# Field Evaluation of Essential Oils for Reducing Attraction by the Japanese Beetle (Coleoptera: Scarabaeidae)

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**ABSTRACT** Forty-one plant essential oils were tested under field conditions for the ability to reduce the attraction of adult Japanese beetles, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), to attractant-baited or nonbaited traps. Treatments applied to a yellow and green Japanese beetle trap included a nonbaited trap, essential oil alone, a Japanese beetle commercial attractant (phenethyl proprionate:eugenol:geraniol, 3:7:3 by volume) (PEG), and an essential oil plus PEG attractant. Eight of the 41 oils reduced attractiveness of the PEG attractant to the Japanese beetle. When tested singly, wintergreen and peppermint oils were the two most effective essential oils at reducing attractiveness of the PEG attractant by 4.2× and 3.5×, respectively. Anise, bergamont mint, cedarleaf, dalmation sage, tarragon, and wormwood oils also reduced attraction of the Japanese beetle to the PEG attractant. The combination of wintergreen oil with ginger, peppermint, or ginger and citronella oils reduced attractiveness of the PEG attractant by 4.7× to 3.1×. Seventeen of the 41essential oils also reduced attraction to the nonbaited yellow and green traps, resulting in 2.0× to 11.0× reductions in trap counts relative to nonbaited traps. Camphor, coffee, geranium, grapefruit, elemi, and citronella oils increased attractiveness of nonbaited traps by 2.1× to 7.9× when tested singly, but none were more attractive than the PEG attractant. Results from this study identified several plant essential oils that act as semiochemical disruptants against the Japanese beetle.

**KEY WORDS** *Popillia japonica*, semiochemicals, essential oil, trap

The Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), was introduced into the United States before 1916 and has since become an important pest of a large number of horticultural crops (Fleming 1972). The polyphagous adult can feed on >430 host plants (Fleming 1972). The control costs for Japanese beetle adults and larvae are estimated at >$460 million/yr (USDA–APHIS 2004). Management of adult Japanese beetles mainly involves treating foliage and flowers with conventional insecticides, particularly carbaryl (Potter and Held 2002). The effectiveness of conventional insecticides for controlling adult Japanese beetles has slowed the pursuit of alternative controls, but consistent insecticide deregistration has increased the demand for environmentally friendly and sustainable products.

Biopesticides derived from botanical sources represent an alternative to conventional insecticides. Plant essential oils are one of the major types of botanical products used for insect control (Isman 2006). The oils are a major source of highly active and potent metabolites, with impacts on insect biology, behavior, and physiology (Singh and Upadhyay 1993, Isman 2006). In addition, essential oils exhibit low environmental persistence and mammalian toxicity. Essential oils are also typically available in large quantities at reasonable prices owing to their widespread use as fragrances and food flavors (Isman 2000, 2006).

Plant essential oils are most commonly collected by steam distillation and mainly consist of complex blends of monoterpenes, sesquiterpenes, and phenols that often readily volatilize (Reverchon 1997). Approximately 1,200 compounds have been identified in essential oils, including terpenes and their corresponding aldehydes, ketones, and alcohols; phenylpropanoids; hydrocarbons; esters; oxides; and sulfur compounds (Yeung 1980, Dimandja et al. 2000). Owing to their aromatic properties, several studies have documented the ability of essential oils to repel agriculturally related pests, namely, green peach aphid, *Myzus persicae* (Sulzer) (Hori 1998, Masatoshi 1998);

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onion aphid, *Neotoxoptera formosana* (Takahasi) (Masatoshi and Hiroaki 1997); maize weevil, *Sitophilus zeamais* (Motschulsky) (Ndungu et al. 1995); red flour beetle, *Tribolium castaneum* (Herbst) (Saim and Meloan 1986); and twospotted spider mite, *Tetranychus urticae* Koch (El-Gengaihi et al. 1996). In particular, van Tol et al. (2007) found rubber budding strips impregnated with lavender oil and $\alpha$-terpineol repelled *Resseliella oculiperda* (Rübsaamen) (Diptera: Cecidomyiidae), which decreased infestations of apple tree buds by 95 and 80%, respectively.

Volatile compounds and olfaction play a major role in long-range orientation by the Japanese beetle (Ahmad 1982; Loughrin et al. 1997, 1998), but only a few studies have screened for potential repellents. Early studies (Metzger 1930, Metzger and Grant 1932) identified several essential oils that repelled Japanese beetles from attractant-baited traps and host trees, which were derived from pine (*Pinus* spp.), cade (*Juniperus* spp.), hyssop (*Hyssop* spp.), cajuput (*Melaleuca* spp.), and cascarilla (*Croton* spp.). Similarly, Youssef et al. (2004) found wintergreen and peppermint oils reduced Japanese beetle response to traps baited with an attractant. However, Held et al. (2003) were unable to reduce Japanese beetle populations by hanging mesh bags of aromatic herbs and other purportedly repellent volatiles around potted roses. Methyl salicylate dispensers hung from rose bushes were also unsuccessful at repelling adult Japanese beetles (M.E.R., unpublished data). Repellent mulches may be a more viable approach than repellent-dispensers for managing Japanese beetle populations. For example, when positioned around the base of ornamental nursery stock, mulches soaked with repellent essential oils might reduce long-range orientation by adult Japanese beetles. Thus, the overall objective of this study was to assess the ability of a diverse array of plant essential oils to reduce the attraction of Japanese beetles to attractant-baited traps.

## Materials and Methods

**Trapping Protocol.** Forty-one plant essential oils were obtained from Essential Oil University, Inc. (New Albany, IN) (Table 1). Plant species names are cited as referenced by USDA–NGRP (2008) (Table 1). Mineral oil (Cumberland Swan, Smyrna, TN) also was tested. To reduce the large number of commercially available products to a number reasonable for testing, essential oils with the lowest cost were selected ($0.03–$0.73/ml). For testing purposes, individual essential oil products were pipetted onto GP202 mini-con high void polyethylene foam wafers (Gen-Pore, Reading, PA). When tested singly, 1 ml of undiluted essential oil product was applied to an individual wafer. Tests of two essential oils involved 0.5 ml of each oil being applied to the same wafer, whereas blends of three essential oils consisted of 0.3 ml per oil being applied. A Japanese beetle attractant also was formulated by combining phenethyl propionate, eugenol, and geraniol (Sigma-Aldrich, St. Louis, MO) at a ratio of 3:7:3 (PEG) (Ladd et al. 1981). The PEG attractant or mineral oil treatments were also applied at 1-ml volumes to the polyethylene wafers. When tested on the same trap, the essential oil product and PEG attractant were applied to separate dispensing wafers each held in separate 10-ml Poly-Con plastic containers (Madan Plastics, Cranford, NJ).

On the day of testing, wafers containing PEG or essential oil product(s) were positioned near the funnel entrance of a yellow top and green bottom Japanese beetle trap (Trécé, Adair, OK) (Klein and Edwards 1989). Four trap treatments were used to compare essential oil effect on Japanese beetle response, namely, 1) essential oil (O), 2) PEG attractant (P), 3) PEG attractant and essential oil (P + O), and 4) nonbaited trap (NB) (Table 2). Trap treatments were replicated four times on each test date and arranged in a randomized complete block design at the Tennessee State University Otis L. Floyd Nursery Research Center in McMinnville, TN. Traps within each block were 5 m apart and blocks were separated by 8 m.

Essential oil products were evaluated over a 4.5-h period from ≈1030 to 1500 hours. All trapping experiments were conducted between mid-July to early August 2003–2007. Wintergreen, peppermint, and wormwood oils were tested on multiple dates, but the remaining oils were only tested once (Table 2). Essential oils were only tested on dates with minimal cloud cover because of adult Japanese beetle preference to fly during sunny conditions. After 4.5 h of trapping, beetles were collected and stored at −8°C. For quantification purposes, the approximate number of beetles per trap was estimated volumetrically by calibrating a graduated cylinder with a known quantity of beetles. However, individual specimens were counted if the trap contained ≈100 beetles or less.

**Statistics.** Due to the large number of essential oils in the study, individual products were tested on different dates. Therefore, statistical comparisons were not made between essential oil products. However, for each essential oil, beetle counts associated with the four trap treatments were compared using one-way analysis of variance (ANOVA) (PROC GLM, SAS Institute 2003). Means were separated using least significant difference (LSD) test at $\alpha = 0.05$ (SAS Institute 2003). Data were $\log_{10}(x + 1)$ transformed to correct for non-normality and heteroscedasticity, but untransformed data are presented.

## Results

Japanese beetle adults were collected on every test date and in all trap treatments during the study (Table 2). For most comparisons, beetle trap counts were lowest in the essential oil alone, followed by the nonbaited, essential oil + PEG, and PEG alone traps. When tested singly or in combination with the PEG attractant, no essential oil product eliminated all Japanese beetle trap counts. However, eight of the 41 oils significantly ($P < 0.05$) reduced the number of adult beetles trapped relative to the PEG attractant. In particular, anise, bergamont mint, cedarleaf, dalmation

**Table 1. Essential oils tested for ability to reduce the attraction of Japanese beetles to attractant-baited traps**

| Essential oil product name | Botanical name | Family | Plant part[a] | Extract[b] |
|---|---|---|---|---|
| Anise seed oil | *Pimpinella anisum* L. | Apiaceae | Seed | SD |
| Benzoin liquid resin | *Styrax benzoin* Dryander | Styracaceae | Bark | SE |
| Bergamot mint oil | *Mentha citrata* Ehrh. | Lamiaceae | LS | SD |
| Black pepper oil | *Piper nigrum* L. | Piperaceae | Fruit | SD |
| Cajeput oil | *Melaleuca cajuputi* Powell | Myrtaceae | Leaf | SD |
| Camphor oil | *Cinnamomum camphora* (L.) J. Presl | Lauraceae | Leaf | SD |
| Cardamon oil | *Elettaria cardamomum* (L.) Maton. | Zingiberaceae | Seed | SD |
| Catnip oil | *Nepeta cataria* L. var. 'Citriodora' | Lamiaceae | LS | SD |
| Cedarleaf oil | *Thuja occidentalis* L. | Cupressaceae | Leaf | SD |
| Cedar wood oil | *Juniperus virginiana* L. | Cupressaceae | Wood | SD |
| Citronella oil | *Cymbopogon nardus* (L.) Rendle | Poaceae | Leaf | SD |
| Clove bud oil | *Eugenia caryophyllata* Thunb. | Myrtaceae | Bud | SD |
| Coffee oil | *Coffea arabica* L. | Rubiaceae | Bean | EXP |
| Cumin oil | *Cuminum cyminum* L. | Apiaceae | Seed | SD |
| Dalmation sage oil | *Salvia officinalis* L. | Lamiaceae | Leaf | SD |
| Davana oil | *Artemisia pallens* Wall. ex DC. | Asteraceae | WP | SD |
| Dill oil | *Anethum graveolens* L. | Apiaceae | LS | SD |
| Elemi oil | *Canarium luzonicum* (Blume) A. Gory | Burseraceae | Resin | SD |
| Eucalyptus oil | *Eucalyptus globulus* Labill. | Myrtaceae | Leaf | SD |
| Eucalyptus oil | *Eucalyptus radiata* Sieber ex DC. | Myrtaceae | Leaf | SD |
| Fir needle oil | *Abies alba* Mill. | Pinaceae | Needle | SD |
| Geranium oil | *Pelargonium roseum* (Andrews) W. T. Aiton | Geraniaceae | Leaf | SD |
| Ginger oil | *Zingiber officinale* Roscoe | Zingiberaceae | Root | SD |
| Grapefruit oil (pink) | *Citrus paradisi* Macfad. | Rutaceae | Peel | EXP |
| Hyssop oil | *Hyssopus officinalis* L. | Lamiaceae | WP | SD |
| Juniperberry oil | *Juniperus communis* L. | Cupressaceae | BS | SD |
| Lavender oil | *Lavandula angustifolia* Mill. | Lamiaceae | Flower | SD |
| Lemongrass oil | *Cymbopogon flexousus* (Nees ex Steud) Will Watson | Poaceae | Leaf | SD |
| Oregano oil | *Origanum vulgare* L. ssp. *hirtum* (Link) Ietsw. | Lamiaceae | LS | SD |
| Peppermint oil | *Mentha × piperita* L. | Lamiaceae | LS | SD |
| Pine needle oil | *Pinus sylvestris* L. | Pinaceae | Needle | SD |
| Rosemary oil | *Rosmarinus officinalis* L. | Lamiaceae | LS | SD |
| Tarragon oil | *Artemisia dracunculus* L. | Asteraceae | LS | SD |
| Tea tree oil | *Melaleuca alternifolia* (Maiden & Betche) Cheel | Myrtaceae | Leaf | SD |
| Thyme oil | *Thymus vulgaris* L. | Lamiaceae | LS | SD |
| Tumeric oil | *Curcuma longa* L. | Zingiberaceae | LS | SD |
| Vetiver oil | *Vetiveria zizanioides* (L.) Nash | Poaceae | Root | SD |
| Wintergreen oil | *Gaultheria procumbens* L. | Ericaceae | Leaf | SD |
| Wormwood oil | *Artemisia absinthium* L. | Asteraceae | LS | SD |
| Yarrow oil (yellow) | *Achillea millefolium* L. | Asteraceae | Fruit | SD |
| Ylang ylang III oil | *Cananga odorata* (Lam.) Hook. f. & Thomson | Annonaceae | Flower | SD |

Essential oil product name, plant part, and extraction method are from the product label as received from Essential Oil University, Inc. Botanical names are cited as referenced by USDA–NGRP (2008).
[a] BS, berry and stem; LS, leaf and stem; WP, whole plant.
[b] EXP, expressed; SE, solvent extraction; SD, steam distillation.

sage, peppermint, tarragon, wintergreen, and wormwood oil significantly reduced Japanese beetle attraction to PEG-baited traps (Table 2). Wintergreen oil in combination with ginger, peppermint, or ginger + citronella oil also significantly ($P < 0.05$) reduced beetle trap counts relative to the PEG-baited trap by 4.7×, 3.4×, and 3.1×, respectively.

Seventeen essential oil products significantly ($P < 0.05$) reduced Japanese beetle visual attraction to nonbaited traps (Table 2). When tested singly, juniperberry, pine needle, and ginger oils reduced Japanese beetle trap counts relative to nonbaited traps by 7.1×, 7.0×, and 6.1×, respectively. Combinations of wintergreen oil with ginger, peppermint, or ginger + citronella also significantly reduced trap counts relative to nonbaited traps. The greatest reduction in beetle counts compared with the nonbaited trap was associated with the wintergreen + peppermint oil treatment (11×). Anise oil, cedarleaf, dalmation sage, peppermint, wintergreen and the combinations of wintegreen + peppermint, wintergreen + ginger, and wintergreen + ginger + citronella were the only essential oil treatments that reduced Japanese beetle trap counts in comparison with both nonbaited and PEG-baited treatments.

Six essential oils significantly ($P < 0.05$) increased trap counts of Japanese beetles up to 7.9× compared with a nonbaited trap, namely, camphor, coffee, geranium, grapefruit, elemi, and citronella (Table 2). However, when tested in combination with the PEG attractant, none of the 41 essential oils were significantly more attractive than the PEG attractant alone. For each test date, traps containing PEG with or without essential oils always collected significantly more beetles than nonbaited or essential oil alone traps (Table 2).

Some variation occurred between test years for oils that were evaluated more than one time. For example,

**Table 2. Mean ± SE adult Japanese beetle collected in nonbaited or attractant-baited traps with or without a test essential oil during 2003–2007**

| Essential oil evaluated on test date[a] | Test date[b] | Adult Japanese beetles collected by trap treatment[c] | | | | Comparisons of interest | | F; P[f] |
|---|---|---|---|---|---|---|---|---|
| | | NB | O | P | P + O | NB vs O (−/+)[d] | P vs P + O (−/+)[e] | |
| Wintergreen | 05AG03 | 3.8 ± 1.9a | 0.5 ± 0.5a | 106.0 ± 40.5b | 25.5 ± 5.7c | | −4.2× | 27.9; <0.0001 |
| Wintergreen | 23JL04 | 8.0 ± 3.1a | 7.5 ± 1.0a | 461.0 ± 52.2b | 211.3 ± 6.2b | | | 44.1; <0.0001 |
| Wintergreen | 18JL05 | 6.8 ± 2.9a | 3.5 ± 1.9a | 366.5 ± 32.0b | 138.0 ± 23.2b | | | 50.0; <0.0001 |
| Wintergreen | 20JL06 | 2.0 ± 1.1a | 0.3 ± 0.3b | 126.0 ± 8.2c | 29.8 ± 2.9d | −6.7× | −4.2× | 96.1; <0.0001 |
| W + G | 19JL06 | 4.5 ± 1.7a | 0.8 ± 0.5b | 283.0 ± 20.7c | 60.3 ± 5.9d | −5.6× | −4.7× | 102.5; <0.0001 |
| W + P | 19JL05 | 19.8 ± 5.9a | 1.8 ± 0.6b | 913.8 ± 63.0c | 272.3 ± 26.9d | −11.0× | −3.4× | 199.8; <0.0001 |
| W + G + C | 20JL06 | 8.8 ± 2.3a | 1.3 ± 0.8b | 250.3 ± 17.3c | 81.5 ± 17.5d | −6.7× | −3.1× | 52.3; <0.0001 |
| Peppermint | 10JL03 | 6.8 ± 3.3a | 1.3 ± 0.5b | 279.0 ± 37.6c | 80.8 ± 8.7d | −5.2× | −3.5× | 88.1; <0.0001 |
| Peppermint | 26JL04 | 7.5 ± 2.7a | 2.3 ± 0.8a | 433.5 ± 99.2b | 191.5 ± 18.7b | | | 76.2; <0.0001 |
| Wormwood | 17JL03 | 29.8 ± 9.2a | 14.3 ± 2.5a | 652.5 ± 237.9b | 921.3 ± 90.2b | | | 65.0; <0.0001 |
| Wormwood | 03AG04 | 2.0 ± 1.1a | 0.5 ± 0.3a | 106.8 ± 8.3b | 66.3 ± 25.9c | | −1.6× | 136.1; <0.0001 |
| Dalmatian sage | 18JL03 | 35.3 ± 5.6a | 7.3 ± 3.6b | 499.8 ± 31.8c | 212.0 ± 28.1d | −4.8× | −2.4× | 67.8; <0.0001 |
| Cedarleaf | 18JL03 | 39.3 ± 9.9a | 10.0 ± 2.5b | 814.3 ± 70.4c | 374.8 ± 45.6d | −3.9× | −2.2× | 147.3; <0.0001 |
| Anise | 25JL05 | 35.8 ± 7.1a | 17.3 ± 8.7b | 1,830.3 ± 179.8c | 832.0 ± 82.2d | −2.1× | −2.2× | 156.7; <0.0001 |
| Juniperberry | 15JL03 | 27.0 ± 6.8a | 3.8 ± 1.3b | 883.3 ± 23.1c | 519.0 ± 42.6c | −7.1× | | 84.8; <0.0001 |
| Pine needle | 09JL03 | 84.5 ± 28.2a | 12.0 ± 4.7b | 800.5 ± 28.3c | 724.8 ± 17.2c | −7.0× | | 34.5; <0.0001 |
| Ginger | 18JL06 | 11.0 ± 5.4a | 1.8 ± 0.8b | 448.8 ± 24.1c | 342.0 ± 36.9c | −6.1× | | 159.7; <0.0001 |
| Thyme | 17JL06 | 13.8 ± 7.0a | 2.5 ± 1.3b | 1,143.5 ± 91.8c | 436.3 ± 60.2c | −5.5× | | 60.9; <0.0001 |
| Oregano | 30JL03 | 38.5 ± 8.8a | 8.5 ± 4.6b | 673.3 ± 139.3c | 413.5 ± 60.2c | −4.5× | | 43.1; <0.0001 |
| Black pepper | 15JL03 | 34.5 ± 11.9a | 9.3 ± 3.1b | 1,429.5 ± 108.4c | 645.3 ± 124.5c | −3.7× | | 73.4; <0.0001 |
| Cajeput | 29JL04 | 10.0 ± 2.9a | 2.8 ± 0.5b | 350.8 ± 34.6c | 317.3 ± 30.1c | −3.6× | | 190.9; <0.0001 |
| Cumin | 11JL03 | 18.8 ± 5.5a | 6.3 ± 4.0b | 401.5 ± 30.0c | 290.0 ± 40.4c | −3.0× | | 50.7; <0.0001 |
| Benzoin (LR) | 13JL06 | 16.8 ± 3.5a | 5.8 ± 1.5b | 930.5 ± 36.8c | 834.0 ± 33.4c | −2.9× | | 291.7; <0.0001 |
| Hyssop | 21JL03 | 8.0 ± 3.8a | 3.3 ± 1.4b | 458.3 ± 80.1c | 342.3 ± 25.4c | −2.4× | | 152.7; <0.0001 |
| Eucalyptus (rad) | 23JL03 | 11.3 ± 2.3a | 5.3 ± 1.7b | 241.3 ± 16.2c | 220.0 ± 36.5c | −2.1× | | 115.6; <0.0001 |
| Fir needle | 17JL03 | 64.3 ± 21.4a | 32.5 ± 10.6b | 1105.3 ± 209.2c | 877.8 ± 168.0c | −2.0× | | 167.2; <0.0001 |
| Bergamont mint | 25JL03 | 54.3 ± 4.1a | 47.0 ± 7.9a | 1,060.0 ± 107.4b | 601.8 ± 96.4c | | −1.8× | 242.0; <0.0001 |
| Tarragon | 23JL03 | 7.0 ± 1.5a | 9.3 ± 2.3a | 186.8 ± 20.9b | 102.5 ± 6.2c | | −1.8× | 83.3; <0.0001 |
| Camphor | 01AG05 | 3.5 ± 1.3a | 27.5 ± 12.4b | 187.5 ± 10.1c | 182.8 ± 43.8c | +7.9× | | 54.3; <0.0001 |
| Coffee | 25JL05 | 22.5 ± 6.4a | 151.0 ± 11.0b | 906.3 ± 103.0c | 930.5 ± 135.3c | +6.7× | | 59.5; <0.0001 |
| Geranium | 13JL06 | 1.8 ± 1.1a | 6.3 ± 2.4b | 291.8 ± 9.7c | 199.3 ± 5.7c | +3.5× | | 72.3; <0.0001 |
| Grapefruit | 27JL05 | 8.8 ± 4.5a | 27.5 ± 8.0b | 639.0 ± 46.0c | 508.8 ± 85.1c | +3.1× | | 35.4; <0.0001 |
| Elemi | 27JL05 | 8.8 ± 7.8a | 25.8 ± 6.3b | 719.3 ± 45.9c | 587.3 ± 31.4c | +2.9× | | 37.6; <0.0001 |
| Citronella | 19JL06 | 6.3 ± 1.9a | 13.5 ± 1.9b | 343.0 ± 24.6c | 280.5 ± 15.2c | +2.1× | | 91.7; <0.0001 |
| Catnip | 18JL03 | 11.7 ± 4.8a | 5.0 ± 2.1a | 643.3 ± 68.5b | 490.3 ± 23.1b | | | 41.2; 0.0002 |
| Cardamon | 06JL07 | 15.5 ± 4.0a | 14.8 ± 2.2a | 501.5 ± 32.4b | 389.8 ± 30.3b | | | 123.1; <0.0001 |
| Cedar wood | 08JL03 | 82.3 ± 36.4a | 40.3 ± 6.4a | 571.3 ± 42.8b | 625.3 ± 17.4b | | | 35.5; <0.0001 |
| Clove bud | 21JL03 | 34.5 ± 8.1a | 81.0 ± 32.1a | 455.5 ± 34.6b | 520.3 ± 84.5b | | | 8.6; 0.0053 |
| Cumin + Coffee | 01AG05 | 6.8 ± 1.9a | 7.0 ± 2.1a | 308.3 ± 28.8b | 171.3 ± 25.5b | | | 112.2; <0.0001 |
| Davana | 17JL06 | 19.8 ± 9.9a | 6.0 ± 2.3a | 1,167.5 ± 77.8b | 992.3 ± 57.3b | | | 42.2; <0.0001 |
| Dill | 26JL05 | 9.8 ± 5.9a | 6.8 ± 3.1a | 1,181.5 ± 125.8b | 925.3 ± 113.7b | | | 83.8; <0.0001 |
| Dill + Grapefruit | 02AG05 | 7.3 ± 3.2a | 7.5 ± 1.3a | 337.8 ± 29.0b | 304.8 ± 36.7b | | | 99.9; <0.0001 |
| Eucalyptus (glo) | 25JL03 | 16.3 ± 4.5a | 15.0 ± 2.9a | 1,194.3 ± 104.1b | 1,039.5 ± 68.9b | | | 200.4; <0.0001 |
| Lavender | 05JL07 | 10.8 ± 3.8a | 6.8 ± 1.8a | 392.8 ± 18.7b | 205.3 ± 15.5b | | | 91.9; <0.0001 |
| Lemongrass | 18JL06 | 6.5 ± 1.8a | 10.0 ± 1.4a | 437.8 ± 4.5b | 317.5 ± 9.1b | | | 220.8; <0.0001 |
| Rosemary | 12JL06 | 8.3 ± 4.8a | 2.5 ± 1.2a | 591.0 ± 47.8b | 465.5 ± 25.7b | | | 60.1; <0.0001 |
| Tea tree | 28JL03 | 21.5 ± 10.3a | 5.5 ± 2.6a | 576.3 ± 123.5b | 170.3 ± 46.6b | | | 22.4; 0.0002 |
| Tumeric | 12JL06 | 6.8 ± 5.8a | 13.5 ± 5.1a | 1,138.3 ± 106.3b | 1,016.3 ± 55.0b | | | 51.1; <0.0001 |
| Vetivar | 30JL03 | 15.3 ± 3.9a | 11.5 ± 2.5a | 460.5 ± 40.3b | 426.5 ± 26.9b | | | 71.0; <0.0001 |
| Yarrow | 29JL05 | 21.0 ± 16.0a | 6.8 ± 1.9a | 687.8 ± 89.8b | 338.3 ± 29.3b | | | 55.9; <0.0001 |
| Ylang ylang III | 26JL05 | 21.3 ± 6.5a | 17.0 ± 6.2a | 1,342.5 ± 96.9b | 798.8 ± 156.6b | | | 124.7; <0.0001 |
| Mineral oil | 05AG03 | 3.3 ± 0.8a | 4.3 ± 3.3a | 104.5 ± 9.7b | 124.5 ± 14.9b | | | 39.9; <0.0001 |

Treatments were arranged in a randomized complete block design with four replicates on each test date.

[a] W, wintergreen oil; G, ginger oil; C, citronella oil; P, peppermint oil; Benzoin (LR), Benzoin liquid resin; Eucalyptus (glo), eucalyptus oil from *Eucalyptus globulus* Labill.; Eucalyptus (rad), eucalyptus oil from *Eucalyptus radiata* Sieber ex DC. Wintergreen, peppermint, and wormwood oils were evaluated on more than one date, so data for these oils are grouped.

[b] Each essential oil treatment was evaluated on the specified date during a single 4.5-h period from ≈1030 to 1500 hours.

[c] Mean Japanese beetle trap catch within the same row for a given date and essential oil, followed by a different letter, were significantly different as indicated by analysis of variance on $\log_{10}(x + 1)$ transformed data with means separated by least significant difference test ($P < 0.05$). Means and errors are presented untransformed. NB, Nonbaited; O, essential oil; P, Japanese beetle attractant consisting of phenethyl propionate:eugenol:geraniol (3:7:3 ratio).

[d] Ratio of NB to O trap catch. −, decrease in beetle collection associated with O; +, increase in beetle collection associated with O. −/+ values are only given for mean comparisons with significant differences detected.

[e] Ratio of P to P + O trap catch. −, decrease in beetle collection associated with P + O; +, increase in beetle collection associated with P + O. −/+ values are only given for mean comparisons with significant differences detected.

[f] *F* and *P* values are for mean comparisons within the same row. Degrees freedom were 3 (MST) and 9 (MSE) for all comparisons.

wintergreen oil significantly lowered Japanese beetle trap catch 4.2× during 2003 and 2006, but no significant reductions were detected during 2004 and 2005. Likewise, peppermint oil reduced Japanese beetle trap catch in 2003, but no significant reductions were detected in 2004, and wormwood oil reduced beetle trap catch in 2004, but no significant reductions were detected in 2003.

## Discussion

Host plant odors play an important role in long-range attraction and host selection by adult Japanese beetles (Fleming 1972, Potter and Held 2002). The formulation of phenethyl propionate, eugenol, and geraniol (3:7:3) is described as a food-type attractant with a high degree of attractiveness to both sexes of the Japanese beetle (Ladd et al. 1981, Ladd and Klein 1986). By combining plant essential oils with the PEG attractant, the present field-based study demonstrated a variety of oils reduce attraction of adult Japanese beetles to PEG attractant-baited traps. The procedure of pairing nonhost volatiles with an attractant to assess olfactory disruption has been used extensively in field studies, particularly with the Scolytinae (Borden et al. 1997, 2001; Huber and Borden 2001; Fettig et al. 2005). Eight of the 41 oils tested with PEG attractant in our study significantly reduced Japanese beetle trap counts relative to traps baited with only the PEG attractant. In particular, wintergreen, peppermint, and combinations of wintergreen with ginger, peppermint, or ginger and citronella oils produced the greatest reductions (3.1× to 4.7×) in beetle trap counts relative to PEG-baited traps. Anise, bergamont mint, cedarleaf, dalmation sage, tarragon, and wormwood oils also significantly reduced attractiveness of the PEG attractant by 1.6× to 2.4×. Because volatiles associated with the PEG attractant are believed to imitate an attractive host to the Japanese beetle, essential oils that reduce orientation to the attractant are promising candidates for subsequent laboratory and field studies aimed at managing beetle populations. In particular, follow-up studies are warranted to assess oviposition deterrence associated with the promising essential oils identified in our study.

In addition to plant-derived cues, Ladd and Klein (1986) documented that color also influences Japanese beetle attraction. Nonbaited traps used in the current study collected adults on all evaluation dates, but the olfactory response to PEG was stronger because nonbaited traps always collected significantly fewer beetles (average 53.1× [range 6.9–168.6×]) than PEG-baited traps. Seventeen of the 41 essential oils tested in the current study significantly disrupted visual attractiveness of the yellow and green traps to the Japanese beetle. The combination of wintergreen and peppermint oils was particularly effective (11×) at reducing Japanese beetle attraction to nonbaited traps.

Metzger (1930) identified several essential oils that allegedly repelled Japanese beetles from attractant-baited traps and host trees, which were derived from pine (*Pinus* spp.), cade (*Juniperus* spp.), hyssop (*Hyssop* spp.), cajuput (*Melaleuca* spp.), and cascarilla (*Croton* spp.). Similarly, Metzger and Grant (1932) evaluated 474 plant extracts against Japanese beetles in a field setting and reported 56 with "reputed" repellent properties. Several species or genera identified by Metzger and Grant (1932) as promising sources of botanical extracts were confirmed in our study, namely, *Pimpinella saxifraga* L., *Pimpinella anisum* L., *Pinus sylvestris* L., and other *Pinus* spp. Essential oils derived from *Achillea millefolium* L., *Artemisia dracunculus* L., *Gaultheria procumbens* L., *Origanum vulgare* L., *Piper nigrum* L., and *Thymus vulgaris* L. also significantly reduced Japanese beetle trap counts in our study, but solvent extracts from these same species or genera were not considered repellent by Metzger and Grant (1932). Alternatively, *Rosmarinus officinalis* L. essential oil did not significantly reduce beetle response to PEG or nonbaited traps in the current study; yet, Metzger and Grant (1932) found this oil exhibited repellence against the Japanese beetle. The majority of plant extracts used by Metzger and Grant (1932) were obtained by tissue extraction with ethyl alcohol or water, as opposed to the steam distillates mainly used in our study (Table 1). Thus, differences in extraction procedures between our studies may have contributed to varying degrees of activity against the Japanese beetle.

Jacobson (1989) noted Lamiaceae plants were among the most promising botanical sources of essential oils for insect control. Plant essential oils that reduced trap counts in the current study were derived from the Apiaceae ($n$ = 1), Asteraceae ($n$ = 2), Cupressaceae ($n$ = 2), Ericaceae ($n$ = 1), Lamiaceae ($n$ = 6), Myrtaceae ($n$ = 2), Pinaceae ($n$ = 2), Piperaceae ($n$ = 1), Styraceae ($n$ = 1), and Zingiberaceae ($n$ = 1). Japanese beetles exhibit little or no feeding on many species within these families (Fleming 1972), which may explain, in part, why essential oils derived from these plants reduced PEG and/or trap attractiveness. Essential oils from plants within each of the aforementioned families are mainly composed of mono- and sesquiterpenes (Belleau and Collin 1993, Holm et al. 1997, Chalcat et al. 1997, Adams 1998, Miraldi 1999, Homer et al. 2000, Santos et al. 2001, Macchioni et al. 2003, Rustaiyan et al. 2006), which are well known to act as insect repellents and fumigant toxicants (Isman 2000).

When tested singly, wintergreen was the most effective essential oil at reducing PEG attractiveness (4.2×) to the Japanese beetle. Gas chromatography-mass spectrometry (GC-MS) studies by Baruah and Bhagat (1976) determined wintergreen oil was 99.6% methyl salicylate, with minor and trace amounts of mono- and sesquiterpenes. Methyl salicylate, which is a metabolite of salicylic acid, is particularly repellent to aphids (Hardie et al. 1994, Pettersson et al., 1994). Peppermint tested singly was the second most effective essential oil at reducing PEG attractiveness (3.5×). Menthol, menthone, menthyl acetate, and eucalyptol are four of the main components comprising peppermint essential oil, in addition to smaller amounts of menthofuran, isomenthone, neomenthol, limonene, and pulegone (Dimandja et al. 2000). Overall, the combination of wintergreen and ginger oils resulted in the greatest reduction (4.7×) in attractiveness of the PEG lure. Ginger essential oil consists of a wide array of mono- and sesquiterpenes, alcohols, and carbonyl compounds, with major constituents being zingiberene, ar-curcumene, β-farnesene, and shogaol (Onyenekwe and Hashimoto 1999, Zancan et al. 2002). Subsequent olfactometer and field bioassays are warranted to determine components within wintergreen, peppermint, and ginger essential oils that disrupt the attraction of Japanese beetles.

Wintergreen and ginger oil combined produced the greatest reduction in Japanese beetle response to the PEG attractant, indicating the potential for synergism or additive effects among different essential oil products. The effects of a given essential oil are highly variable among different insect species, thus blending oils can often result in an optimal spectrum of activity against a specific pest (Isman 2000). Synergism was not detected among a few of the essential oils that were tested as blends in the current study for disrupting the olfactory response of Japanese beetles. Loughrin et al. (1998) found as the number of components in a volatile blend increase, there is a greater chance the polyphagous Japanese beetle will be more attracted to the mixture. However, additional synergism studies are required after active individual components from promising oils are identified.

Essential oils that are the most efficacious against insects often cause plant phytotoxicity (Isman 2000). The undiluted essential oil formulations tested in the current study would probably be phytotoxic if applied directly to plant foliage. However, certain scenarios may be appropriate for using concentrated essential oil formulations. One promising scenario is the application of concentrated formulations to mulches, thereby reducing attraction by adult Japanese beetles or deterring oviposition. Based on results from the current study, additional in-depth studies are warranted to assess oviposition deterrence associated with several essential oils, along with the efficacy of repellent/deterrent mulches. Even if pure essential oils have limited value for pest management programs, the goal of our study was to identify low-cost essential oils with bioactive properties against the Japanese beetle and to exclude ineffective oils from further consideration. If candidate oils do not possess the ability to reduce Japanese beetle attraction in a highly concentrated formulation, the oil is less likely to have value for further testing at lower concentrations.

Japanese beetle adults are attracted to floral and fruit-like odors (Fleming 1972, Loughrin et al. 1998), as represented by components of the PEG attractant. Six essential oils tested in the current study significantly increased Japanese beetle trap counts relative to a nonbaited trap, but none of the oils increased trap collections when paired with the PEG attractant. The monoterpene camphor was the most attractive essential oil when tested alone. Attractive essential oils were derived from the Burseraceae ($n = 1$), Geraniaceae ($n = 1$), Lauraceae ($n = 1$), Poaceae ($n = 1$), Rubiaceae ($n = 1$), and Rutaceae ($n = 1$). Many plant species from these families are characterized as having light to extensive feeding damage by Japanese beetle (Fleming 1972). Within a plant family, the species evaluated in this study produced essential oils that were either attractive or nonattractive to Japanese beetle, but not both.

Some variation in Japanese beetle response occurred for certain essential oils that were tested repeatedly in multiple years, such as wintergreen, peppermint, and wormwood oils. Variation in environmental factors and changes in beetle populations may have contributed to differences in trap counts for oils tested on more than one date. However, results from this study indicate that wintergreen and peppermint, in addition to anise, bergamont mint, cedarleaf, dalmation sage, and wormwood essential oils, are promising candidates for further chemical structure and bioactivity experiments. Follow-up studies also are warranted to assess the ability of promising essential oils to deter oviposition by the Japanese beetle, particularly when applied to various mulches. The relatively low cost of promising essential oils, such as wintergreen (≈$0.04/ml), may enhance their utility for pest control purposes. In addition, some essential oils have minimum-risk status for pesticide registration (USEPA 2000). Ultimately, such research could lead to sustainable and environmentally friendly tactics for managing Japanese beetles.

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