (Gordin and Amirav 2000). An adsorbent tube was loaded into the probe, which was then inserted into the modified GC injector. The injector

split vent was opened (1:5) and the injector heated to 40°C to flush any air from the system. The split vent was closed after 2 min and the injector was heated to 200°C/min and then held at 250°C for 4.05 min, after which the split vent was opened (1/10) and the injector was cooled down. Carrier gas flow was 1.0 ml min^{-1}. The GC oven temperature was held at 40°C for 1 min, and then it was increased 6°C/min to 250°C.

Chemicals and Formulation of Attractant Blends. Benzaldehyde (98%), benzyl alcohol (99%), methyl benzoate (≥98%), phenylacetaldehyde (90%), (±)-linalool (97%), phenyl ethyl alcohol (≥99%), methyl salicylate (99%), and dimethyl salicylate (99%), benzyl benzoate (99%), and *p*-anisaldehyde (98%) were obtained from Sigma-Aldrich (St. Louis, MO). (E,E)-α-Farnesene was 99% pure and was synthesized by Barry Bunn (HortResearch-Palmerston North) as described in Murray (1969).

Field Trapping Experiments. In the first field trapping experiment (12–25 July 2006), the relative attractiveness of various doses (i.e., 0, 10, 100, 200, and 400 mg) of the main floral volatile compound, phenylacetaldehyde, were tested near Maricopa, AZ (355 m above sea level, 33° 4′ 49.1″ N; 111° 58′ 28.6″ W). The attractant blends were formulated in a permeable polyethylene bag of 150-μm wall thickness (45 by 50 mm), with a piece of felt (15 by 45 mm) inserted as a carrier substrate.

In the second trapping experiment (5–25 September 2006) at the same location, the relative attractiveness of various floral volatile blends was tested. The loadings of five floral volatile blends were as follows: B1, 100 mg of phenylacetaldehyde; B2, 100 mg of phenylacetaldehyde, 3 mg of benzaldehyde, 1 mg of methyl benzoate, 3 mg of linalool, 5 mg of phenyl ethyl alcohol, and 25 mg of methyl salicylate; B3, 100 mg of phenylacetaldehyde, 3 mg of benzaldehyde, 1 mg of methyl benzoate, and 3 mg of linalool; B4) 100 mg of phenylacetaldehyde, 3 mg of benzyl alcohol, 3 mg of benzaldehyde, 1 mg of methyl benzoate, 3 mg of linalool, 5 mg of phenyl ethyl alcohol, 25 mg of methyl salicylate, 20 mg of dimethyl salicylate, 5 mg of benzyl benzoate, 5 mg of *p*-anisaldehyde, and 1 mg (E,E)-α-farnesene; and B5, 100 mg of phenylacetaldehyde, 20 mg of benzyl alcohol, 20 mg of benzaldehyde, 30 mg of phenyl ethyl alcohol, 30 mg of methyl salicylate, and 45 mg of dimethyl salicylate. The 15 most commonly attracted moths in field tests, although battered in the live traps, were identified by Carl Olson (Associate Curator of Insects at the University of Arizona, Tucson, AZ).

In both experiments, green plastic bucket traps were washed in a 2% Decon solution (Decon Laboratories Ltd., Sussex, England) and rinsed in clean water before use. Each trap had an insect killing strip (active ingredient 15% diazinon) at the bottom of the trap. Five replicates of each treatment were arranged in a random block design. This was achieved by establishing five trap lines at ≈20-m intervals consisting of 25 "trapping stations" in the first trapping experiment, and 30 trapping stations in the second trapping experiment. Approximately 20-m intervals were present between trapping stations in each trap line. Traps containing only a blank lure were used as the controls. The traps were checked once a week, and insects were frozen in glass tubes for later identification.

Statistical Analysis. The variance of mean captures obtained with each dose of phenylacetaldehyde or each floral blend was stabilized using the angular transformation of counts and the significance of treatment effects tested using analysis of variance (ANOVA). Significantly different treatment means were identified using Fisher protected least significant difference (LSD) test (SAS Institute 1998). The Shannon–Weiner diversity index (Magurran 1988) was calculated as an indicator of species richness for insects attracted to each dose of phenylacetaldehyde or to each floral blend.

Results

Chemical Analysis. Chemical analyses of the headspace of the Canada thistle flowers by using both the dynamic headspace collection method and the MicroSPE collection method are given in Table 1. The ratio of the compounds in headspace samples collected using both methods were similar (Table 1). Nineteen compounds were either positively or tentatively identified in the headspace volatiles of flowers of Canada thistle. Phenylacetaldehyde was the main compound in the headspace in both sample types and contributed up to 56% of total headspace volatiles. Four other compounds represented up to 31% of the total headspace volatiles. These were methyl salicylate (14%), dimethyl salicylate (8%), pyranoid linalool oxide (4.5%), and benzaldehyde (3.5%). Other minor compounds, including benzyl alcohol, methylbenzoate, linalool, and phenylethyl alcohol also were identified in the headspace volatiles.

Dose–Response Experiment for Phenylacetaldehyde. The amount of phenylacetaldehyde loaded into polyethylene bags significantly affected the number of moths captured (treatment: $F_{4, 20} = 21.93$; $P < 0.01$), with the greatest number of moths captured at the highest loading (Fig. 1A). There was no difference in the mean number of moths captured in blank traps and traps loaded with 10 mg, whereas increasing the loading from 10 to 100 and 200 mg resulted in a significant increase in the mean number of moths captured (Fig. 1A). A further increase of the dose from 200 to 400 mg did not result in a significant increase in the number of moths captured (Fig. 1A). Similarly, the amount of phenylacetaldehyde loaded into polyethylene bags significantly affected the number of bees and wasps captured (treatment: $F_{4, 20} = 11.94$; $P < 0.01$), with the greatest number of bees and wasps captured at 200- and 400-mg loading (Fig. 1B). There was no difference in the mean numbers of bees and wasps captured using blank trap and 10-mg loaded traps, whereas increasing the loading from 10 to 100, 200, and 400 mg resulted in a significant increase in the mean number of bees and wasps captured (Fig. 1B).

Table 1. Average relative amounts (percentages) of compounds identified in the headspace of the flowers of Canada thistles

Compound	Kovats[a]	Floral odor			
		Concentrated headspace extracts		Thermodesorption, MicroSPE	
		Mean (n = 3)	SD	Mean (n = 3)	SD
Benzaldehyde[b]	963	3.05	1.32	4.36	0.71
Benzyl alcohol[b]	1,035	1.48	0.46	2.95	1.53
Phenylacetaldehyde[b]	1,045	54.77	9.42	55.56	3.67
Furanoid linalool oxide	1,089	0.94	0.93	3.64	1.05
Methyl benzoate[b]	1,093	0.47	0.79		
Linalool[b]	1,098	1.01	0.86	2.55	0.59
Phenylethyl alcohol[b]	1,110	2.03	0.40	2.96	1.41
2,6-Dimethyl-1,3,5,7-octatetraene	1,134			0.08	0.07
Benzylacetate[b]	1,163	0.16	0.27		
Pyranoid linalool oxide[b]	1,179	3.65	2.49	6.13	1.51
Methyl salicylate[b]	1,187	15.55	5.88	12.97	2.78
p-Anisaldehyde[b]	1,252	3.66	2.59	0.96	0.65
Dimethyl salicylate[b]	1,322	9.15	3.12	7.05	1.46
Benzyl tiglate	1,497	0.45	0.38		
Unknown sesquiterpene	1,499	0.01	0.02		
(E,E)-α-Farnesene[b]	1,503	0.56	0.32	0.32	0.28
Benzyl benzoate[b]	1,762	2.49	1.98	0.29	0.25
Isopropyl myristate[b]	1,824	0.13	0.08	0.12	0.07
2-Phenylethyl ester benzoic acid	1,858	0.44	0.36	0.07	0.08

[a] Kovats index on a DB-5 column.
[b] Compound identity was confirmed by comparison of MS and retention time of authenticated standard, the rest of compounds were tentatively identified by comparison with published Kovats and mass spectral data.

Blend Composition. The composition of the blends loaded into polyethylene bags significantly affected the number of moths captured (treatment: $F_{5,\ 23} = 7.66$; $P < 0.01$), with the greatest number of moths captured in traps baited with the 11-component blend formulated at a ratio similar to the ratio found in the volatiles of Canada thistle flowers (Fig. 2A), whereas traps baited with phenylacetaldehyde alone captured the lowest number of moths (Fig. 2A). The addition of benzaldehyde, methyl benzoate, linalool, benzyl benzoate, or benzaldehyde, methyl benzoate, linalool, phenyl ethyl alcohol, and methyl salicylate to phenylacetaldehyde in five- or six-component blends, respectively, did not enhance trap catch (Fig. 2A). Significantly more moths were captured in traps baited with the 11-component blend containing [compound (ratio)]: benzaldehyde (3), benzyl alcohol (3), phenylacetaldehyde (100), methyl benzoate (1), linalool (3), phenyl ethyl alcohol (5), methyl salicylate (25), *p*-anisaldehyde (5), dimethyl salicylate (20), (E,E)-α-farnesene (1), benzyl benzoate (5), and the 6-component blend containing benzaldehyde (20), benzyl alcohol (20), phenylacetaldehyde (100), phenyl ethyl alcohol (30), methyl salicylate (30), and dimethyl salicylate (45) than any other blends tested in this experiment (Fig. 2A). In contrast to moths, the composition of the attractant blend did not affect the number of bees and wasps captured in traps (Fig. 2B).

Biodiversity. Increasing the release rate of phenylacetaldehyde resulted in an increase in the number of moth species captured and an increase in the Shannon–Weiner index (Table 2). Similarly, increasing the release rate of phenylacetaldehyde resulted in increases in the number of wasp species captured and this was also corroborated by an increase in the Shannon–Weiner index. Surprisingly, the biodiversity of species showed lesser dependence on the composition of the attractant blend, because phenylacetaldehyde alone captured 32 different species, whereas the best attractant blend (11-component blend) captured 29 different species (Table 2). Similarly, changing blend composition had little impact on the biodiversity of wasp species captured (Table 2). In the first experiment, the diversity index for 100 mg of phenylacetaldehyde alone was 2.46, whereas the diversity index for the same treatment in the second experiment was 3.16 (Table 2). This variation might reflect changes in habitat structure or indicate that insect populations were different at the two testing periods. The most common moth species caught in the experiments were in the following order: 136 *Forsebia perlaeta* (Noctuidae), 102 *Euchromius ocelleus* (Pyralidae), 101 Noctuidae (unknown genus), 60 microlepidopteran (unknown genus), 50 *Trichoplusia ni* (Noctuidae), 32 Noctuidae (unknown genus), 27 *Helicoverpa zea* (Noctuidae), 25 microlepidopteran (unknown genus), 21 Noctuidae (unknown genus), 20 microlepidoptera (unknown genus), 19 *Melipotis jucunda* (Noctuidae), 18 Pyralidae (unknown genus), and 15 Pyralidae (unknown genus). The most common hymenopteran species was the honey bee, *Apis mellifera* L. (Apidae) at 133, or 39% of all hymenopteran specimens.

Discussion

Chemical analysis of the headspace of the Canada thistle flowers reveals the presence of at least 19 floral compounds. Phenylacetaldehyde was the main compound in the headspace sample with other compounds

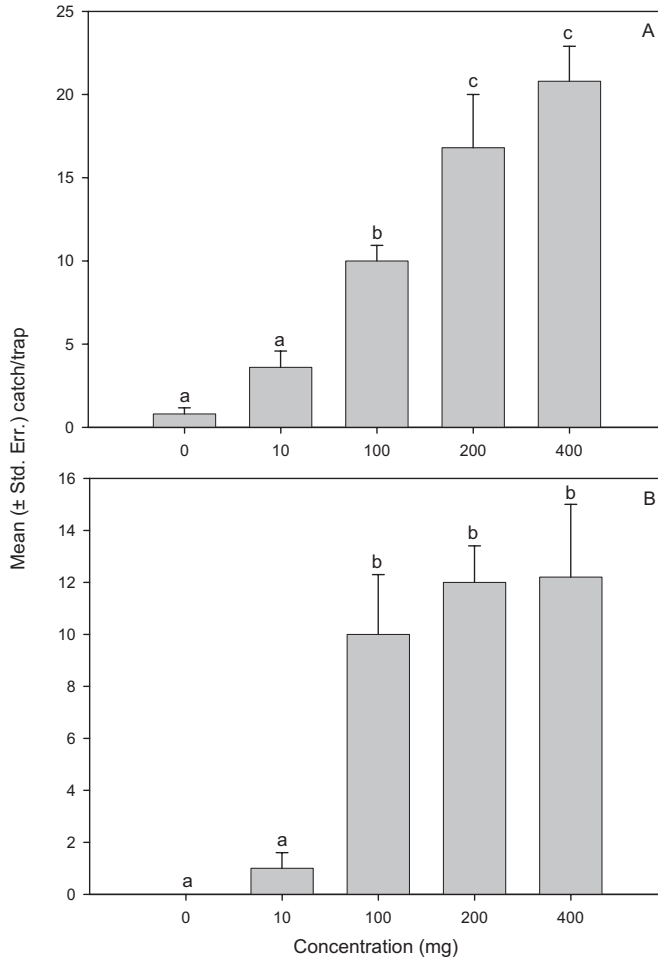

Fig. 1. Mean ± SE numbers of insects captured in green bucket traps baited with different doses of phenylacetaldehyde (0, 10, 100, 200, and 400 mg. (A) Moths. (B) Bees and wasps.

being mainly benzenoids, monoterpenes, sesquiterpenes, and furanoids (Table 1). Other major compounds identified in the headspace were methyl salicylate, dimethyl salicylate, and benzaldehyde (≈28% of the total scent production by flowers). Several compounds not previously reported were identified in the volatiles of the Canada thistle flowers: methyl benzoate, benzylacetate, benzyl tiglate, (E,E)-α-farnesene, isopropyl myristate, and 2-phenylethyl ester benzoic acid. 2,6-Dimethyl-1,3,5,7-octatetraene was only detected with the MicroSPE device. Most of the compounds identified have been shown to have a behavioral function as insect attractants (El-Sayed 2007).

Phenylacetaldehyde has been reported to attract a wide range of insects, mainly noctuid moths (Smith et al. 1943; Creighton et al. 1973; Cantelo and Jacobson 1979; Landolt et al. 2001; Meagher 2001a, 2001b). Similarly, phenylacetaldehyde attracted a large number of insects including moths, bees, and wasps in our study. However, the addition of other compounds identified in the headspace of Canada thistle flowers significantly increased the number of insects caught. The floral blend formulated to mimic the volatiles produced by flowers attracted a significantly larger number of insects compared with any other partial floral blend tested in this study. This phenomenon is common in the attraction of male moths to sex pheromones, where a complete blend formulated to mimic the pheromone blend produced by female moths attracts more males than partial blends (El-Sayed et al. 1999). This is mainly because a complete pheromone blend stimulates the maximum number of pheromone component receptor cells on male antennae, creating a very specific communication channel attracting only conspecific males while preventing the attraction of males of sympatric species (Byers 2005). It is likely that the complete floral odor blend formulated to mimic the flower also would stimulate the maximum number of receptor cells for flower volatiles on male and female antennae thus causing significant stimulation in the insect olfactory system, resulting in significant attraction to the odor source in comparison to single compounds or partial blends. A refined and optimized pheromone blend would make the chem-

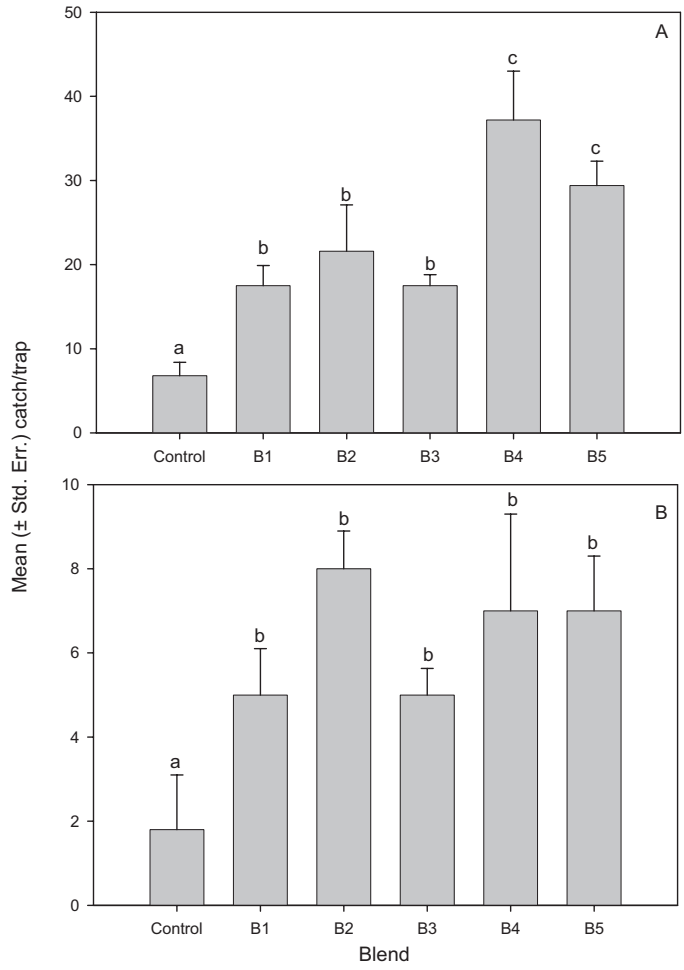

Fig. 2. Mean ± SE numbers of insects captured in green bucket traps baited with different blends formulated using floral volatiles compounds identified in Canada thistle flowers. (A) Moths. (B) Bees and wasps. For details of blend composition, see Materials and Methods.

ical communication channel very specific compared with using a single compound (e.g., Z11–14Ac, which is the main pheromone compound for many moth species; El-Sayed 2007). However, in this study the diversity index obtained with a single compound was similar to the diversity index for the complete blend, indicating that the addition of other compounds did not result in tuning the odor blend toward a specific insect group. This might be because of the presence of receptors tuned to phenylacetaldehyde in all species caught, which account for the diversity of species. Many of the other volatile compounds produced by

Table 2. Number of species, individuals, and the Shannon–Weiner diversity index of moths, bees, and wasps caught in field-trapping experiments with different concentrations of phenylacetaldehyde and different odor blends

	Phenylacetaldehyde (mg)					Floral blend[a]					
	10	100	200	400	Control	B1	B2	B3	B4	B5	Control
	Moths										
No. of species caught	9	20	19	27	5	32	30	15	29	29	12
Shannon–Weiner index of diversity	1.51	2.46	2.31	2.76	1.61	3.16	2.99	2.26	2.65	2.85	1.8
	Bees and wasps										
No. of species caught	3	10	13	13	2	6	5	8	8	9	1
Shannon–Weiner index of diversity	0.95	1.89	1.99	1.96	0.64	1.27	1.09	1.64	1.46	2.06	0

[a] See Materials and Methods for blend composition.

Canada thistle flowers are commonly found in other plants, so it is likely that many insects would have olfactory receptors for these compounds as well. It is possible that the addition of these floral volatile compounds results in an increase of catch of the same species. In contrast, increasing the loading of phenylacetaldehyde in the bag resulted in an increase in the diversity index of species caught. This could be due to an increase in the release rate that would increase the effective attraction radius of the trap, which results in increasing the probability of attracting more rare species because they would more often encounter the volatiles farther from the trapping station (Byers et al. 1989; Byers 1999). An alternative possibility is that the polyethylene bags with low loading of compounds became prematurely exhausted in the high Arizona temperatures (>40°C midday) compared with the higher loadings that lasted throughout the test and thus would likely catch more species.

The behavioral activity of some of the compounds produced by Canada thistle flowers have been previously tested for insect attraction (Theis 2006). Theis (2006) tested 10 compounds identified from the flowers of Canada thistles individually and caught a wide range of insects, although the catch was generally low and lepidopteran species were excluded from the analysis. Our work is the first to provide insight into the attraction of insects to various floral blends based on Canada thistle volatiles. However, we stress that the complete picture of the potential of this blend for attraction of various insect species cannot be fully realized from our limited field trials in one location. Work is underway to test the blend in different geographical locations around the world, and preliminary results indicate that different insect groups can be caught in traps in significant numbers (A.M.E.-S., et al. unpublished data).

We have identified a floral blend that is attractive to a wide range of insect species. This floral blend consists of commercially available low-cost chemicals that can be formulated in a convenient releasing device for field application. The floral blend developed in this study can be used as a tool for the monitoring of invasive species, and economically important insect species. Traps baited with this blend can be deployed around ports and cargo facilities for detection of unwanted insect species. It is likely that many invasive species will be marginally or not attracted to this floral volatile blend, although the range of species potentially not attracted remains to be established. In the second field trapping experiment, 56 species in total were caught, whereas 15–32 species were caught per blend; therefore, floral blends can be useful tool for monitoring invasive species or used in long-term pest management.

Acknowledgments

Technical assistance was provided by LeAnne Elhoff (USDA–ARS, Maricopa, AZ). This work was supported by the Foundation for Research Science and Technology (FRST) COX0301 (Insecticide Risk Reduction) and Better Border Biosecurity (http://www.b3nz.org/public/index.php).

References Cited

Andersson, S., L. A. Nilsson, I. Groth, and G. Bergstrom. 2002. Floral scents in butterfly pollinated plants: possible convergence in chemical compositions. Bot. J. Linn. Soc. 140: 129–153.

Balkenius, A., W. Rosén, and A. Kelber. 2006. The relative importance of olfaction and vision in a diurnal and a nocturnal hawkmoth. J. Comp. Physiol. A 192: 431–437.

Brockerhoff, E. G., D. C. Jones, M. O. Kimberley, D. M. Suckling, and T. Donaldson. 2006. Nationwide survey for invasive wood-boring and bark beetles (Coleoptera) using traps baited with pheromones and kairomones. For. Ecol. Manage. 288: 234–240.

Byers, J. A. 1999. Effects of attraction radius and flight paths on catch of scolytid beetles dispersing outward through rings of pheromone traps. J. Chem. Ecol. 25: 985–1005.

Byers, J. A. 2005. Chemical constraints on the evolution of olfactory communication channels of moths. J. Theor. Biol. 235: 199–206.

Byers, J. A., O. Anderbrant, and J. Löfqvist. 1989. Effective attraction radius: a method for comparing species attractants and determining densities of flying insects. J. Chem. Ecol. 15: 749–765.

Cantelo, W. W., and M. Jacobson. 1979. Phenylacetaldehyde attracts moths to bladder flower and to blacklight traps. Environ. Entomol. 8: 444–447.

Connick, W. J., and R. C. French. 1991. Volatiles emitted during the sexual stage of the Canada thistle rust fungus and by thistles flowers. J. Agric. Food Chem. 39: 185–188.

Creighton, C. S., T. L. McFadden, and E. R. Cuthbert. 1973. Supplementary data on phenylacetaldehyde: an attractant for Lepidoptera. J. Econ. Entomol. 66: 114–115.

El-Sayed, A., J. Gödde, P. Witzgall, and H. Arn. 1999. Characterization of pheromone blend for grapevine moth, *Lobesia botrana* by using flight track recording. J. Chem. Ecol. 25: 389–400.

El-Sayed, A. M., V. J. Heppelthwaite, L. M. Manning, A. R. Gibb, and D. M. Suckling. 2005. Volatile constituents of fermented sugar baits and their attraction to lepidopteran species. J. Agric. Food Chem. 53: 953–958.

El-Sayed, A. M. 2007. The Pherobase: database of insect pheromones and semiochemicals. (http://www.pherobase.com).

Murray, K. E. 1969. Farnesene: isolation from the natural coating of apples. Aust. J. Chem. 22: 197–204.

Gordin, A., and A. Amirav. 2000. SnifProbe: new method and device for vapour and gas sampling. J. Chromatogr. A 903: 155–172.

Landolt, P. J., and P. C. Hammond. 2001. Species composition of moths captured in traps baited with acetic acid and 3-methyl-1-butanol, in Yakima County, Washington. J. Lepid. Soc. 55: 53–58.

Landolt, P. J., T. Adams, H. C. Reed, and R. S. Zack. 2001. Trapping alfalfa looper moths (Lepidoptera: Noctuidae) with single and double component floral chemical lures. Environ. Entomol. 30: 667–672.

Magurran, A. E. 1988. Ecological diversity and its measurement. Princeton University Press, Princeton, NJ.

Maini, S., and G. Burgio. 1990. Influence of trap design and phenylacetaldehyde upon field capture of male and female *Ostrinia nubilalis* (Hb.) (Lepidoptera, Pyralidae) and other moths. Boll. Inst. Entomol. "G Grandi" Univ. Bologna 45: 157–165.

Meagher, R. L. 2001a. Collection of soybean looper and other noctuids in phenylacetaldehyde-baited field traps. Fla. Entomol. 84: 154–155.

Meagher, R. L. 2001b. Trapping fall armyworm (Lepidoptera: Noctuidae) adults in traps baited with pheromone and a synthetic floral volatile compound. Fla. Entomol. 84: 288–292.

Meagher, R. L. 2002. Trapping noctuid moths with synthetic floral volatile lures. Entomol. Exp. Appl. 103: 219–226.

Meagher, R. L., and P. Mislevy. 2005. Trapping *Mocis* spp. (Lepidoptera: Noctuidae) adults using different attractants. Fla. Entomol. 88: 414–430.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. Bioscience 50: 53–65.

Plepys, D., F. Ibarra, W. Francke, and C. Löfstedt. 2002. Odour-mediated nectar foraging in the silver Y moth, *Autographa gamma* (Lepidoptera: Noctuidae): behavioural and electrophysiological responses to floral volatiles. Oikos 99: 75–82.

Pombal, E.C.P., and L.P.C. Morellato. 2000. Differentiation of floral color and odor in two fly pollinated species of Metrodorea (Rutaceae) from Brazil. Plant Syst. Evol. 221: 141–156.

Proctor, M., P. Yeo, and A. Lack. 1996. The natural history of pollination. HarperCollins, London, United Kingdom.

SAS Institute 1998. Statview. SAS Institute, Cary, NC.

Smith, C. E., N. Allen, and O. A. Nelson. 1943. Some chemotropic studies with *Autographa* spp. J. Econ. Entomol. 36: 619–621.

Suckling, D. M., A. R. Gibb, P. R. Dentener, D. S. Seldon, G. K. Clare, L. Jamieson, A. M. El-Sayed, D. Baird, and D. Kriticos. 2005. Gum leaf skeletoniser *Uraba lugens* in New Zealand: pheromone trapping for delimitation and phenology. J. Econ. Entomol. 98: 1187–1192.

Suckling, D. M., and A. R. Gibb. 2003. Use of pheromones and other attractants to combat insect incursions, p. 153. *In* S. L. Goldson and D. M. Suckling [eds.], Defending New Zealand's green oasis: the role of science in biosecurity. New Zealand Plant Protection Society, Hastings, New Zealand.

Theis, N. 2006. Fragrance of Canada thistle (*Cirsium arvense*) attracts both floral herbivores and pollinators. J. Chem. Ecol. 32: 917–927.

Received 29 July 2007; accepted 1 November 2007.