Deterrency and Toxicity of Essential Oils to Argentine and Red Imported Fire Ants (Hymenoptera: Formicidae)[1]

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Abstract Laboratory assays were conducted to evaluate deterrency and contact toxicity of six essential oils to the Argentine ant, *Linepithema humile* (Mayr), and the red imported fire ant, *Solenopsis invicta* Buren. In choice tests, both Argentine ants and fire ants crossed barriers treated with multiple rates of basil, citronella, lemon, peppermint, or tea tree oil less frequently than paired control barriers. Eucalyptus oil did not prevent movement of either species at any of the rates tested. In continuous exposure assays, citronella oil killed 50% of Argentine ants in 34.3 min and was the only treatment to cause 100% Argentine ant mortality after 24 h. Argentine ant mortality after 24 h was 89.8% with peppermint oil and 85.7% with tea tree oil, with the remaining treatments having mortality not significantly different from the control. Only citronella oil caused significant mortality of red imported fire ants, with 50.6% of the ants being dead after 24 h of continuous exposure.

Key Words *Linepithema humile, Solenopsis invicta*, essential oil, deterrency, contact toxicity

The Argentine ant, *Linepithema humile* (Mayr), and red imported fire ant, *Solenopsis invicta* Buren, are important invasive species in natural, agricultural, and urban settings. While the primary control strategies for ants are broadcast and individual mound treatments and the use of toxic baits, barrier treatments are sometimes needed to exclude ants from structures, equipment, or fruit trees (Shorey et al. 1992, Drees et al. 2000, Vega and Rust 2001). The Argentine ant is a secondary pest in vineyards and citrus groves because it disrupts the control of honeydew-producing homopteran insects by aggressively interfering with their predators and parasitoids (Prins et al. 1990). Although they usually nest outdoors, Argentine ants sometimes invade homes in search of food, moisture, or warmth (Gordon et al. 2001). Red imported fire ants frequently invade areas such as nursing homes, small animal traps, and electrical equipment, making repellent or toxic barriers necessary (Chabreck et al. 1986, MacKay et al. 1992, deShazo et al. 1999). Homeowners have become increasingly concerned about the use of traditional insecticides around the home and schools and, therefore, are interested in less toxic or "natural" substances for ant control, either as a toxicant or a repellent barrier (Drees and Lennon 1998, Potter and Bessin 1998).

Both plants and insects produce chemicals that are repellent to ants. Aromatic cedar mulch is repellent to red imported fire ants, Argentine ants, and odorous house

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ants (Thorvilson and Rudd 2001, Meissner and Silverman 2001, 2003); leaf-cutting ants are deterred by terpenoids produced by many tropical plants (Hubbell et al. 1984), and cat thyme is repellent to the Pharaoh ant, *Monomorium pharaonis* (L.) (Eisner et al. 2000). Methyl palmitate, a component of the defensive secretion of *Polistes fuscatus* (F.), is repellent to several ant species (Henderson and Jeanne 1989). A barrier of farnesol, a component of the alarm pheromone of some ants (Schildknecht 1976), has been used to disrupt Argentine ant foraging in citrus trees (Shorey et al. 1992).

There are anecdotal reports of several essential oils, herbs, and spices being repellent to ants and other insects. However, there are no reports of ant deterrency tests in the scientific literature for most of these products. In tests against other urban and medical pests, essential oils and their components that are repellent include mint, cedarwood, vetiver, and catnip oils, nookatone, citronellal, citral, geraniol, and eugenol (Eisner 1964, Grace and Yamamoto 1994, Cornelius et al. 1997, Ngoh et al. 1998, Appel et al. 2001, Zhu et al. 2001, Maistrello et al. 2001, Peterson and Ems-Wilson 2003). Essential oils and monoterpenoids derived from them have been shown to have insecticidal activity against cockroaches (Appel et al. 2001, Ngoh et al. 1998), termites (Cornelius et al. 1997, Bläske and Hertel 2001, Zhu et al. 2001), mosquitoes (Watanbe et al. 1993), and ticks (Lwande et al. 1999). Vogt et al. (2002) found that three formulations containing orange oil were toxic to red imported fire ants. The purpose of this study was to determine the deterrency and toxicity of essential oils against Argentine ants and red imported fire ants.

Materials and Methods

Test insects. Argentine and red imported fire ant colonies were collected in Spalding Co., GA. Argentine ants in their nesting material (mulch, leaf litter, or soil) were placed in plastic pans (58 × 43 × 15 cm, Sterilite Corporation, Townsend, MA) coated on the inside walls with a thin layer of Fluon™ (Northern Products, Inc., Woonsocket, RI) and provided water, 25% sugar water, frozen house crickets (*Acheta domesticus* (L.)), and nest cells constructed from 100 × 25 mm Petri dishes containing a 1.0 cm thick layer of hardened dental plaster (Castone; Dentsply International Inc., York, PA) to retain moisture. Dish sides and lids were painted black, and three 4-mm holes were drilled into the sides to allow ants to enter. As the nesting material in the pans dried, workers moved the entire colony into the moistened cells. Red imported fire ants were separated from soil by connecting two 19 × 13 × 10 cm Fluon-lined plastic boxes (Pioneer Plastics, Dixon, KY) with paper bridges (10 × 50 cm strips of cardstock, with the ends taped to the bottom of each box). Soil containing red imported fire ants was placed in one box and nest cells, food, and water in the other, without soil. As soil dried, workers moved the entire colony into the nest cells. For both species, nest cells containing ants were transferred to clean 31 × 23 × 10 cm Fluon-lined plastic boxes (Pioneer Plastics, Dixon, KY) and colonies maintained at room temperature (23°-26°C) on a diet of water, 25% sugar water, and crickets.

Test chemicals. Pure essential oils of six plant species were evaluated for deterrency and toxicity to Argentine ants and red imported fire ants: sweet basil, *Ocimum basilicum* L. (Wyndmere Naturals, Inc. Minneapolis, MN); citronella, *Cymbopogon nardus ceylon* (L.) (Now Foods, Bloomingdale, IL); eucalyptus, *Eucalyptus globulous* Labillardiere (Now Foods, Bloomingdale, IL); lemon, *Citrus limon* L. (Wyndmere

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Naturals, Inc. Minneapolis, MN); peppermint, *Mentha piperita* L. (Now Foods, Bloomingdale, IL); and tea tree, *Melaleuca alternifolia* (Maiden and Betche) Cheel (Now Foods, Bloomingdale, IL).

Deterrency tests. Tests were conducted to determine whether ants would cross essential oil barriers to reach a food source. Choice tests were conducted in a 3-chambered apparatus consisting of 19 × 13 × 10 cm Fluon-lined plastic boxes arranged linearly, with each of the end boxes connected to the center box by a paper bridge. Bridges were constructed from 38 × 5 cm strips cut from legal sized manila file folders. Before installing bridges in the boxes, the center 10 × 5 cm section of each was treated by pipetting the test solution onto the paper, then allowing it to air dry for 1 h. The bridge to one box was treated with one of the essential oils dissolved in hexane (1 ml total volume) and the bridge to the other box with 1 ml hexane. Trials for each of the essential oils were conducted on different dates. Therefore, a separate group of controls was run for each of the essential oils. Six treatments were tested for each trial: four rates of the essential oil (1, 20, 100, or 500 µL; 0.02, 0.4, 2, or 10 µL essential oil/cm^2), a negative control (hexane), and a positive control (0.6 ml 1.5% cinnamaldehyde (Cinnamite™; Mycotech Corporation, Butte, MT); final rate = 9 µL cinnamaldehyde/cm^2).

Ants were starved for 2 d with access to only water, then 100 ants were placed in the center box (nest chamber). The boxes on either side (feeding chambers) contained a nest cell, a sugar water-soaked cotton ball, and a water-soaked cotton ball. To prevent a moisture differential that might influence ant movement, all nest cells were prepared by oven drying for 24 h at 50°C, cooling at room temperature and humidity for 2 h, then adding 6 ml water. The numbers of live and dead ants in each of the 3 chambers were recorded after 24 h. Tests were replicated 10 times for each treatment and species.

Toxicity tests. Continuous exposure toxicity tests were conducted in Petri dishes containing filter paper treated at a rate of 0.4 µL essential oil/cm^2. Disposable Petri dishes (100 × 25 mm) were prepared by coating the inside walls with Fluon to prevent ant escape and force the ants to remain on the treated paper. For each replicate, 25 µL of one of the essential oils dissolved in 1 ml hexane was pipetted onto a filter paper circle (90 mm diam, Whatman #1), the paper was dried under a fume hood for 1 h, and placed in the bottom of a Petri dish. Control filter papers were treated with 1 ml hexane. In each of 10 replicates per species, 10 ants were placed on top of the treated filter paper. Dishes were left uncovered to allow assessment of mortality due to contact toxicity, as opposed to fumigation. To prevent desiccation, while forcing ants to remain on the treated filter paper, water was provided in a plastic cap, cut from the top of a 0.5 ml microcentrifuge tube and placed on top of the filter paper. Mortality was assessed every 15 min for 2 h, then a final time after 24 h.

Statistical analysis. For the deterrency assays, paired *t*-tests were performed to compare the total number of ants (dead + alive) in treated and control sides of choice tests and to compare mortality on each side. Because ants occasionally escaped from Petri dishes in continuous exposure toxicity tests, total ant numbers used for mortality calculations were determined by adding the total number dead in each dish to the number alive after 24 h. Mortalities were analyzed by probit analysis (PROC PROBIT, SAS Institute 1985) and the LT_{50} in each treatment was estimated. Non–overlapping 95% confidence intervals were used to determine significant differences among treatments.

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Table 1. Number (mean ± SE) of Argentine ants on treated and control sides of barrier choice tests after 24 h. Each replicate contained a total of 100 ants. Numbers do not total 100 because some ants did not cross either bridge. Data were compared using paired t-tests

Treatment	Rate (µl)	*n*	# treated side	# control side	T	*P*
Basil	0	10	43.2 ± 8.0	53.4 ± 8.6	–0.618	0.5522
	1	10	44.8 ± 9.6	48.9 ± 9.9	–0.211	0.8375
	20	10	26.1 ± 8.4	71.1 ± 9.0	–2.600	0.0288
	100	10	17.0 ± 3.6	81.6 ± 3.6	–9.405	<0.0001
	500	10	8.1 ± 2.2	88.2 ± 3.4	–15.483	<0.001
	Cinnamite	10	9.5 ± 2.5	84.6 ± 2.7	–15.044	<0.0001
Citronella	0	10	48.6 ± 13.1	50.2 ± 12.4	–0.063	0.9512
	1	10	31.3 ± 9.0	60.0 ± 9.1	–1.584	0.1477
	20	10	24 ± 10.3	74.6 ± 10.9	–2.396	0.0402
	100	10	5.1 ± 2.6	95.4 ± 4.3	–13.521	<0.0001
	500	10	1.4 ± 0.7	99.3 ± 2.4	–34.214	<0.0001
	Cinnamite	10	4.1 ± 1.1	95.3 ± 2.4	–27.959	<0.0001
Eucalyptus	0	10	55.1 ± 9.1	47.3 ± 9.4	0.426	0.6804
	1	10	43.8 ± 5.7	43.6 ± 5.3	0.019	0.9854
	20	10	34.5 ± 10.3	63.4 ± 9.8	–1.445	0.1825
	100	10	59.8 ± 10.5	42.8 ± 10.9	0.798	0.4453
	500	10	37.1 ± 10.4	59.5 ± 10.4	–1.076	0.3100
	Cinnamite	10	10.2 ± 1.8	93.1 ± 1.0	–41.058	<0.0001
Lemon	0	10	51.8 ± 7.6	44.6 ± 7.4	0.481	0.6421
	1	10	39.4 ± 7.9	49.6 ± 8.3	–0.635	0.5411
	20	10	13.1 ± 6.5	77.9 ± 8.1	–4.448	0.0016
	100	10	7.9 ± 0.9	85.4 ± 1.3	–39.728	<0.0001
	500	10	8.3 ± 0.07	84.1 ± 1.8	–31.366	<0.0001
	Cinnamite	10	7.0 ± 0.6	88.9 ± 0.8	–64.456	<0.0001
Peppermint	0	10	42.4 ± 8.9	52.9 ± 9.1	–0.585	0.5731
	1	10	34.3 ± 6.2	53.4 ± 6.4	–1.528	0.1608
	20	10	25.5 ± 3.8	67.1 ± 3.7	–5.645	0.0003
	100	10	11.7 ± 3.6	82.5 ± 2.9	–10.931	<0.0001
	500	10	8.5 ± 2.1	86.5 ± 2.2	–18.699	<0.0001
	Cinnamite	10	7.8 ± 1.0	86.5 ± 2.2	–33.794	<0.0001

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Table 1. Continued.

Treatment	Rate (µl)	*n*	# treated side	# control side	T	*P*
Tea tree	0	10	40.8 ± 8.4	58.0 ± 8.4	−1.027	0.3310
	1	10	48 ± 10.8	43.6 ± 10.4	0.208	0.8400
	20	10	20.5 ± 8.3	75.2 ± 8.1	−3.364	0.0083
	100	10	14.0 ± 6.9	80.9 ± 7.4	−4.768	0.0010
	500	10	5.3 ± 1.0	90.8 ± 1.5	−34.954	<0.0001
	Cinnamite	10	7.6 ± 1.0	90.2 ± 1.9	−33.102	<0.0001

Results and Discussion

Tables 1 and 2 summarize the results of the deterrency tests. Both Argentine ants and red imported fire ants crossed barriers treated with multiple rates of basil, citronella, lemon, peppermint, or tea tree oil less frequently than paired control barriers. Eucalyptus oil did not prevent movement of either species at any of the rates tested. Significant differences between the numbers of ants in the two chambers never occurred for the negative control (0 µL treatment) and always occurred for the deterrent control (Cinnamite).

Essential oils exhibited little or no contact toxicity to either species following limited exposure from crossing treated bridges. With each essential oil treatment, the average number of ants that died after crossing a treated bridge was ≤2.6 Argentine ants and ≤4.5 red imported fire ants. As a percentage of the ants that had crossed the treated bridges, mortality rates were ≤17.8% for Argentine ants and ≤24.3% for fire ants. Mortality levels were significantly higher on treated sides than the paired control sides for Argentine ants in the 100 and 500 µL lemon treatments and for red imported fire ants in the 100 and 500 µL basil and lemon treatments (Table 3). While significant, mortality rates at these concentrations do not translate to any appreciable level of control under field conditions. The fact that mortality rates are low confirms that deterrency, not mortality, is responsible for the low numbers of ants crossing treated bridges. We have previously found that this assay evaluates a chemical's efficacy as a barrier by combining deterrency and recruitment effects (unpubl. data). We found that fewer ants crossed bridges treated with bifenthrin than the paired control bridges. Because we observed mortality levels of 80% among Argentine ants and 94% among fire ants crossing bifenthrin-treated bridges, we attributed at least part of the barrier effect to a lack of recruitment. In the current assays, low mortality after crossing treated bridges indicate that differences between sides are due to deterrency, not toxicity.

Toxicity tests were conducted at a single rate of 25 µL per filter paper, the equivalent volume per area of the 20 µL treatment in the deterrency choice test. This rate was selected because, in general, it was the lowest effective rate in the deterrency tests. In continuous exposure assays citronella oil required 34.3 min to kill 50% of Argentine ants and was the only treatment to cause 100% Argentine ant mortality after 24 h (Table 4). Argentine ant mortality after 24 h was 89.8% with peppermint oil

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Table 2. Number (mean ± SE) of red imported fire ants on treated and control sides of barrier choice tests after 24 h. Each replicate contained a total of 100 ants. Numbers do not total 100 because some ants did not cross either bridge. Data were compared using paired t-tests

Treatment	Rate (µl)	*n*	# treated side	# control side	T	*P*
Basil	0	10	38.5 ± 9.6	49.5 ± 10.1	−0.604	0.5607
	1	10	36.8 ± 4.8	50.1 ± 5.9	−1.268	0.2367
	20	10	33.1 ± 4.9	66.1 ± 4.9	−3.370	0.0083
	100	10	18.1 ± 1.0	79.2 ± 2.3	−23.490	<0.0001
	500	10	7.0 ± 1.0	81.5 ± 3.6	−23.195	<0.0001
	Cinnamite	10	5.6 ± 0.9	87.3 ± 4.1	−23.716	<0.0001
Citronella	0	10	49.2 ± 8.9	53.8 ± 9.3	−0.256	0.8041
	1	10	28.6 ± 5.0	55.9 ± 4.9	−2.823	0.0200
	20	10	39.4 ± 5.7	63.1 ± 7.3	−1.911	0.0883
	100	10	28.1 ± 6.8	72.6 ± 7.0	−3.270	0.0097
	500	10	14.0 ± 2.8	78.6 ± 5.5	−10.146	<0.0001
	Cinnamite	10	18.5 ± 2.5	88.0 ± 2.3	−16.481	<0.0001
Eucalyptus	0	10	49.7 ± 7.3	43.8 ± 7.4	0.402	0.6969
	1	10	40.2 ± 6.8	47.5 ± 5.5	−0.597	0.5655
	20	10	53.4 ± 9.0	46.4 ± 8.9	0.403	0.6963
	100	10	52.0 ± 8.9	47.1 ± 9.5	0.269	0.7939
	500	10	48.1 ± 9.9	50.7 ± 11.2	−0.124	0.9042
	Cinnamite	10	8.9 ± 1.9	89.6 ± 2.4	−26.289	<0.0001
Lemon	0	10	48.6 ± 6.5	41.3 ± 6.5	0.562	0.5877
	1	10	36.9 ± 7.6	47.9 ± 7.5	−0.729	0.4845
	20	10	39.9 ± 7.0	54.4 ± 6.5	−1.077	0.3095
	100	10	30.2 ± 2.8	59.6 ± 2.7	−5.932	0.0002
	500	10	14.1 ± 1.3	77.6 ± 1.6	−26.128	<0.0001
	Cinnamite	10	8.1 ± 0.5	88.0 ± 1.3	−65.262	<0.0001
Peppermint	0	10	47.3 ± 8.4	42.5 ± 8.5	0.286	0.7814
	1	10	29.1 ± 6.5	62.7 ± 5.3	−2.909	0.0173
	20	10	33.7 ± 6.6	61.1 ± 6.4	−2.199	0.0555
	100	10	7.6 ± 1.5	87.0 ± 1.6	−34.225	<0.001
	500	10	6.8 ± 1.7	87.1 ± 2.4	−21.512	<0.0001
	Cinnamite	10	10.3 ± 1.4	85.9 ± 2.3	−21.840	<0.0001

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Table 2. Continued.

Treatment	Rate (µl)	*n*	# treated side	# control side	T	*P*
Tea tree	0	10	44.1 ± 6.5	50.4 ± 6.3	−0.497	0.6312
	1	10	42.8 ± 8.4	40.8 ± 8.0	0.123	0.9050
	20	10	30.2 ± 7.2	61.3 ± 7.3	−2.143	0.0607
	100	10	10.9 ± 1.1	79.3 ± 1.4	−32.592	<0.0001
	500	10	10.5 ± 1.8	80.9 ± 2.2	−18.366	<0.0001
	Cinnamite	10	8.6 ± 0.6	84.5 ± 0.8	−69.000	<0.0001

Table 3. Deterrency choice tests having significantly higher mortality on treated side than control side. Data were compared using paired t-tests ($\alpha = 0.05$)

Ant species	Oil	Rate (µl)	Treated mortality (mean ± SE)	Control mortality (mean ± SE)	T	*P*
L. humile	Lemon	100	17.5 ± 2.8	4.3 ± 0.6	4.557	0.0014
		500	17.8 ± 3.8	5.4 ± 1.0	2.885	0.0180
S. invicta	Basil	100	10.6 ± 1.5	4.4 ± 0.6	3.753	0.0045
		500	24.3 ± 9.0	4.9 ± 0.8	2.300	0.0470
	Lemon	100	6.4 ± 2.3	4.2 ± 1.4	2.443	0.0372
		500	13.5 ± 7.4	3.1 ± 1.3	4.970	0.0008

and 85.7% with tea tree oil, with the remaining treatments having mortality not significantly different from the control. After 24 h of continuous exposure, red imported fire ant mortality was 50.6% with citronella oil, the only treatment in which mortality was significantly greater than the control.

With the exception of peppermint oil, this is the first report of effects of each of these essential oils against ants. Appel et al. (2004) found that mint oil granules (Earth Care Naturals, Insect Killer Granules, Spectrum Group, St. Louis, MO) were both toxic and repellent to red imported fire ants. While the mint species used in this formulation was not specified, active components are likely the same as those in the peppermint oil we tested. Phytochemicals in *Mentha* spp. that have insecticidal and repellent activity against insects include limolene, menthone, and menthol (USDA 2005). Deterrent or toxic effects of mint oils or monoterpenoids found in mint oils also have been reported for the American cockroach, *Periplaneta americana* (L.); German cockroach, *Blattella germanica* (L.) (Appel et al. 2001); human head louse, *Pediculus humanus capitis* De Geer (Yang et al. 2004); housefly, *Musca domestica* (L.); red flour beetle, *Tribolium castaneum* (Herbst); and southern corn rootworm, *Diabrotica undecimpunctata howardi* Barber (Rice and Coats 1994). Mint was ineffective in field

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Table 4. Probit analysis and 24 h mortality of Argentine ants and red imported fire ants continuously exposed to filter paper treated with 25 µl essential oil

Species	Treatment	n[a]	24 h mortality	$(\chi^2)^b$	Slope ± SE	LT_{50} (min)	95% CI[c]
Argentine ants	Basil	98	10.0 ± 2.6	94.1	0.02 ± 0.01	>1d	—
	Citronella	99	100.0 ± 0.0	74.7	5.2 ± 0.3	34.3	31.8-36.8
	Eucalyptus	97	9.1 ± 3.2	145.2*	0.03 ± 0.02	>1d	—
	Lemon	98	11.2 ± 2.8	117.9*	0.03 ± 0.01	>1d	—
	Peppermint	99	89.8 ± 3.4	140.5*	0.17 ± 0.02	660.9	62.6-792.7
	Tea tree	98	85.7 ± 2.8	80.7	0.17 ± 0.01	799.4	708.8-912.4
	Control	98	6.1 ± 2.2	83.8	0.02 ± 0.02	>1d	—
Fire ants	Basil	97	6.2 ± 1.7	81.5	0.06 ± 0.02	>1d	—
	Citronella	96	50.6 ± 6.3	166.9*	0.15 ± 0.01	1405.5	1215.1-1670.3
	Eucalyptus	97	2.0 ± 1.3	7.9	0.41 ± 2753	>1d	—
	Lemon	98	3.0 ± 2.1	13.8	0.42 ± 2243	>1d	—
	Peppermint	97	1.0 ± 1.0	8.8	0.39 ± 3699	>1d	—
	Tea tree	99	3.3 ± 3.3	164.6*	0.03 ± 0.02	>1d	—
	Control	98	1.0 ± 1.0	8.9	0.39 ± 3680	>1d	—

[a] Number of ants used in the probit analysis.
[b] Pearson's chi-square-goodness-of-fit test (SAS Institute 1985). Excessively large χ^2 values ($P < 0.100$) have failed this test and are indicated by an asterisk (*). A t-value of >1.96 was used to compute the fiducial limits.
[c] Treatments with overlapping 95% CI are not significantly different. Confidence intervals could not be calculated for treatments with insufficient 24 h mortality.

trials against the Japanese beetle, *Popillia japonica* Newman (Held et al. 2003), and the mosquito *Anopheles gambiae* Giles (Barasa et al. 2002). Citronella was the only oil that we found to be repellent and toxic to both the Argentine ant and fire ant. Although citronella is best known as a mosquito repellent, Lindsay et al. (1996) reported that citronella candles and incense were ineffective at reducing the biting pressure of mosquitoes (primarily *Aedes* spp. at the study site). Another citronella-based repellent, Pyranha, had no effect on Africanized honey bee, *Apis mellifera* L., attack behavior when delivered in a stream of air directed toward the colony entrance (Schmidt et al. 2003). Tea tree oil, the third substance that we found to be both deterrent and toxic, is toxic to both the whitefly *Trialeurodes vaporiorum* Westwood (Choi et al. 2003) and the human head louse (Yang et al. 2004). Basil essential oil, which was deterrent but did not have residual toxicity to fire ants or Argentine ants, is toxic to the two spotted spider mite *Tetranychus urticae* Koch, the whitefly *Bemisia tabaci* Genn. (Aslan et al. 2004), and the human head louse (Yang et al. 2004) and both toxic and somewhat repellent to bean weevils, *Acanthoscelides obtectus* (Say) (Papachristos and Stamopoulos 2002). Lemon oil, which we also found to be deterrent but not toxic, has not been widely tested against other species, but when delivered as a fumigant was not toxic to *T. vaporiorum*, *T. urticae*, or the predatory mite

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Phytoseiulus persimilis (Choi et al. 2003, 2004). Eucalyptus oil was the only essential oil we tested that did not exhibit repellent or toxic effects against *S. invicta* or *L. humile*. Likewise, Zhu et al. (2001) found that it was not active against the Formosan subterranean termite, *Coptotermes formosanus* Shiraki. However, activity has been demonstrated against several other species, including the human head louse (Yang et al. 2004), bean weevil (Papachristos and Stamopoulos 2002, 2004), maize weevil, *Sitophilus zeamais* Motschulsky, and the confused flour beetle, *Tribolium confusum* du Val (Tapondjoua et al. 2005).

In some situations, the use of deterrent or toxic natural products may be more desirable than contact insecticides or baits or may be used in conjunction with these methods to provide additional protection. Based on the results of this study, basil, citronella, lemon, peppermint, and tea tree oils offer promise as potential deterrent barriers. In addition, in continuous exposure tests, citronella oil was toxic to both Argentine ants and fire ants, and peppermint and tea tree oils demonstrated mild toxicity to Argentine ants. Additional testing is needed to determine dose responses for oils that demonstrated toxic effects.

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