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# Bioactivity of Wild Carrot (*Daucus carota*, Apiaceae) Essential Oil Against Mosquito Larvae

**Ephantus J. Muturi,[1,3] Kenneth Doll,[2] Jose L. Ramirez,[1] and Alejandro P. Rooney[1]**

[1]Crop Bioprotection Research Unit, Agricultural Research Service, U.S. Department of Agriculture, 1815 N. University Street, Peoria, IL 61604, [2]Bio-Oils Research Unit, U.S. Department of Agriculture, ARS, 1815 N. University Street, Peoria, IL 61604, and [3]Corresponding author, e-mail: ephantus.muturi@ars.usda.gov

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## Abstract

Invasive alien plants wreak havoc on native ecosystems and using them as a source of biopesticides could improve their management. We examined the toxicity of essential oil of wild carrot (also known as 'Queen Anne's Lace', *Daucus carota* Linnaeus), an aggressive invader throughout the United States, against *Aedes aegypti* L., *Culex pipiens* L., and *Culex restuans* Theobald larvae. Comparisons were made between essential oil extracted from umbels of local populations of wild carrot versus a commercial brand. Methyl isoeugenol (60.7%) was by far the most abundant constituent in commercial brand oil, whereas α-pinene (33.0%) and β-pinene (25.8%) were the dominant constituents in essential oil extracted from local wild carrot populations. The commercial brand essential oil was significantly more toxic to *Cx. restuans* larvae ($LC_{50}$ = 44.4 ppm) compared with *Cx. pipiens* ($LC_{50}$ = 51.0 ppm) and *Ae. aegypti* ($LC_{50}$ = 54.5 ppm). Essential oil from local populations of wild carrot was significantly more toxic to both *Cx. pipiens* ($LC_{50}$ = 42.9) and *Cx. restuans* ($LC_{50}$ = 40.3) larvae compared with *Ae. aegypti* ($LC_{50}$ = 64.6 ppm) larvae. Three of the nine tested chemical constituents of wild carrot essential oil (terpinolene, para cymene, and γ-terpinene) were consistently more toxic to larvae of the three mosquito species than the whole essential oil. These findings suggest that exploiting wild carrot essential oil and its chemical constituents as a biopesticide for mosquito control could be used as part of multifaceted approaches for controlling this invasive alien plant species.

**Key words:** wild carrot, essential oil, larvicidal, mosquito control, biopesticide

Invasive alien plant species are exotic plants that escape cultivation outside their native range and competitively displace or eradicate their new neighbors. The spread of these plants has been accelerated by global travel and trade, and now virtually all ecosystems throughout the world have been invaded (Millennium Ecosystem Assessment 2005). Invasive alien plants threaten the integrity of agricultural and natural systems and often affect ecosystem processes in ways that degrade ecosystem services and affect human well-being (Pejchar and Mooney 2009, Funk et al. 2014). They are recognized as one of the leading causes of global ecological change and biodiversity loss around the globe (Pejchar and Mooney 2009, Pysek and Richardson 2010). To minimize current and potential future impacts of invasive alien plants, many countries have launched far-reaching integrated strategies for preventing and managing biological invasions (McNeely et al. 2001). In general, however, managing invasive species remains a challenge because they are difficult to detect, and damage can go unnoticed for a long time. Additionally, large-scale efforts against well-established species are very costly and ironically, there may be objection to control efforts before the effects are obvious and widespread (Pitt and Witmer 2014).

Despite their destructive nature, some invasive alien plants can also provide valuable economic and ecological benefits sparking a controversy as to whether they are friends or foe, pest or providence, and weed or wonder (Pasiecznik 1999, Foster and Sandberg 2004). For instance, the powder obtained from dried roots of water hyacinth (*Eichhornia crassipes* (Martius) SolmsLaubach), a noxious invader of freshwater ecosystems, has been shown to reduce arsenic contaminants from water, rendering it safe for human consumption (Mukul et al. 2006). This invasive plant is also a rich source of compost and manure for agricultural use (Sandilyan and van't Klooster 2016). Some local communities particularly in poor developing countries also use certain invasive alien plants as food (e.g., *Sonchus oleraceus* L.), biofuel (e.g., *Xanthium indicum* L.), biofertilizer (*Lantana camara* L.), fodder (*Leucaena leucocephala* (Lamarck) de Wit), and as a source of traditional medicine (e.g., *Ricinus communis* L., *Bidens pilosa* L., and *Echinops echinatus* Roxburgh) and insecticide (*Ocimum americanum* L.) (Maema et al. 2016, Sandilyan and van't Klooster 2016). Other invasive alien plants not only disrupt local ecosystems but also provide habitats to native wildlife species. For example, Amur honeysuckle (*Lonicera maackii* (Ruprecht)

Herder) is a woody shrub native to Asia that has wreaked havoc on native plant diversity and abundance in many deciduous forests of eastern North America (Gould and Gorchov 2000, Dorning and Cipollini 2006) but has also been shown to support large populations of native bird species by providing new nesting and foraging resources (McCusker et al. 2010, Gleditsch and Carlo 2014).

A comprehensive understanding of the detrimental and beneficial impacts of a particular invasive alien plant may facilitate development of appropriate strategies for its management. For example, management strategies for an invasive alien plant species that is harmful to resident species but provides critical ecosystem services and facilitates an endemic species would be different from those targeting an invasive alien plant species that harms the resident biota without providing any beneficial effects (Rodriguez 2006). Additionally, unraveling the benefits provided by an invasive alien plant species may provide unique opportunities to manage them by converting them into value-added products with ecological or economic value (Geesing et al. 2004). In general, however, little is known about the beneficial effects of many invasive alien plant species.

In the United States, an estimated 5,000 alien plant species have escaped cultivation posing a serious threat to native biota (Morse et al. 1995). One particularly invasive alien plant is the wild carrot or 'Queen Anne's Lace', (*Daucus carota* L.) a flowering plant that is native to Europe and southwest Asia. This aggressively growing herb was introduced to the United States by European settlers and is now widespread across most of temperate North America. It invades disturbed dry prairies, abandoned fields and road sides, and poses a significant threat to native species especially recovering grasslands. It is also a serious threat to domesticated carrot seed production due to unwanted hybridization/cross-pollination (Mandel et al. 2016). Understanding the potential economic benefits of this invasive plant may facilitate development of strategies to improve its management through exploitation of these benefits. Such a strategy would not only help to contain the plant but also cover the costs of its clearance from native habitats and likely create an additional source of income to the surrounding communities.

To improve current understanding of the benefits of this invasive alien plant, we extracted essential oil from umbels of local populations of wild carrots and examined its toxicity against *Culex pipiens* L., *Culex restuans* Theobald, and *Aedes aegypti* L. larvae relative to a commercial brand of wild carrot essential oil extracted from dried seeds of wild carrot from Corsica, France. *Culex pipiens* and *Cx. restuans* are the primary vectors of West Nile virus in the midwestern and northeastern United States, whereas *Ae. aegypti* is the primary vector of yellow fever, dengue, and chikungunya viruses. Historically, these vectors have mostly been controlled using synthetic insecticides, but the need to maintain environmental stewardship and tackle the rising cases of insecticide resistance has led to renewed interest in the discovery and development of new ecofriendly tools to complement or even replace the use of synthetic insecticides. The wild carrot essential oil had substantial activity against larvae of the three mosquito species demonstrating the potential to manage this invasive plant by converting it into a biopesticide for mosquito control. The findings of this study provide critical insights that link two major disciplines that often work in isolation: vector biology and invasion biology.

## Materials and Methods

### Collection of Flower Buds and Essential Oil Extraction

Essential oil was extracted using steam distillation from umbels of wild carrot populations collected in Peoria, IL (Boutekedjiret et al. 2003). The oil was stored in amber colored bottles until use.

### Gas Chromatography-Mass Spectrophotometry Analysis of Essential Oil

Two different Agilent 7890 (Santa Clara, CA) gas chromatographs, each using Agilent's Mass Hunter software to acquire and process data were employed. For product identification, a 5975 mass spectrometry detector and NIST05a library were used, whereas flame ionization detection was used for quantitation. Identical columns, sample preparation, and temperature/injection programs were used for each instrument: Agilent/J&W DB35-MS column (30m × 320 mm, 0.25-mm film thickness), column flow of helium at 1.37 ml per minute, samples of ~10 µl diluted in 1 ml of heptane and 1 µl was injected by autosampler using a 50:1 split ratio; the temperature program started at 40°C for 3 min, then was raised 10°C/min to 190°C and held for 5 min, then raised 25°C/min to 340°C. Where available, commercial compounds were purchased and diluted in heptane, and used for comparison of retention time. The following were purchased from Sigma-Aldrich, and used as received: alpha-pinene 98%, camphene 95%, beta-pinene >99%, myrcene 97%, limonene 97%, para-cymene 99%, gamma-terpinene 97%, terpinolene >90%, borneol 97%, bornyl acetate 95%, beta-elemene, methyl isoeugenol 98%, and caryophyllene oxide 95%.

### Mosquitoes

*Aedes aegypti* (Rockefeller strain) larvae were reared on yeast: lactose albumin (1:1) diet in batches of ~200 larvae. *Culex pipiens* and *Cx. restuans* egg rafts were collected from nearby woodlots and residential areas in Peoria, IL, using oviposition traps comprising of 5-gallon buckets baited with 5 liter of grass infusion. In total, >1,000 *Culex* egg rafts were collected and each egg raft was hatched individually in tripour beakers containing 300 ml of deionized water. The larvae were reared on yeast: lactose albumin (1:1) and a single third-instar larva from each container was used for species identification based on morphological characteristics (Darsie and Ward 1981). All mosquito species were maintained at 26°C, 70% relative humidity (RH), and 10:14 (L:D) h. For each mosquito species, larvae from all rearing containers were pooled before the bioassays.

### Bioassays

Twenty late third instar larvae of either *Cx. pipiens, Cx. restuans* or *Ae. aegypti* were added into 120 ml of DI water held in 400 ml tripour beakers. Treatments included wild carrot essential oil from local plant populations, and commercial brand of essential oil extracted from dried seeds of wild carrot from Corsica, France. This oil was purchased from Floracopeia Aromatics (Grass Valley, CA). Each treatment was tested at 11 concentrations ranging from 30 to 70 ppm. A control group received 84 µl of absolute ethanol without oil treatment, which is equivalent to the largest volume of oil treatment added to the containers. The stock solution for each essential oil (100,000 ppm) was prepared by mixing 900 µl of absolute ethanol with 100 µl of the target essential oil and vortexing the mixture for 30 s. The experiment was replicated three times and three separate trials were conducted. The containers were held at room temperature and the total number of larvae surviving 24-h posttreatment were counted and recorded. Probit analysis conducted using 'ecotox' package in R version 3.3.2 was used to calculate $LC_{50}$ values for each oil treatment.

Nine constituents of wild carrot were tested for their toxicity to mosquito larvae at 30 ppm concentration to determine their contribution to the overall toxicity of the whole essential oil. These were α-pinene, β-pinene, γ-terpinene, myrcene, limonene, para-cymene, terpinolene, bornyl acetate and methyl isoeugenol. One-way

ANOVA was used to compare differences in toxicity of these constituents against larvae of each mosquito species. Tukey HSD test was used for multiple comparisons.

## Results

### Chemical Composition of Essential Oil

The commercial brand of wild carrot essential oil had eight chemical constituents compared to 14 chemical constituents for the oil extracted from umbels of local populations of wild carrot (Table 1). There were marked variations in the proportion of various chemical constituents identified from the two essential oils. The four most abundant constituents in essential oil extracted from umbels of local populations of wild carrot were α-pinene (33.0%), β-pinene (25.8%), borneol (10.4%), and myrcene (6.4%). For the commercial brand of wild carrot essential oil, the four most abundant constituents were methyl isoeugenol (60.7%), α-pinene (15.8%), caryophyllene oxide (7.6%), and β-bisabolene (6.1%).

### Larvicidal Effect of Wild Carrot Essential Oil and Some of Its Chemical Constituents

The larvae of the three mosquito species differed in their sensitivity to local versus commercial brand of wild carrot essential oil (Fig. 1; Table 2). Essential oil extracted from local populations of wild carrot was significantly more toxic to *Cx. pipiens* larvae compared with the commercial brand of wild carrot essential oil (*Cx. pipiens*: $LC_{50}$ = 42.9 vs 51.0 ppm). A similar pattern was observed for *Cx. restuans* ($LC_{50}$ = 40.3 vs 44.4 ppm), but the differences were not statistically significant. Conversely, the commercial brand of wild carrot essential oil was significantly more toxic to *Ae. aegypti* larvae than the essential oil extracted from local populations of wild carrot ($LC_{50}$ = 54.5 vs 64.6 ppm). The commercial brand of wild carrot essential oil was more toxic to *Cx. restuans* larvae compared with *Ae. aegypti* and *Cx. pipiens* larvae (Table 2), whereas essential oil extracted from local populations of wild carrot was more toxic to both *Cx. restuans* and *Cx. pipiens* compared to *Ae. aegypti* (Table 2).

To determine the role of individual constituents toward the observed toxicity of wild carrot essential oil against mosquitoes, nine individual constituents were tested at 30 ppm concentration. Toxicity varied significantly among chemical constituents (*Cx. restuans*: $F = 31.04$, df = 10, 88, $P < 0.0001$; *Cx. pipiens*: $F = 13.21$, df = 10, 88, $P < 0.0001$; *Ae. aegypti*: $F = 48.88$, df = 10, 88, $P < 0.0001$). For *Ae. aegypti*, borynl acetate, methyl isoeugenol, and myrcene were equally as toxic as the whole essential oil while terpinolene, limonene, α-pinene, β-pinene, paracymene, and γ-terpinene were more toxic than the whole essential oil (Fig. 2). For *Cx. pipiens*, bornyl acetate, terpinolene, γ-terpinene, and paracymene were more toxic than the whole essential oil, whereas the remaining constituents had similar toxicity as the whole essential oil (Fig. 2). For *Cx. restuans*, methyl isoeugenol, limonene, and myrcene were equally as toxic as the whole essential oil, whereas the other six constituents were more toxic than the whole essential oil (Fig. 2).

## Discussion

Invasive alien plants are a major threat to biological diversity and human well-being and can be difficult and costly to control. Finding new solutions to offset the cost of their control would be highly desirable, such as developing new, value-added products from the harvest of invasive alien plant species. In that context, the goal of this study was to explore the potential for utilizing wild carrot as a source of mosquito biopesticide(s). Our finding that wild carrot

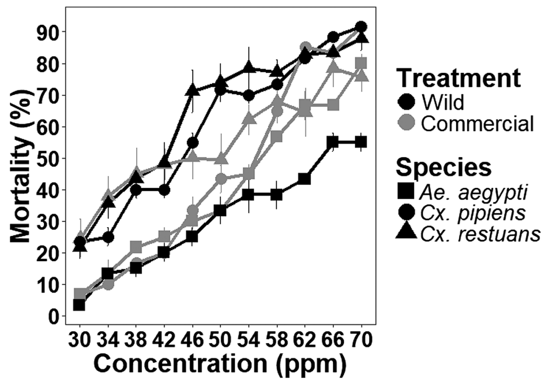


**Fig. 1.** Mean mortality (±SE) of late third instar larvae of *Cx. pipiens*, *Cx. restuans* and *Ae. aegypti* in different concentrations of wild carrot essential oil. Wild = oil from umbels of local populations of wild carrot, commercial = commercial brand of wild carrot essential oil.

**Table 1.** Chemical composition of wild carrot essential oil from local plants (QAW) or purchased from commercial vendor (QAC)

| Compound | Retention time | Compound type | QAW | QAC |
|---|---|---|---|---|
| Alpha-pinene | 7.92 | Monoterpene | 33.02 ± 0.03 | 15.81 ± 0.12 |
| Camphene | 8.42 | Monoterpene | 1.47 ± 0.00 | 0.00 |
| Beta-pinene | 8.98 | Monoterpene | 25.77 ± 0.04 | 4.62 ± 0.03 |
| Myrcene | 9.19 | Monoterpene | 6.41 ± 0.01 | 2.43 ± 0.02 |
| Alpha-terpinene | 9.82 | Monoterpene | 2.51 ± 0.01 | 0.00 |
| Limonene | 10.03 | Monoterpene | 5.34 ± 0.01 | 1.37 ± 0.01 |
| Beta-phellandrene | 10.16 | Monoterpene | 2.14 ± 0.01 | 0.00 |
| Para-cymene | 10.32 | Reduced monoterpene | 1.93 ± 0.01 | 0.00 |
| Gamma-terpinene | 10.67 | Monoterpene | 4.97 ± 0.01 | 0.00 |
| Terpinolene | 11.16 | Monoterpene | 1.19 ± 0.01 | 0.00 |
| Borneol | 13.07 | Terpene derivative | 10.40 ± 0.02 | 0.00 |
| Bornyl acetate | 14.50 | Terpene derivative | 2.31 ± 0.00 | 0.00 |
| Isocaryophyllene | 15.73 | Sesquiterpene | 1.10 ± 0.00 | 0.00 |
| Methyl eugenol | 16.86 | Guaiacol derivative | 0.00 | 1.35 ± 0.01 |
| Germacrene | 16.94 | Sesquiterpene | 1.46 ± 0.01 | 0.00 |
| Beta-bisabolene | 16.95 | Sesquiterpene | 0.00 | 6.1 ± 0.02 |
| Methyl isoeugenol | 18.20 | Guaiacol derivative | 0.00 | 60.73 ± 0.18 |
| Caryophyllene oxide | 18.81 | Oxidized sesquiterpene | 0.00 | 7.61 ± 0.02 |

**Table 2.** $LC_{50}$ values for wild carrot essential oil against *Ae. aegypti*, *Cx. restuans* and *Cx. pipiens* larvae

| Oil type | Species | $LC_{50}$ (95% CI) | $LC_{95}$ (95% CI) | Equation | Chi-square |
|---|---|---|---|---|---|
| Commercial | *Aedes aegypti* | 54.5 (52.3–57.0) | ND | $y = 5.90x - 10.25$ | 11.19 |
| | *Culex pipiens* | 51.0 (49.4–52.6) | 81.3 (76.2–88.5) | $y = 8.10x - 13.83$ | 18.26 |
| | *Culex restuans* | 44.4 (41.0–47.6) | ND | $y = 3.49x - 5.76$ | 311.72 |
| Wild | *Aedes aegypti* | 64.6 (60.5–70.6) | ND | $y = 4.54x - 8.22$ | 10.52 |
| | *Culex pipiens* | 42.9 (40.9–44.8) | 82.4 (75.4–92.9) | $y = 5.81x - 9.48$ | 9.14 |
| | *Culex restuans* | 40.3 (38.4–42.1) | 83.3 (76.4–93.5) | $y = 5.23x - 8.39$ | 211.61 |

Wild = oil from umbels of local populations of wild carrot, Commercial = commercial brand of wild carrot essential oil, ND = not determined because it was higher than the oil concentrations that were tested.

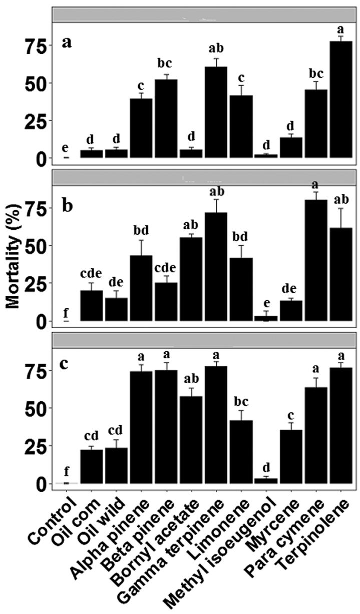


**Fig. 2.** Toxicity of nine chemical constituents of wild carrot essential oil against larvae of a) *Ae. aegypti*, b) *Cx. pipiens*, and c) *Cx. restuans* relative to whole essential oil at 30 ppm after 24-h exposure. Oil com, commercial brand of wild carrot essential oil; oil wild, essential oil extracted from wild populations of wild carrot.

essential oil has substantial activity against larvae of *Cx. restuans*, *Cx. pipiens*, and *Ae. aegypti* with $LC_{50}$ values ranging from 40.3 to 64.6 ppm, demonstrate the potential to harness this invasive alien plant as a source of biopesticides for mosquito control. Additionally, the findings provide critical insights that link the disciplines of vector biology and invasion biology which in the past have worked in isolation.

Essential oils are promising sources of ecofriendly insecticides, because they have low mammalian toxicity, degrade quickly in the soil and water, possess ovicidal, larvicidal, adulticidal, and repellent activity against mosquitoes and have multiple modes of action and sites of action that makes it difficult for mosquitoes to develop resistance (Isman, 2000, Isman et al. 2011). Several essential oils have been commercialized for use in pest control (Isman et al. 2011) and recent studies suggest that some essential oils can work in synergy with pyrethroids and carbamates (Norris et al. 2018, Tong et al. 2013). These findings demonstrate that essential oil-based insecticides could be used to tackle the rising problem of insecticide resistance. Although our results show that wild carrot essential oil is not as toxic to mosquito larvae as commonly used synthetic insecticides (e.g., permethrin and temephos) or some other essential oils such as garlic and asafoetida (Table 3; Kimbaris et al. 2009, Muturi et al. 2018), their $LC_{50}$ values (range 40.3–64.6 ppm) are within the range that is considered active for natural products (Cheng et al. 2003, Komalamisra et al. 2005, Kiran et al. 2006). Additionally, these $LC_{50}$ values are much lower than those reported for many other many essential oils (Amer and Mehlhorn 2006, Koliopoulos et al. 2010, Manimaran et al. 2012, Pavela et al. 2014). Our results are also comparable to those of essential oil from seeds and root of domestic carrots (Lee 2006, Park and Park 2012, Seo et al. 2015). Exposure of *Ae. aegypti* and *Culex pipiens pallens* Coquillet larvae to 50 ppm of essential oil from roots of domestic carrots resulted in 100% mortality (Lee 2006). A similar level of mortality was achieved for *Cx. pipiens pallens* and *Aedes albopictus* Skuse following exposure to 100 ppm of the same oil (Park and Park 2012, Seo et al. 2015).

We found notable differences in chemical composition between essential oil extracted from local populations of wild carrots and the commercial brand. Some constituents were either differentially abundant between the two essential oils or were entirely absent in one of the oils. In particular, methyl isoeugenol (60.7%) was by far the most abundant constituent in commercial brand, whereas α-pinene (33.0%) and β-pinene (25.8%) were the dominant constituents in essential oil from local wild carrot populations. We tested some of the major and minor constituents for toxicity against larvae of the three mosquito species and found them to be either more or equally toxic to the whole essential oil. Of particular interest, terpinolene, paracymene, and γ-terpinene were consistently more toxic than the whole essential for all the three mosquito species demonstrating their potential to be harnessed as biopesticides for mosquitoes. With exception of methyl isoeugenol, all the chemical constituents tested here have previously been evaluated for larvicidal effects against other mosquito species with varying results (Table 3).

The insecticidal properties and chemical composition of the essential oil of a particular plant species is known to vary considerably depending on the geographical origin of the essential oil source population, growing conditions, plant parts from which the oil is extracted, developmental stage of the plant at the time of extraction, solvent used for extraction, photosensitivity of some of the compounds in the extractions, and the methods used to isolate the essential oils (Clark and Menary 1981, Hansted et al. 1994, Regnault-Roger et al. 2012). Thus, it is not surprising that the two essential oils had varying toxicity against the three mosquito species given that each species may react differently to the same essential oil due to a number of intrinsic factors. In fact, variation in the toxicity of a particular essential oil against different mosquito species, as observed in this study, is not uncommon (Dharmagadda et al. 2005, Amer and Mehlhorn 2006, Fayemiwo et al. 2014). For example, in a study to examine the larvicidal activity of *Tagetes patula* L. essential oil against mosquito larvae, *Ae. aegypti* ($LC_{90}$ = 37.91) was the most susceptible followed by *An. stephensi* Liston ($LC_{90}$ = 57.62) and *Cx. quinquefasciatus* Say ($LC_{90}$ = 71.89; Dharmagadda et al. 2005).

**Table 3.** Documented toxicity of garlic and asafoetida essential oils and some of the chemical constituents tested in this study against mosquitoes

| Chemical | Species | $LC_{50}$ (95% CI) ppm | Reference |
|---|---|---|---|
| Alpha pinene | *Culex quinquefasciatus* | 95 (89–121) | Pavela (2015) |
| Beta pinene | *Culex quinquefasciatus* | 65 (58–86) | Pavela et al. (2015) |
| Bornyl acetate | *Aedes aegypti* | < 50% at 100 ppm | Ali et al. (2015) |
| Gamma terpinene | *Culex quinquefasciatus* | 26 (23–29) | Pavela (2015) |
| Limonene | *Culex quinquefasciatus* | 40 (34–47) | Pavela (2015) |
| Limonene | *Aedes aegypti* | 26.11 (24.54–27.66) | Silva et al. (2018) |
| Methyl isoeugenol | – | – | – |
| Myrcene | *Culex quinquefasciatus* | 167 (158–176) | Pavela (2015) |
| Para cymene | *Culex quinquefasciatus* | 21 (20–22) | Pavela (2015) |
| Para cymene | *Culex quinquefasciatus* | 20.6 (19.7–21.5) | Pavela et al. (2018) |
| Para cymene | *Aedes aegypti* | 32.81 (29.08–36.95) | Silva et al. (2018) |
| Terpinolene | *Culex quinquefasciatus* | 21 (18–27) | Pavela (2015) |
| Terpinolene | *Culex quinquefasciatus* | 25.7 (22.8–29.2) | Pavela et al. (2018) |
| Garlic essential oil | *Culex pipiens* | 7.5 (7.0–8.0) | Muturi et al. (2018) |
| Garlic essential oil | *Culex restuans* | 2.7 (2.0–3.2) | Muturi et al. (2018) |
| Garlic essential oil | *Culex pipiens molestus* | 8.01 (7.6–8.4) | Kimbaris et al. (2009) |
| Asafoetida essential oil | *Culex pipiens* | 13.5 (13.0–13.9) | Muturi et al. (2018) |
| Asafoetida essential oil | *Culex restuans* | 10.1 (9.6–10.6) | Muturi et al. (2018) |

Dash (–) indicates data not available.

Similarly, *Ae. aegypti* larvae were more susceptible to *Syzygium aromaticum* L. essential oil compared with *Cx. quinquiefasciatus* larvae (Fayemiwo et al. 2014).

One limitation of this study is that we used insecticide-susceptible *Ae. aegypti* strain that has been colonized in the laboratory since 1930s. However, natural populations of *Ae. aegypti* are frequently exposed to insecticides intended for vector control and often carry insecticide resistance traits (Smith et al. 2016). Thus, although the laboratory strain used in this study provide useful insights into the larvicidal activity of wild carrot essential oil against this mosquito species, additional studies using field populations of *Ae. aegypti* are needed to clarify these results.

Overall, our results demonstrate the potential for wild carrot essential oil to be harvested and harnessed as a biopesticide for mosquito control. Wild carrot essential oil has also been described as a fragrance component in perfumes, cosmetics, and soaps, and as an antifungal, antibacterial, and anti-inflammatory agent (Maxia et al. 2009, Alves-Silva et al. 2016). In the light of growing public interest in natural products, these findings suggest that exploitation of economic benefits of wild carrot and other invasive alien plants could be used as part of a multifaceted strategy for managing biological invasions. Although concerted efforts should be made to control this plant where it is a threat to agriculture and natural ecosystems, more research is needed on integrated approaches for sustainable management of this aggressive invader, including utilization projects that create value-added products with economic and public health benefits. This research should involve bottom-up strategies where communities living within the invaded areas are actively engaged because they respond to biological invasions both as the victims and beneficiaries. More importantly, this research should take an interdisciplinary approach where researchers from diverse fields such as vector biology, conservation biology, ethnobotany, and social science, work in concert with local communities and policymakers to achieve the twin goals of conserving biodiversity and managing biological invasions using an integrated approach that includes economic exploitation of invasive alien plants. Managing an invasive alien plant species by exploiting its economic benefits is a practical approach as demonstrated in Niger and Yemen, where exploitation of *Prosopis* species for fuel, fodder, and food was shown to counterbalance its damage (Geesing et al. 2004). Many farmers in the United States face the challenge of controlling wild carrots in their farms. Providing them with an economic incentive to harvest the plant may not only diversify their source of income but also will go a long way toward improving the management of this invasive alien plant.

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## References Cited

**Ali, A., N. Tabanca, B. Demirci, E. K. Blythe, Z. Ali, K. H. Baser, and I. A. Khan. 2015.** Chemical composition and biological activity of four salvia essential oils and individual compounds against two species of mosquitoes. J. Agric. Food Chem. 63: 447–456.

**Alves-Silva, J. M., M. Zuzarte, M. J. Gonçalves, C. Cavaleiro, M. T. Cruz, S. M. Cardoso, and L. Salgueiro. 2016.** New claims for wild carrot (*Daucus carota subsp. carota*) essential oil. Evid. Based. Complement. Alternat. Med. 2016: 9045196.

**Amer, A., and H. Mehlhorn. 2006.** Larvicidal effects of various essential oils against *Aedes*, *Anopheles*, and *Culex* larvae (Diptera, Culicidae). Parasitol. Res. 99: 466–472.

**Boutekedjiret, C., F. Bentahar, R. Belabbes, and J. M. Bessiere. 2003.** Extraction of rosemary essential oil by steam distillation and hydrodistillation. Flav. Fragran. J. 18: 481–484.

**Cheng, S. S., H. T. Chang, S. T. Chang, K. H. Tsai, and W. J. Chen. 2003.** Bioactivity of selected plant essential oils against the yellow fever mosquito *Aedes aegypti* larvae. Bioresour. Technol. 89: 99–102.

**Clark, R. J., and R. C. Menary. 1981.** Variations in composition of peppermint oil in relation to production areas. Econ. Botany. 35: 59–69.

**Darsie, R. F. J., and R. A. Ward. 1981.** Identification and geographical distribution of the mosquitoes of North America, north of Mexico. Mosq. Syst. Suppl. 1: 1–313.

**Dharmagadda, V. S., S. N. Naik, P. K. Mittal, and P. Vasudevan. 2005**. Larvicidal activity of *Tagetes patula* essential oil against three mosquito species. Bioresour. Technol. 96: 1235–1240.

**Dorning, M., and D. Cipollini. 2006**. Leaf and root extracts of the invasive shrub, *Lonicera maackii*, inhibit seed germination of three herbs with no autotoxic effects. Plant Ecol. 184: 287–296.

**Fayemiwo, K. A., M. A. Adeleke, O. P. Okoro, S. H. Awojide, and I. O. Awoniyi. 2014**. Larvicidal efficacies and chemical composition of essential oils of *Pinus sylvestris* and *Syzygium aromaticum* against mosquitoes. Asian Pac. J. Trop. Biomed. 4: 30–34.

**Foster, J., and L. A. Sandberg. 2004**. Friends or foe? Invasive species and public green space in Toronto. Geogr. Rev. 94: 178–198.

**Funk, J. L., V. Matzek, M. Bernhardt, and D. Johnson. 2014**. Broadening the case for invasive species management to include impacts on ecosystem services. Bioscience. 64: 58–63.

**Geesing, D., M. Al-Khawlani, and M. L. Abba. 2004**. Management of introduced *Prosopis* species: can economic exploitation control an invasive species? Unasylva. 55: 36–44.

**Gleditsch, J. M., and T. A. Carlo. 2014**. Living with aliens: effects of invasive shrub honeysuckles on avian nesting. Plos One. 9: e107120.

**Gould, A. M. A., and D. L. Gorchov. 2000**. Effects of the exotic invasive shrub *Lonicera maackii* on the survival and fecundity of three species of native annuals. Am. Midland Naturalist. 144: 36–50.

**Hansted, L., H. B. Jakobsen, and C. E. Olsen. 1994**. Influence of temperature on the rhythmic emission of volatiles from ribes nigrum flowers in-situ. Plant Cell Environ. 17: 1069–1072.

**Isman, M. B. 2000**. Plant essential oils for pest and disease management. Crop Protect. 19: 603–608.

**Isman, M. B., S. Miresmailli, and C. Machial. 2011**. Commercial opportunities for pesticides based on essential oils in agriculture, industry and consumer products. Phytochem. Rev. 10: 197–204.

**Kimbaris, A. C., E. Kioulos, G. Koliopoulos, M. G. Polissiou, and A. Michaelakis. 2009**. Coactivity of sulfide ingredients: a new perspective of the larvicidal activity of garlic essential oil against mosquitoes. Pest Manag. Sci. 65: 249–254.

**Kiran, S. R., K. Bhavani, P. Sita Devi, B. R. Rajeswara Rao, and K. Janardhan Reddy. 2006**. Composition and larvicidal activity of leaves and stem essential oils of *Chloroxylon swietenia* DC against *Aedes aegypti* and *Anopheles stephensi*. Bioresour. Technol. 97: 2481–2484.

**Koliopoulos, G., D. Pitarokili, E. Kioulos, A. Michaelakis, and O. Tzakou. 2010**. Chemical composition and larvicidal evaluation of Mentha, Salvia, and Melissa essential oils against the West Nile virus mosquito *Culex pipiens*. Parasitol. Res. 107: 327–335.

**Komalamisra, N., Y. Trongtokit, Y. Rongsriyam, and C. Apiwathnasorn. 2005**. Screening for larvicidal activity in some Thai plants against four mosquito vector species. Southeast Asian J. Trop. Med. Public Health. 36: 1412–1422.

**Lee, H. S. 2006**. Mosquito larvicidal activity of aromatic medicinal plant oils against *Aedes aegypti* and *Culex pipiens pallens*. J. Am. Mosq. Control Assoc. 22: 292–295.

**Maema, L. P., M. Potgieter, and S. M. Mahlo. 2016**. Invasive alien plant species used for the treatment of various diseases in limpopo province, south africa. Afr. J. Tradit. Complement. Altern. Med. 13: 223–231.

**Mandel, J. R., A. J. Ramsey, M. Iorizzo, and P. W. Simon. 2016**. Patterns of gene flow between Crop and Wild Carrot, *Daucus carota* (Apiaceae) in the United States. Plos One. 11: e0161971.

**Manimaran, A., M. M. Cruz, C. Muthu, S. Vincent, and S. Ignacimuthu. 2012**. Larvicidal and knockdown effects of some essential oils against *Culex quinquefasciatus* Say, *Aedes aegypti* (L.) and *Anopheles stephensi* (Liston). Adv. Biosc. Biotech. 3: 855–862.

**Maxia, A., B. Marongiu, A. Piras, S. Porcedda, E. Tuveri, M. J. Gonçalves, C. Cavaleiro, and L. Salgueiro. 2009**. Chemical characterization and biological activity of essential oils from *Daucus carota* L. *subsp. carota growing* wild on the Mediterranean coast and on the Atlantic coast. Fitoterapia. 80: 57–61.

**McCusker, C. E., M. P. Ward, and J. D. Brawn. 2010**. Seasonal responses of avian communities to invasive bush honeysuckles (*Lonicera* spp.). Biol. Invasions. 12: 2459–2470.

**McNeely, J. A., H. A. Mooney, L. E. Neville, P. Schei, and J. K. Waage. 2001**. Global strategy on invasive alien species. IUCN on behalf of Global Invasive Species Program, Gland, Switzerland.

**Millennium Ecosystem Assessment. 2005**. Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

**Morse, L. E., J. T. Kartesz, and L. S. Kutner. 1995**. Native vascular plants, pp. 205–209. *In* E. T. LaRoe, G. S. Farris, C. E. Puckett, P. D. Doran, and M. J. Mac (eds.), Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals and ecosystems. U.S. Department of the Interior, National Biological Service, Washington, DC.

**Mukul, S. A., M. B. Uddin, and M. R. Tito. 2006**. Study on the status and various uses of invasive alien plants species in and around Satchari National Park, Sylhet, Bangladesh. Tiger paper. 33: 28–32.

**Muturi, E. J., J. L. Ramirez, B. Zilkowski, L. B. Flor-Weiler, and A. P. Rooney. 2018**. Ovicidal and larvicidal effects of garlic and asafoetida essential oils against West Nile virus vectors. J. Insect Sci. 18: 43; 1–6.

**Norris, E. J., J. B. Johnson, A. D. Gross, L. C. Bartholomay, and J. R. Coats. 2018**. Plant essential oils enhance diverse pyrethroids against multiple strains of mosquitoes and inhibit detoxification enzyme processes. Insects. 9: 132.

**Park, H. M., and I. K. Park. 2012**. Larvicidal activity of *Amyris balsamifera*, *Daucus carota* and *Pogostemon cablin* essential oils and their components against *Culex pipiens pallens*. J. Asia-Pac. Entomol. 15: 631–634.

**Pasiecznik, N. 1999**. Prosopis- pest of providence, weed or wonder tree? Europ. Trop. Forest Res. Network Newslet. 28: 12–14.

**Pavela, R. 2015**. Acute toxicity and synergistic and antagonistic effects of the aromatic compounds of some essential oils against *Culex quinquefasciatus* Say larvae. Parasitol. Res. 114: 3835–3853.

**Pavela, R., K. Kaffkova, and M. Kumsta. 2014**. Chemical composition and larvicidal activity of essential oils from different *Mentha* L. and *Pulegium* species against *Culex quinquefasciatus* Say (Diptera: Culicidae). Plant Protect. Sci. 50: 36–42.

**Pavela, R., F. Maggi, K. Cianfaglione, M. Bruno, and G. Benelli. 2018**. Larvicidal activity of essential oils of five apiaceae taxa and some of their main constituents against *Culex quinquefasciatus*. Chem Biodivers. 15: e1700382.

**Pejchar, L., and H. A. Mooney. 2009**. Invasive species, ecosystem services and human well-being. Trends Ecol. Evol. 24: 497–504.

**Pitt, W. C., and G. W. Witmer. 2014**. Invasive vertebrate species and the challenge of management, pp. 12–14. *In* R. M. Timm and J. M. O'brien (eds.), Proceedings of the 26th Vertebrate Pest Conference, 2014. University of California, Davis, CA.

**Pysek, P., and D. M. Richardson. 2010**. Invasive species, environmental change and nanagement, and health. Annu. Rev. Env. Resour. 35: 25–55.

**Regnault-Roger, C., C. Vincent, and J. T. Arnason. 2012**. Essential oils in insect control: low-risk products in a high-stakes world. Annu. Rev. Entomol. 57: 405–424.

**Rodriguez, L. F. 2006**. Can invasive species facilitate native species? evidence of how, when, and why these impacts occur. Biol. Invasions. 8: 927–939.

**Sandilyan, S., and C. I. E. A. van't Klooster. 2016**. The other sides of invasive alien plants of India-With special reference to medicinal values. J. Nat. Conserv. 31: 16–21.

**Seo, S. M., C. S. Jung, J. Kang, H. R. Lee, S. W. Kim, J. Hyun, and I. K. Park. 2015**. Larvicidal and acetylcholinesterase inhibitory activities of apiaceae plant essential oils and their constituents against *aedes albopictus* and formulation development. J. Agric. Food Chem. 63: 9977–9986.

**Silva, I. M., G. F. Martins, C. R. Melo, A. S. Santana, R. R. Faro, A. F. Blank, P. B. Alves, M. C. Picanço, P. F. Cristaldo, A. P. A. Araújo, et al. 2018**. Alternative control of *Aedes aegypti* resistant to pyrethroids: lethal and sublethal effects of monoterpene bioinsecticides. Pest Manag. Sci. 74: 1001–1012.

**Smith, L. B., S. Kasai, and J. G. Scott. 2016**. Pyrethroid resistance in *Aedes aegypti* and *Aedes albopictus*: important mosquito vectors of human diseases. Pestic. Biochem. Physiol. 133: 1–12.

**Tong, F., and J. R. Bloomquist. 2013**. Plant essential oils affect the toxicities of carbaryl and permethrin against *Aedes aegypti* (Diptera: Culicidae). J. Med. Entomol. 50: 826–832.