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Pheromone Disruption of Argentine Ant Trail Integrity

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Abstract Disruption of Argentine ant trail following and reduced ability to forage (measured by bait location success) was achieved after presentation of an oversupply of trail pheromone, (*Z*)-9-hexadecenal. Experiments tested single pheromone point sources and dispersion of a formulation in small field plots. Ant walking behavior was recorded and digitized by using video tracking, before and after presentation of trail pheromone. Ants showed changes in three parameters within seconds of treatment: (1) Ants on trails normally showed a unimodal frequency distribution of walking track angles, but this pattern disappeared after presentation of the trail pheromone; (2) ants showed initial high trail integrity on a range of untreated substrates from painted walls to wooden or concrete floors, but this was significantly reduced following presentation of a point source of pheromone; (3) the number of ants in the pheromone-treated area increased over time, as recruitment apparently exceeded departures. To test trail disruption in small outdoor plots, the trail pheromone was formulated with carnuba wax-coated quartz laboratory sand (1 g quartz sand/0.2 g wax/1 mg pheromone). The pheromone formulation, with a half-life of 30 h, was applied by rotary spreader at four rates (0, 2.5, 7.5, and 25 mg pheromone/m^2) to 1- and 4-m^2 plots in Volcanoes National Park, Hawaii. Ant counts at bait cards in treated plots were significantly reduced compared to controls on the day of treatment, and there was a significant reduction in ant foraging for 2 days. These results show that trail pheromone disruption of Argentine ants is possible, but a much more durable formulation is needed before nest-level impacts can be expected.

Keywords Argentine ant · Trail pheromone · Disruption · Track angle · Trail integrity · Invasive species

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Introduction

The Argentine ant, *Linepithema humile* (Mayr) is a highly invasive species worldwide and has a diverse array of negative impacts (Holway et al. 2002). It displaces native ants (Human and Gordon 1997; Suarez et al. 1998; Holway 1999), reduces abundance of non-ant arthropods (Cole et al. 1992; Human and Gordon 1997; Liebherr and Krushelnycky 2007), and may even compete with vertebrates for food resources (Suarez and Case 2002; Lach 2005). Furthermore, in human-modified landscapes, they may reduce the effectiveness of biocontrol agents in orchards (Moreno et al. 1987; Itioka and Inoue 1996) and are a nuisance in urban environments (Vega and Rust 2001).

A variety of poison baits have been tested to control Argentine ants, but no single baiting system has proven entirely reliable (e.g., Krushelnycky and Reimer 1998; Hooper-Bui and Rust 2000; Klotz et al. 2000; Greenberg et al. 2006), and many containerized baits are not practical for landscape scale applications. Poison baits also may carry non-target risks to pets and wildlife. In natural areas, particularly those sensitive to perturbation or of high ecological value, impacts on native invertebrates can be considerable (Balança and de Visscher 1997; Zhakharov and Thompson 1998). Thus, effective and environmentally benign control tactics are needed for management and control of these invasive ants.

Wright (1964) proposed that if sufficient synthetic sex pheromone were distributed in the air, the normal pheromone communication systems of certain species would be disrupted, and the sexes might be incapable of locating each other. The feasibility of the disruption approach by using pheromones was demonstrated for the cabbage looper (Gaston et al. 1967), and "mating disruption" is now an effective direct control option against certain pests (Suckling and Karg 2000; El-Sayed 2008).

The development of more environmentally benign treatments based on semiochemicals could be used for managing invasive ants in sensitive natural ecosystems. Despite the discovery and characterization of a variety of ant pheromones, relatively little work has been undertaken using them for management (Robinson and Cherrett 1978; Shorey et al. 1992).

The Argentine ant uses (*Z*)-9-hexadecenal (Cavill et al. 1979) as its trail pheromone to orient and communicate the location of food, and it is probably critical to successful mass recruitment to ephemeral food resources. Van Vorhis Key et al. (1981) and Van Vorhis Key and Baker (1982a, b, c) studied this system and recognized that it might be possible, without elaborating how, to modify trail-following behavior with synthetic compounds. Shorey et al. (1992) tested other volatile compounds as barrier treatments for disruption of Argentine ant trails, but these were not very effective.

The recent demonstration of partial disruption of Argentine ant trails by using polyethylene tubing dispensers that release (*Z*)-9-hexadecenal in orchards (Tatsuki et al. 2005) raises the possibility of development of a new control tactic against this species in different environments, including sensitive ecosystems, by using formulations that could be applied at landscape level. Trail disruption could have a potential as a stand-alone pest management tactic or in combination with others.

In this study, we first examined close-range disruption of trail-following behaviors on different substrates when a single point source was placed near a trail. Second, we carried out small plot field tests to examine foraging at bait cards in areas by using a widely dispersed point source strategy. In both cases, the pheromone was placed within the boundary layer of the foraging ants, which was not the case in the study by Tatsuki et al. (2005).

Methods and Materials

Chemicals The Argentine ant trail pheromone (*Z*)-9-hexadecenal (94% purity; Bedoukian Research, Danbury, CT, USA) was loaded in micronized carnuba wax (Eggar & Co. Ltd. (Reading, UK), as plant wax is an effective carrier for pheromones (Karg et al. 1994). In single point source tests at close range, the pheromone source was prepared either as (a) 0.1 g pheromone in hexane (10% by vol.) steeped in 1 g of carnuba wax in a closed 1-ml glass screw cap vial at room temperature for 2 h, and then the solvent was evaporated off, or (b) by coating particles of white quartz sand (−50 + 70 mesh, Sigma Aldrich, Saint Louis, MO, USA) with melted wax (20% wax by weight) in a rotary evaporator, and then adding pheromone to give a mixture consisting of 1 g quartz sand/200 mg wax/1 mg pheromone.

Disrupting Trail Following from a Point Source Ant density and trail walking behaviors, before and after treatment, were used to characterize disruption from a single point source on a range of vertical and horizontal substrates in and around a wooden office building located at ca 1,200 m altitude in Hawaii Volcanoes National Park, Hawaii. A Logitech webcam (640×480 pixels, Notebook Pro, Logitech, Freemont, CA, USA) recorded avi files at rate of 15 frames/s onto a laptop computer (actual screen size 10×12 cm at 480×640 pixels). A plastic ruler was used for frame calibration before treatment. All experimental data were collected between 10 A.M. and 3 P.M.

Video Recording and Statistical Analysis The position of ants in the frame, number of ants per frame, and walking track angle were measured in the first trial, but only the position of ants was analyzed for the subsequent three experiments. The position and movement of individual ants was analyzed with MaxTraq v1.92 trial edition (Innovision Systems, Lapeer, MI, USA). The *x*–*y* positions of the ants were either recorded continuously (15 frames/s) or from individual frames at 5-s intervals, as this was sufficient time for the ants to leave the video frame under control conditions, thus rendering the samples independent. Walking angles of individual ants were analyzed from sequential frames and were calculated as: $\theta\,^\circ = \text{Arctan}\,\Delta X/\Delta Y \times 180/\pi$, where $\theta\,^\circ$ is the walking angle, and ΔX and ΔY are the distance traveled between two consecutive frames on the *X*–*Y* axes, respectively. Values generated when an ant apparently did not move in two consecutive frames were discarded, as these rare cases would be erroneous. Regression statistics for trail integrity (r^2) were calculated from the position of digitized ants, before and after treatment. A *t* test was used to determine the significance of trail integrity in each of the tests, following Shapiro and Wilk tests for normality (Zar 1984). For experiment 1, the number of ants present in the video frame on the wall before and after the vial was introduced was analyzed by regression of count over time over 40 min. Sampling of the avi file at 5-s intervals was undertaken at the beginning and end of the time series to improve precision. The walking track angles of individual ants walking on a painted internal wall at high traffic density were compiled into histograms, and the track angle distributions were compared by two-sample *F* test for variance for before and after exposure to the pheromone.

Test 1.1 Ants (between 20 and 40 per frame) on a vertical interior wall were recorded as in a continuous stream, diagonally across the frame for 2 min at 300 and 120 s before the experiment, and confirmed that the foraging trail was linear. Activity was recorded continuously for 60 s before the glass vial with pheromone was opened within the camera view (2 cm to the right of the lower left corner) and after a 20-s behavior was recorded for another 60 s. Recordings were made continuously over the next 30 min, at which time the vial was removed and activity was recorded for an additional 7 min. The same experimental procedure was carried out on a painted outdoor wall (*Test 1:2*) at low to moderate density (range one to 13 ants per frame), but in this case, the ant positions were digitized for 100 s following treatment.

Test 1.3 and 1.4 Ant walking tracks, on an interior wooden floor (five to 30 ants per frame) or on an outdoor concrete step covered by a roof eave (four to 13 ants per frame), were recorded as above, before and after a 10-mg sample of carnuba wax containing 1 mg trail pheromone was placed in the view, ca. 4 cm from the trail. Ants were recorded, and positions were digitized for up to 340 s post-treatment.

Experiment 2.1: Small Plot Disruption (1 m^2) Semi-field plots (>3 m between plots) were established under the eaves of the office building (to avoid rainfall). There were four treatments (a sand alone control or 2.5, 7.5, and 25 mg of pheromone), and in each case, the ant sand was mixed with local Kilauea cinder soil to give a final amount of 50 g that was applied to each 1 m^2 plot by using a hand-held rotary spreader (Handy Green II, Scott's, Mayville, OH, USA).

A plastic-coated 3×5 cm card was baited with a small dab of 1:1 macerated tuna (chunky light tuna in water, Bumblebee Foods, San Diego, CA, USA) and Karo light corn syrup (ACH Food Companies, Memphis TN, USA) and placed in the center of a white sheet of paper taped to a firm backing in the center of each plot for 1 h before treatment. The number of ants at the bait card and the presence of the trails (a 1-min visual assessment) were recorded pre-treatment and then at 1, 2, 3, 24, 48, 72, 120, 144, and 196 h after treatment. Baits were covered each night with inverted plastic bins to protect them against vermins. The experiment was replicated three times, and fresh baits were used for each assessment in each replicate. Video files (15 frames/s) were also recorded in the sand control and the high rate (25 mg/m^2) plots, 24 h post-treatment, so that walking track angles could be calculated as with the single point experiment above.

Experiment 2.2: Trail Disruption Impacts on Ant Foraging Twenty-four plots (4 m^2), at least 10 m apart, were established in the Broomsedge Burn (19°25′59.6″ N, 155° 17′35.2″ W) of Hawaii Volcanoes National Park (1,200 m elevation), an area with few trees but dominated by clumps (1–3/m^2) of about 1-m-high broomsedge bluestem (*Andropogon virginicus*). Thus, the study site was exposed to prevailing trade winds, making it a challenging natural ecosystem to test rigorously the concept of trail disruption.

Sand samples were mixed with Kilauea cinder soil to give 200 g lots of soil containing 0, 10, 30, and 100 mg of pheromone, and at the start, each of the six replicates were applied to the plots by using a hand-held rotary spreader. Bait cards were placed directly on the ground at the center of each plot and protected from the direct rays of the sun by inverted plastic plates (25 cm diam.) suspended 15 cm above ground level. New baits were used for each observation period, except between the pre-treatment and first post-treatment ones.

Measurements of ant density at the bait card and visual assessment of the presence/absence of visible trails ants in 1-m^2 core of each plot were carried out just before treatment and then 1, 2, 3, 24, and 48 h after treatment. Wind speeds at ground level (2 cm), as well as at 1 and 2 m height, and shaded ground temperature were recorded at the time of application and toward the end of the observation period each day (2–3 P.M.).

In both field trials, analyses of variance were conducted on log-transformed counts of ants for each time interval, with Tukey tests to separate treatment effects.

Pheromone Release Rate Ant sand was aged in a laboratory fume hood (ca. 20°C) with an airflow (0.5 m/s) at Lincoln, New Zealand so that pheromone release rates could be estimated. The pheromones in three subsamples were extracted by adding 1,800 µl ethanol with 200 µl of 1 mg/ml decanal as the internal standard, vortexed, sonicated at 25°C for 30 min, centrifuged at 3,000 rpm for 10 min, and then filtered through 0.45-µm PTFE filter. Samples were analyzed by gas chromatography with a GC-

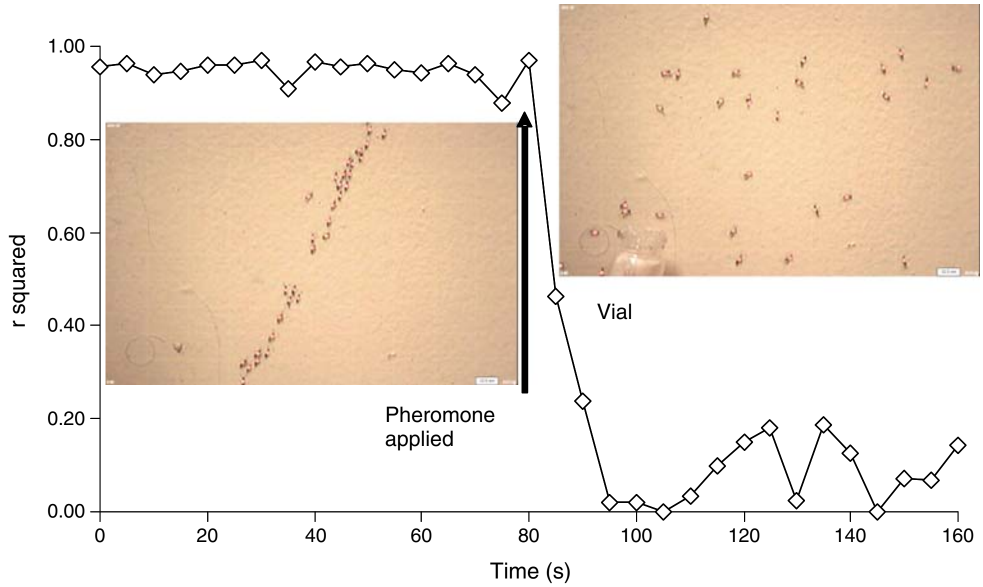

Fig. 1 Disruption of trail integrity (r^2) of high-density foraging trails of Argentine ant after the introduction of a vial at 80 s, containing a slow release formulation of carnuba wax with 100 mg of the trail pheromone, (*Z*)-9-hexedecenal. Ants are shown with *numbered dots*, before and after treatment

FID BPX-70 polar column, splitless, injector 220°C, flow 1 ml/min He, with a temperature program of 80°C for 1 min then ramped up to 220°C at 5°C/min and held for 1 min (total 30 min). The entire procedure was repeated twice.

Results

Disrupting Trail Following from a Point Source Ant trails at high traffic density on the wall (between 20 and 40 ants in the field of view) were <1 cm wide and linear. Upon introduction of the synthetic trail pheromone, the integrity of the trail was disrupted completely within seconds (Fig. 1; Test 1.1, Table 1; supplementary material, video A), as evidenced by an immediate drop in the value of the r^2 statistic. Trail-following behavior was disrupted for 30 min that the vial was present and for at least 7 min after its removal. Inspection the next day showed some evidence of disruption, although this was not quantified, possibly due to absorption of pheromone in the wall paint.

The number of ants increased significantly over time at the site (Fig. 2), probably due to ants arriving for both the food source and the nest but unable to leave by using the normal trail because of the pheromone treatment.

Ants initially showed a unimodal distribution of walking angles (with a SE 7.18 from 560 observations), but after presentation of the trail pheromone, there was no clear peak (an SE of 2.94 from 340 observations; Fig. 3; $F_{18,18}$=5.94, P<0.001).

Experiment 2.1: Small Plot Disruption (1 m²) There was no difference in bait card visitation between bait cards before treatment and after 1 h in the sand control ($F_{3,8}$=0.34, P= 0.798), but there was a significant decline in visitation in all pheromone-treated plots (Fig. 4). There was an overall difference in the number of foraging workers at bait cards between pheromone and control over 24 h (1 h, $F_{3,8}$=4.71, P=0.035; 2 h, $F_{3,8}$=10.05, P=0.004; 3 h, $F_{3,8}$=12.62, P= 0.002; 4 h, $F_{3,8}$=13.20, P=0.002; 24 h, $F_{3,8}$=11.05, P= 0.003). The disruption effect was marginally significant

Table 1 Impact of treatment with synthetic argentine ant trail pheromone ((*Z*)-9-hexadecenal) on trail integrity (r^2), recorded at 5-s intervals before and after treatment with a single point source of pheromone, on four different substrates

Test/substrate	Pheromone quantity, formulation	Before treatment		After treatment		n1, n2[a]	*t*	*P*
		Mean trail integrity, r^2 (no. ants)[b]	SEM	Mean trail integrity, r^2 (no. ants)[b]	SEM			
Interior painted wall	100 mg, vial	0.947 (517)	0.060	0.164 (530)	0.058	16, 16	13.55	0.001
Exterior painted wall	100 mg, vial	0.945 (59)	0.019	0.135 (70)	0.044	9, 7	17.06	0.001
Interior wooden floor	1 mg, wax	0.867 (170)	0.04	0.298 (150)	0.091	12, 11	5.76	0.001
Exterior concrete floor	1 mg, wax	0.967 (85)	0.025	0.229 (147)	0.061	11, 13	12.01	0.001

[a] Number of samples of r^2 used in the *t* test before (n1) and after (n2) treatment
[b] Total number of ants digitized for position

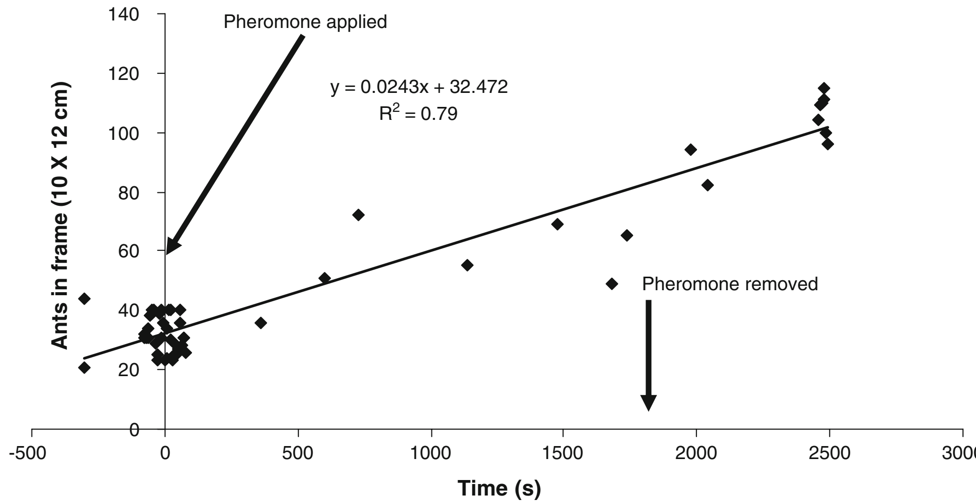

Fig. 2 Increase in the number of Argentine ants in the video frame after the introduction of a vial containing a slow release formulation of carnuba wax with 100 mg of the trail pheromone (*Z*)-9-hexedecenal

after 48 h ($F_{3,8}$=0.041) but not at any later times (Fig. 4). Tukey tests indicated significant differences (P<0.05) between the control and all pheromone treatments at 1, 2, 3, and 4 h, while at 24 h, only the 2.5- and 7.5-mg/m^2 application rates differed from the control. By 48 h, this effect had started to decline in these treatments. The absence of evident trails lasted 72 h in all three treated plots (Supplementary material, Fig. A).

Ants in the three sand controls all showed unimodal distributions of walking track angles, which was not the case in the 25 mg/m^2 pheromone treatment (Fig. 5). The difference in walking track angles between the treatment and controls was significant (P<0.05, t=4.06, df=3).

Experiment 2.2: Trail Disruption Impacts on Ant Foraging There was no difference in the number of foraging ants in the different plots before treatment ($F_{3,\ 20}$=0.53, P= 0.66). However, there was a decline in the number of visiting bait cards for 2 h (1 h, $F_{3,\ 20}$=8.61, P<0.001; 2 h, $F_{3,\ 20}$=4.63, P=0.013, Fig. 6) when comparing treated vs. control plots, but after that, there were no significant differences (3 h, $F_{3,\ 20}$=2.92, P=0.059; 24 h, $F_{3,\ 20}$=0.66, P=0.59). The significant differences observed were due to the two higher concentrations of pheromone (Tukeys tests, P<0.05). There was evidence of trail-following behaviors in control plots for the duration of each trial but none for 24 h after treatment in the pheromone ones (Supplementary material, Fig. B). There was a correlation (r^2=0.36, P< 0.05) between the methods assessing disruption of counts at bait cards and disruption of trails in this experiment.

Pheromone Release Rate The experimental wax formulation had a high first-order release rate with ca. 30% loss of the applied material in 2 days at 20°C under laboratory conditions, giving an estimated half-life of 30 h for the ant sand preparation (Supplementary material, Fig. C). Using this laboratory data, the estimated release rates for the 25 mg/m^2 treatment in the field, where temperatures averaged about 22°C, were 260 and 200 μg/h/m^2 1 and 4 h after treatment (Figs. 4 and 6).

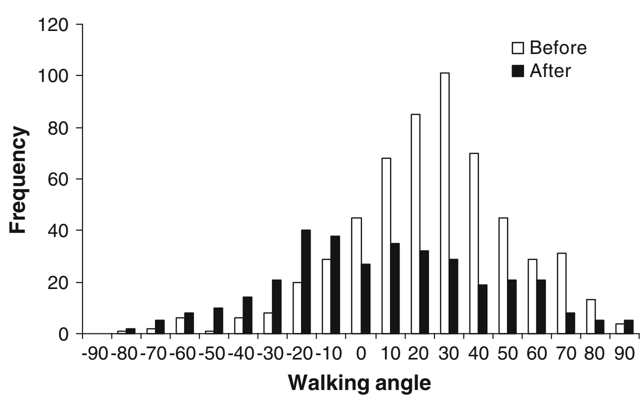

Fig. 3 Change in walking track angles of Argentine ant on a vertical kitchen wall before and after the introduction of a vial containing a slow release formulation of carnuba wax containing 100 mg of (*Z*)-9-hexedecenal

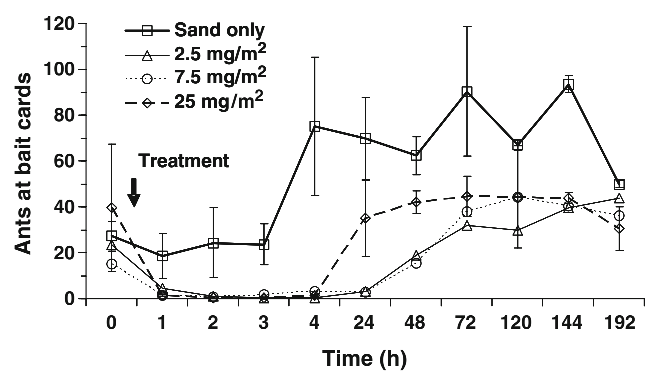

Fig. 4 Mean (±SEM) number of Argentine ants present at bait cards before and after treatment with a trail pheromone-laden wax and sand formulation at three rates in 1-m^2 plots at Hawaii Volcanoes National Park

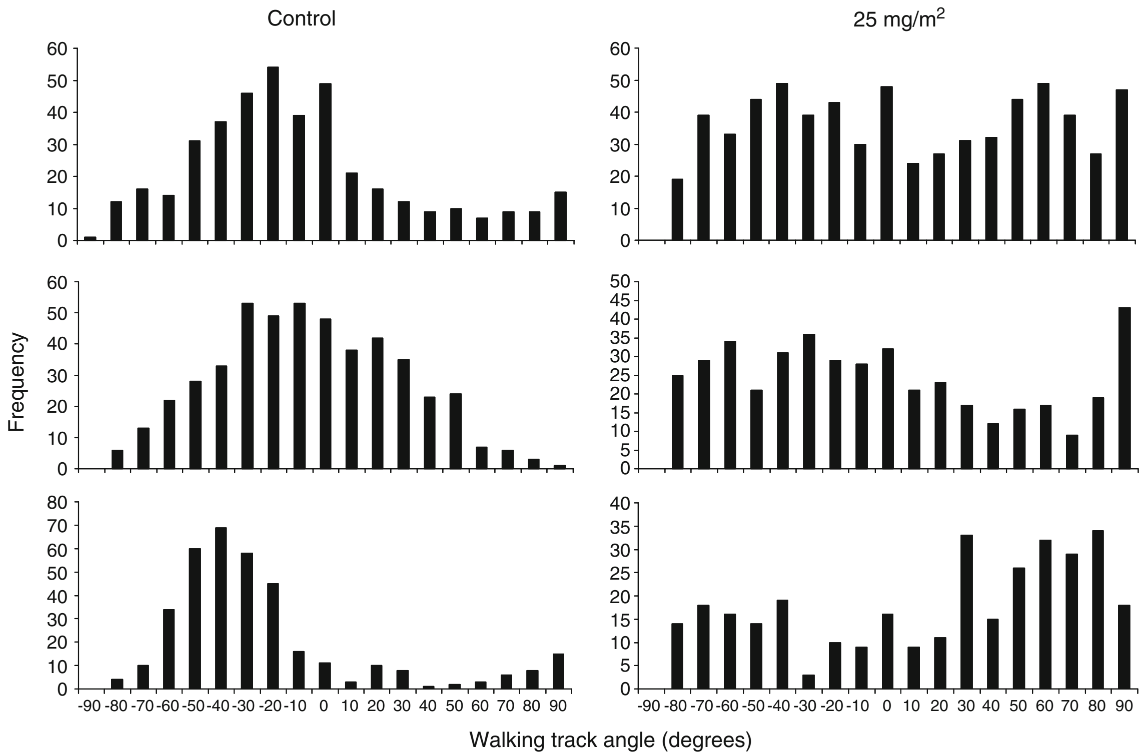

Fig. 5 Walking track angles for Argentine ants, 24 h after exposure to untreated control sand and sand laden with wax containing trail pheromone (active ingredient at 25 mg/m^2), from webcam recordings in the center of each of three replicate plots (1 m^2)

Discussion

The results of this study demonstrate the proof of concept of trail disruption against the Argentine ant indoors, as well as in small semi-field and field plots. Close-range trail orientation behaviors were significantly disrupted when the ants were exposed to an excess of their trail pheromone, resulting in a virtually instantaneous increase in turning behavior and a complete lack of orientation to the natural foraging trail. Furthermore, the deployment of a dispersible formulation, such as the ant sand used here, would have a natural advantage over a few large emission rate point sources for trail disruption (Suckling and Angerilli 1996). When applied, the material would fall within the boundary layer of the pest species, thus ensuring maximum atmospheric concentrations at the most suitable site (Suckling et al. 1999).

However, the effects observed were of quite short duration, especially in field plots where a variety of abiotic conditions (such as temperature, UV, and wind; Supplementary material, Fig. D) could markedly affect both release rates and persistence of the pheromone. Clearly, more research is required to determine the feasibility of this technique at a practical level. The fact that the highest concentration tested varied in efficacy in the field trials underlines the need to develop new formulations to provide longer and more consistent pheromone release under a range of different climatic conditions.

One also needs to find the minimum dose that would effectively disrupt trail-following behavior for an extended period of time. (*Z*)-9-Hexadecenal, being a lepidopteran sex pheromone (Nesbitt et al. 1975; Piccardi et al. 1977; Mayer and McLaughlin 1991), is more readily available than many other ant trail pheromones, but if the concentration required is too high, then trail disruption may not be economically

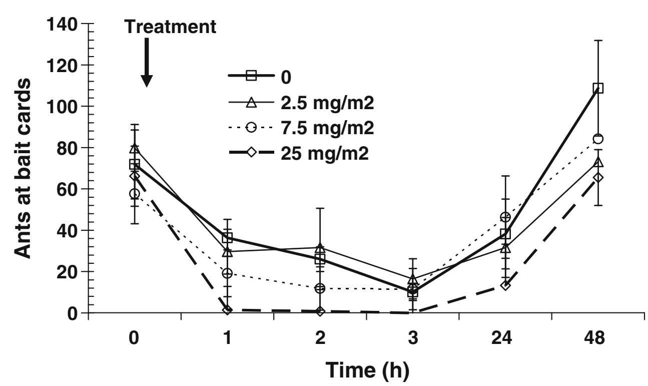

Fig. 6 Mean (±SEM) number of Argentine ants present at bait cards before and after treatment with three rates (milligrams per square meter) in 4-m^2 plots of a trail pheromone-laden wax and sand formulation at the Broomsedge Burn area of Hawaii Volcanoes National Park

viable as a stand-alone management tool, even for sensitive ecosystems. Cavill et al. (1979) reported many other compounds from the Argentine ant, and these merit investigation, as some of these minor compounds might improve both trail following and its disruption. Even if this were not the case, the integration of trail disruption with other control tactics warrants investigation.

Additional work on the trail-following behavior of the ants also is required, including further evaluation of the proposed trail integrity statistic, r^2. Van Vorhis Key and Baker (1986) reported that workers are more likely to follow trails if they meet an engorged con-specific, and they have other complex behaviors that may render trail disruption unsuccessful. For example, ants crossing an uninterrupted portion of the trail deposit more pheromone than those crossing "odor" gaps. Thus, if workers respond by increasing the concentration they release, this could reduce the duration of trail disruption.

Our results suggest that it would be worth trying a similar approach for the disruption of trail following in the Red Imported Fire Ant since they are an even more significant ecological problem in urban and sensitive environments world wide, causing billions of dollars of loss every year (Pimentel et al. 2000). Successful application of trail pheromones to tackle such pest ants may have significant environmental and social benefits.

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