Performance of the Microsprayer, with Application for Pheromone-Mediated Control of Insect Pests

RUFUS ISAACS, MICHAEL ULCZYNSKI,[1, 2] BRIAN WRIGHT,[1] LARRY J. GUT, AND JAMES R. MILLER

Department of Entomology and Center for Integrated Plant Systems, Michigan State University, East Lansing, MI 48824

J. Econ. Entomol. 92(5): 1157–1164 (1999)

ABSTRACT An electronically controlled device has been designed to provide reliable, precise, season-long release of insect pheromones without the need for maintenance, refilling, or component replacement. The operational performance of this dispenser technology was evaluated under laboratory and field conditions throughout the summer of 1998 in orchards of Michigan apple (*Malus* spp.). A simple electronic circuit controlled the opening of an automotive fuel injector connected to a pressurized canister containing pheromone solution. By controlling the duration and frequency of pheromone release and the concentration of pheromone within the canister, this device, referred to as the *Microsprayer*, dispensed a desired quantity of pheromone to achieve mating disruption. Containment of multiple pheromones within the light- and oxygen-free environment provided release of active ingredients throughout the growing season for disruption of mating by >1 pest insect species. The volume released increased linearly with canister pressure, and this increase was positively correlated with ambient temperature. The spatial pattern of primary pheromone deposition was measured, in still air the largest volume deposited was ≈80 cm from the point of release. Release from increasing heights above a target surface caused an exponential reduction in the volume of liquid reaching the surface because of solvent evaporation. In orchard trials, microsprayers powered by single 0.5 A Hr 9 V lithium batteries released pheromone every 170 s for 5 mo without appreciable voltage drop. Weight loss from the microsprayers was steady and predictable, and canister pressure remained above 50 psi for the duration of the season. This device shows promise for practical control of insect pests amenable to pheromone mating disruption.

KEY WORDS Tortricidae, fruit, integrated pest management, mating disruption, pest management, pheromone, puffer

DISRUPTION OF INTRASPECIFIC chemical communication in insects can be accomplished by controlled release of synthetic pheromone to permeate the air within a crop (Cardé and Minks 1995). Commercial application of this principle for control of crop pests has led to the development of various devices that provide a pheromone reservoir and controlled release of the contents into the crop. A common method of pheromone release relies upon evaporation from small pieces of polymer impregnated or filled with pheromone. These devices can be relatively simple to construct and apply, but a high density of devices is required per unit area (McDonough et al. 1992). Because the pheromones of some insect species are prone to oxidative and photodegradation (Millar 1995), precautions must be taken to shield labile pheromones to maintain behavioral activity throughout a full growing season. Pheromone also can be encapsulated in semipermeable polymeric membranes to produce a formulation that is applied directly onto the crop by using standard agricultural technology (Vickers and Rothschild 1991). These systems are usually characterized by 1st-order decay release rates, making long-term disruption with a single application problematic. Application from a high density of sources is conducted to uniformly permeate a crop with pheromone.

A more recently developed approach is to release the same total amount of pheromone per unit area, but from far fewer point sources, thus relying on wind movement to disperse the pheromone throughout the crop. The superlow-density approach to dispensing pheromones has been tested with devices that provide intermittent release, predetermined release rates, and a stable environment for a large reservoir of pheromone before its release. Reduction of insect pest populations and crop damage has been reported in studies of the efficacy of this approach in field crops (Shorey et al. 1996, 1994; Baker et al. 1997); tree crops (Shorey and Gerber 1996a, b; Shorey et al. 1996); stored products (Mafra-Neto and Baker 1996); and cranberry marshes (Baker et al. 1997, Fadamiro et al. 1998). The release devices have been referred to as *puffers* (Shorey et al. 1996) and *misters* (MSTRS) (Baker et al. 1997), and although these studies have demonstrated the effectiveness of this approach, the devices are

[1] Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824.
[2] Current address: Ford Motor Company, Dearborn, MI 48121.

0022-0493/99/1157–1164$02.00/0

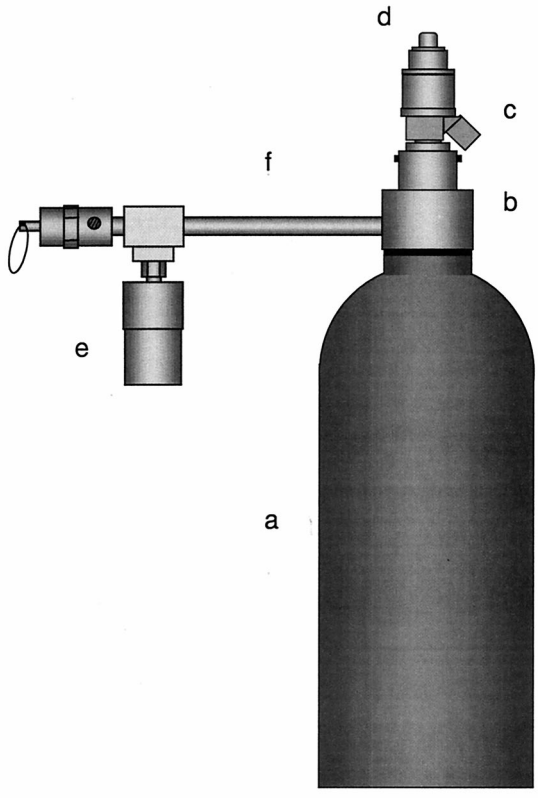

Fig. 1. Microsprayer assembly. (a) pheromone canister; (b) connection coupling; (c) solenoid power connector, (d) spray nozzle; (e) nonreturn valve coupling for attaching propellant canister; (f) safety pressure release valve. Total height = 29 cm.

modifications of pre-existing technology designed for indoor use. Hardware reliability is critical with this approach because at the low density of deployment, any failure to release pheromone has a large impact on the total release rate per unit area. This requirement may exceed the design limits of current technologies for superlow-density release of pheromone, and for commercial use the grower would expect season-long operation.

Herein we describe the microsprayer system for use in mating disruption of insect pests that provides a high degree of control over release and protection of pheromone molecules, and sets a new standard for durability and reliability. The microsprayer (Fig. 1) was developed based on specific design principles. First, the pheromone must be protected from oxygen and UV light to retain behavioral activity. Second, the device must release pheromone within a narrow range of release rates throughout a 6-mo growing season, without maintenance. And third, the cost averaged over 10 yr must be competitive with other mating disruption technologies.

Any technology for mating disruption of insect pests will be more effective if the operating characteristics and limitations are studied in both the laboratory and field. This approach enables engineers and entomologists to plan field trials based on an informed understanding of how the pheromone will be released and how far it will travel during the primary release from the microsprayer. Daily and weekly variations in environmental conditions impact pheromone release to some extent, and by quantifying this variation in the field, we aimed to develop an effective insect control method based on microsprayer technology. The current study was initiated to measure the operational performance characteristics of this device to enable educated field deployment for mating disruption of insect pests. An associated report will detail the pest control efficacy of pheromones released from the microsprayer.

Materials and Methods

The microsprayer (Fig. 1) consists of a pheromone canister, the opening of which is sealed with an automotive fuel injector providing a high-quality, durable solenoid valve connected to a reservoir of propellant. A simple and inexpensive electronic circuit, powered by a 9-V battery, controlled the frequency and duration of the solenoid opening the release valve. At each firing, a milligram quantity of pheromone solution, which was under pressure in the canister, was forced out of the valve unit nozzle through 4 holes (0.15 mm diameter) to produce a spray jet. The circuit was designed to draw minimal current at each firing of the solenoid, thus enabling season-long operation. The microsprayer and its control circuit are the subject of pending U.S. patent applications.

Although simpler configurations are envisioned, deployment of the microsprayer in tree fruit crops was achieved using a 45° PVC Wye-joint fixed onto a PVC pole 1.8 m in length by 7.6 cm in diameter fitted inside a slightly wider pipe of the same length (Fig. 2). A bolt drilled through the 2 poles held the top fitting at the correct height, and the poles were mounted on a wooden stake and tied to the tree trunk. The electronic circuit box was attached to the mounting poles at waist height, and an electrical cable connected the circuit to the solenoid valve.

Laboratory tests of microsprayer performance were conducted with 95% EtOH (vol:vol) inside the canister at 23 ± 1°C unless stated otherwise. The control circuit was powered by a new 9-V lithium cell (Ultralife Batteries, Newark, NY) and constructed of standard electronic components. Measurements were taken throughout the 1998 field season during microsprayer efficacy trials in Michigan.

Effect of Temperature on Canister Pressure. An analog pressure gauge was fitted to the top of the canister such that it directly measured the pressure inside the microsprayer. EtOH (300 ml) was added to the canister and the system was sealed. Canister pressure was recorded from the gauge across the range of temperatures expected to be encountered in cropping systems when placed in direct sunlight (i.e., 7–55°C). The canister was placed first into a refrigerator, and the temperature and canister pressure were recorded

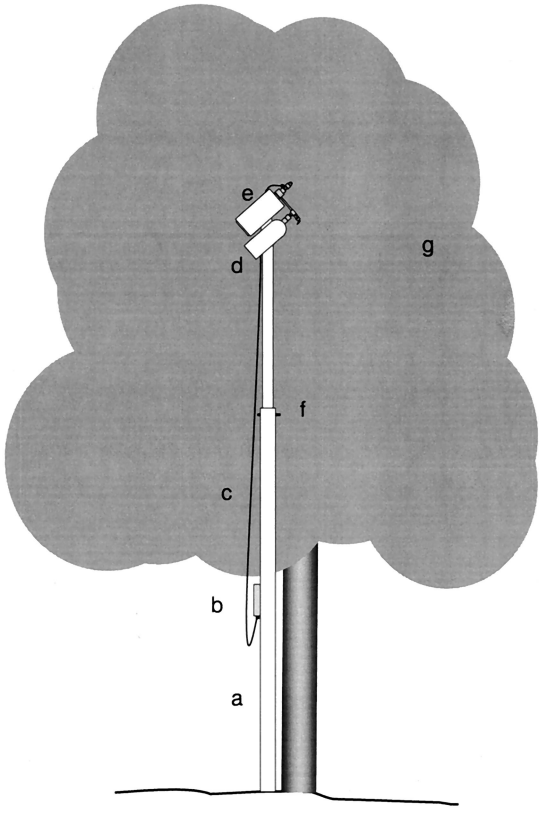

Fig. 2. Microsprayer unit mounted in a fruit tree for release of pheromone. (a) PVC pole held in place on a wooden stake; (b) timing circuit box attached to the mounting pole; (c) electrical wire connecting the control circuit to the solenoid valve; (d) canister of propellant; (e) PVC T-joint housing the pheromone canister; (f) retaining bolt to set the height of the microsprayer in the tree; (g) fruit tree foliage onto which pheromone is emitted.

after equilibration. All measurements were taken after at least 1 h of equilibration, and repeated every 5 min until 2 consecutive measurements were the same. Next, these measures were taken at ambient laboratory temperature. Thereafter, the canister was placed in a variable temperature oven, and readings were taken at increasing temperatures up to ≈55°C. This procedure was repeated 3 times, and the relationship between canister pressure and temperature was determined by regression analysis.

Effect of Firing Duration on Volume of Emission at Different Canister Pressures. The microsprayer canister was filled with 300 ml of EtOH and attached to a regulated nitrogen tank for pressure control. A pressure gauge was attached to the canister and used to set the internal pressure to either 40, 60, or 80 psi. At each of these pressures, emission from the canister was quantified at different firing durations by changing the resistance within the control circuit. Thus, the solenoid valve was made to open for 5, 10, 15, 50, 100, 150 and 500 ms, with a 2-s interval between firings. These durations were verified using a PM3365 oscilloscope (Fluke, Everett, WA) connected to the solenoid firing circuit. A clean glass scintillation vial and its lid were weighed, and the vial was then placed over the tip of the fuel injector for a single spray emission. The vial was then capped and reweighed. This procedure was repeated 10 times for each duration and pressure combination, and mean release volumes were calculated. Linear regression of volume emitted versus release duration was performed for each pressure to determine the variability in release rate over 2 orders of magnitude of release duration.

Effect of Canister Pressure on Firing Frequency. Accurate prediction of release rates in the field would be complicated if release frequency varied with canister pressure. The effect of canister pressure on release frequency was tested by timing the duration between emissions when the canister pressure was set at increments between 20 and 120 psi. For this experiment, a field-ready circuit was used that was designed to fire every 170 s. At each pressure, the time between 15 emissions was recorded, and the effect of pressure on emission frequency tested with a one-way analysis of variance (ANOVA).

Spatial Pattern and Size Distribution of Spray Droplets. The spatial pattern of droplet release was measured by placing a grid of 20-cm^2 cards of Novartis water-sensitive paper (Spray Systems, Wheaton, IL) on the floor beneath the area of spray release. The cards change color where water touches the surface, enabling counting of droplets and measurement of their size. Cards were placed 20 cm apart in a grid (1.8 by 1.8 m) of 81 cards. The experiment was conducted inside a cage (3 by 3 by 3 m) with plastic walls to provide a still atmosphere. A microsprayer pressurized to 50 psi, containing 300 ml of 75% EtOH in distilled water, was placed with the release nozzle directly above the middle card of one edge of the grid. This concentration of EtOH was similar to that expected to be used in mating disruption of insects with this technology. The microsprayer nozzle was directed across the grid, perpendicular to the edge on which it was placed, at 45° above the horizontal. Once the air was still, the sprayer was fired 20 times with a release duration of 10 ms and 10 s between each release. Cards onto which the spray landed were collected and replaced with clean cards. Measurements were taken with the sprayer placed at 0, 50, 100, and 150 cm above the cards, and repeated 4 times for each height. The number of drops on each card was counted and thereafter, a graticule eyepiece was used to measure the diameter of 20 drops per card, selected at random. For each height, the mean volume of liquid landing per square centimeter was calculated, assuming the diameter of each spot equaled the diameter of the drop that formed it. From these data, contour maps were generated to represent the spatial pattern of spray deposition.

Field Performance and Release Rates. Microsprayers were deployed at the Clarksville Horticultural Experiment Station (CHES), Clarksville, MI, and the Trevor Nichols Research Center (TNRC), Fennville,

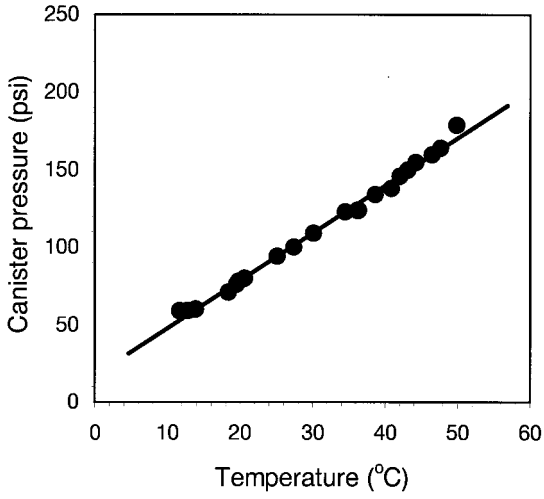

Fig. 3. Effect of increasing temperature on the internal canister pressure of the pheromone microsprayer.

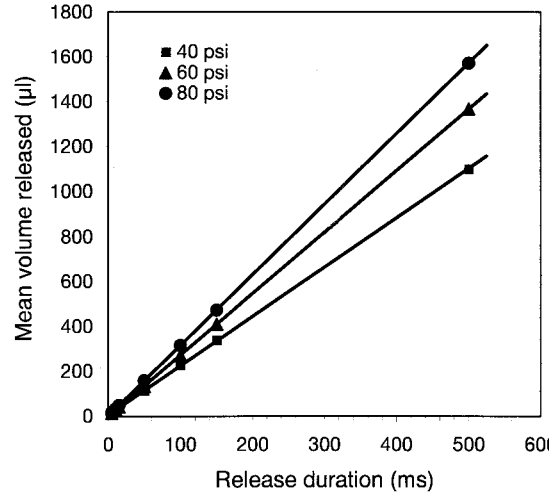

Fig. 4. Effect of canister pressure on the volume of ethanol released by the microsprayer when the solenoid valve was opened for different durations. Each data point is the mean of 10 individual releases ($n = 10$). Linear regression showed complete correlation between pressure and volume emitted ($r^2 = 1.0$) at all 3 pressures tested.

MI, in May 1998 as described previously. Canisters were filled with 550 ml of an ethanolic solution of major pheromone components for disruption of tortricid apple pests. Each contained a 96:4 blend of *Z*:*E* 11-tetradecenyl acetate, released at 800 mg/acre per day for disruption of obliquebanded leafroller, *Choristoneura rosaceana* Harris, and redbanded leafroller, *Argyrotaenia velutinana* Walker (8.7% vol:vol). The same canisters contained (*E*,*E*) 8,10-dodecadienol, released at 400 mg/acre per day for disruption of codling moth, *Cydia pomonella* (L.) (4.3% vol:vol).

Microsprayers were placed in apple trees at the top of the crown foliage. Ten sprayers were fitted with pressure gauges; 6 were placed in the orchards at TNRC, and 4 were deployed at CHES. On the same day each week, measurements were taken between 1200 and 1400 (EST) hours and at 1400 hours from each unit, and the meteorological conditions were recorded <20 m from one of the units at each site. An infrared thermometer (Omega Engineering, Stamford, CT) was used to measure the temperature of the canister and of the solenoid valve, and a subset of 10 sprayers was weighed on an electronic top pan balance powered from an automotive battery power supply. Battery voltage of 48 microsprayers were recorded weekly from 48 U throughout the growing season by connecting a digital multimeter to the circuit connection port. Air temperature at the ground, and wind speed, wind direction, and temperature at the height of the microsprayers were measured throughout these experiments at CHES and TNRC by using a Weather Monitor II recorder (Davis Instruments, Hayward, CA) placed between trees in a row.

Results

In laboratory experiments, the pressure within the microsprayer canister increased from 28 to 164 psi as temperature varied from 7.0 to 53.0°C (Fig. 3). The best-fit regression between the 2 variables was a linear relationship with the equation pressure = 17.3 + 3.1 temperature, with a high degree of correlation between canister pressure and temperature ($r^2 = 0.99$, $P < 0.0001$).

The volume of EtOH released by the microsprayer at each opening of the solenoid increased linearly in relation to solenoid opening duration (Fig. 4). Under these conditions, there was no detectable minimum time that the solenoid had to be open before the emitting liquid reached maximum velocity. Liquid was dispensed from the microsprayer at a rate of 2.19 ml/s when the canister was pressurized to 40 psi, as shown by the slope of the best-fit regression line at this pressure ($r^2 = 1.0$, $P < 0.0001$) (Fig. 4). When the canister pressure was raised to 60 psi, the rate of release increased to 2.73 ml/s, and then to 3.14 ml/s at 80 psi. Thus, increasing the canister pressure by 20 psi led to an increased release rate of ≈0.5 ml/s.

Firing frequency of the field-ready circuit was not significantly affected by the pressure inside the pheromone canister ($F = 2.20$; df = 5, 84; $P = 0.062$) and there was minimal variation in firing frequency of the circuit at different pressures (Table 1). For this system, the increasing power required to open the solenoid valve at higher pressures has no effect on short-term circuit performance.

In still air, droplets were detected up to 160 cm from the nozzle when the sprayer was placed at the same level as the cards compared with 80 cm when the sprayer was raised to 150 cm (Fig. 5). Droplets were recorded 40 cm on either side of the mean spray direction at the lowest height, compared with only 20 cm at the highest. Therefore we expect that solutions released from the microsprayer will impact crop foliage as tiny droplets, or as a vapor travelling away on

Table 1. Mean duration between firing of the microsprayer solenoid at different canister pressures

Canister pressure, psi	Duration between firings, S ± SE
20	169.6 ± 0.4
40	169.5 ± 0.2
60	168.6 ± 0.6
80	168.9 ± 0.2
100	168.3 ± 0.3
120	170.1 ± 0.7

$n = 15$.

wind currents from the point of release, and land over a large area of foliage. The largest droplets landed away from the sprayer nozzle, as expected from their greater momentum at release, although droplets of this size were rare. In contrast, the smallest droplets with the least momentum were found nearest to the nozzle under these still-air conditions. During descent to the ground, the volume of spray remaining in liquid form decreased as EtOH evaporated (Fig. 5). The net effect of this change in droplet size was a logarithmic

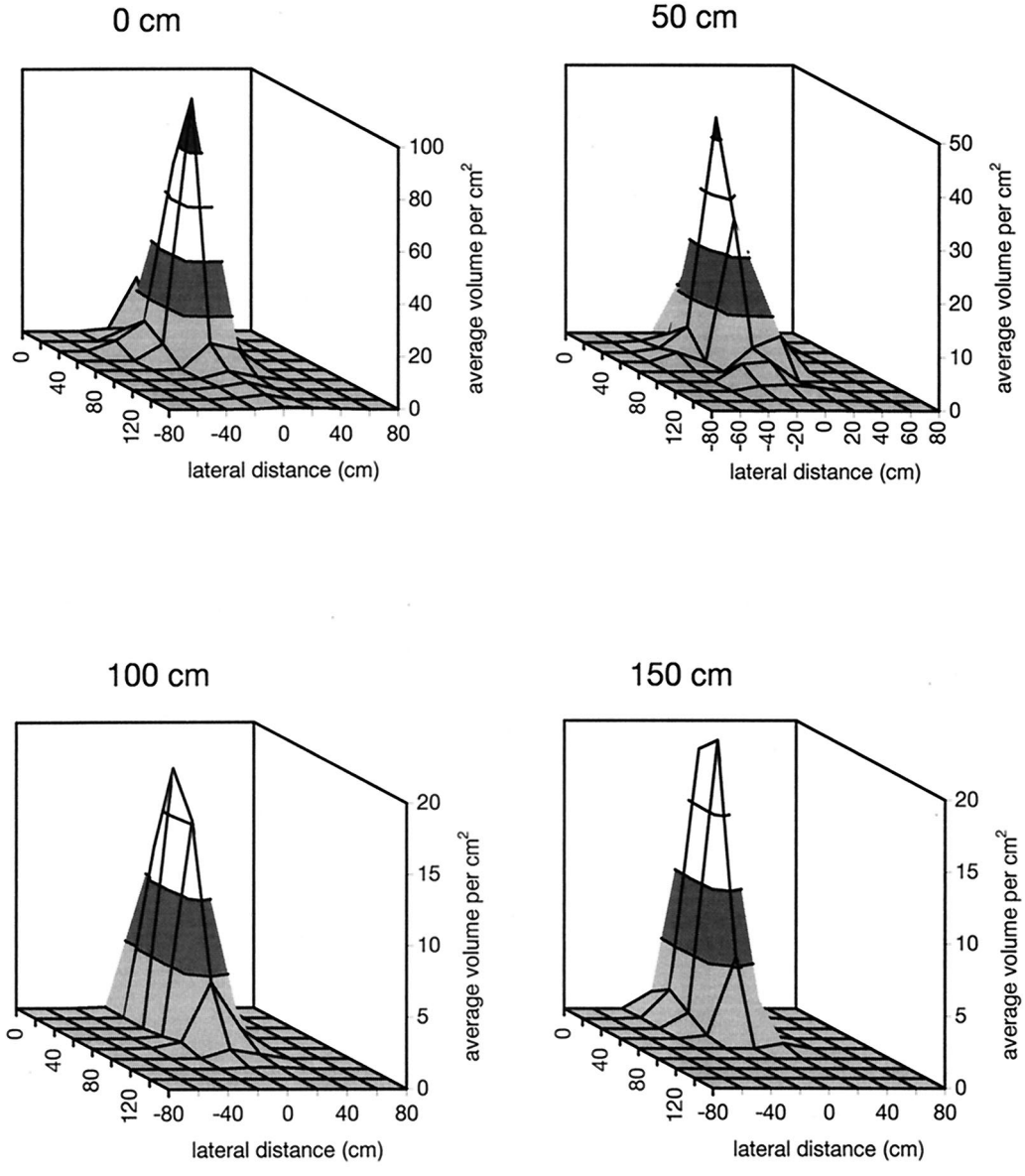

Fig. 5. Spatial pattern of droplets landing on a horizontal surface beneath the microsprayer nozzle when the droplets fell 0, 50, 100, and 150 cm from the nozzle to the surface. The y-axes show mean volume landing per square centimeter (in (μl/cm^2). The plot represents the distribution of spray volume viewed toward the sprayer, with the point of release on the back wall of the graph. Note the different y-axis scales.

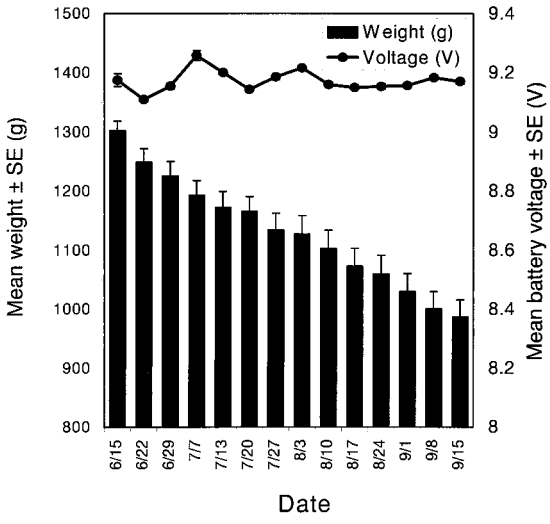

Fig. 6. Field performance of microsprayers during 1998, demonstrating steady pheromone release and the maintenance of battery voltage. Bars are the mean weight of microsprayers, and the line represents the mean battery voltage from the same units.

reduction in total spray volume as the microsprayer height increased from 0 to 150 cm above the ground.

Microsprayers tested under field conditions operated throughout a summer fruit growing season in 1998, and emitted the 13% (vol:vol) ethanolic solution of 2 moth pheromones throughout this period, releasing pheromone approximately every 170 s (Table 1). Canister pressures measured in situ varied between 50 and 80 psi, with a positive relationship to the temperature of the canister recorded at the same time (pressure = 0.92 temperature + 38.5). The correlation coefficient for this regression ($r^2 = 0.38$) was not significantly greater than that for the correlation between pressure and injector temperature ($r^2 = 0.29$) ($t = 7.44$, df = 1, $P = 0.09$). Over the period of the field trials, the minimum reading from the batteries was 9.02 and the maximum was 9.81, with a mean reading of 9.19 V, showing that the minimal current drawn by the circuit achieved the desired property of more than season-long battery life. Weekly measurements of the microsprayers revealed that an average of 25.45 ± 1.32 g was lost from the units every 7 d (Fig. 6). Assuming that the system comes to equilibrium after pressurization, 8.19% of this weight loss was active pheromone ingredients, whereas the rest comprised solvent and propellant.

Discussion

Laboratory and field testing of the microsprayer showed that this device provides a robust, reliable method for dispensing defined quantities of pheromone under field conditions. Pheromone release rates can be set in advance to provide the optimal combination of release frequency and duration that will apply sufficient pheromone into the crop for the duration required. The results from field tests clearly demonstrate that our design goals were achieved, whereby this new technology was designed to operate throughout a growing season without the need for maintenance.

Particularly important for the adoption of this technology for mating disruption is the demonstration that microsprayers can be powered by a single 9-V battery for the desired period of operation, thus enabling a grower to place the devices in a crop at any time before the start of a seasonal pest cycle when labor is available. Before degree-day models or monitoring traps indicate that the target pests are present, the units can be easily turned on to begin pheromone release for mating disruption. If there are long periods between generations of adult moths, growers may elect to switch the units off to save pheromone. At the end of the season, microsprayers can be left in the orchard until labor is available, such as during pruning, and recharged in preparation for the following spring, thus enhancing the saving of labor of using low-density devices and precluding the need for re-entry to replace short-lived dispensers.

The release rate of pheromone from almost all release systems, and that for revaporation from foliage, will be temperature-dependent. For evaporative technologies, pheromone release rates increase with temperature (McDonough et al. 1992), and the ratio of blend components is often not conserved over time (Lopez et al. 1991, Brown et al. 1992). In contrast, with pressurized systems the component ratio is retained at the initial point of release and is independent of temperature, with subsequent variation in blend composition during secondary emission. Our data show that for the microsprayer, as the ambient air temperature increased, the canister pressure also increased, thus providing greater force for expulsion of liquid while the solenoid valve is open. The greater release rate at higher temperatures may prove to be a valuable property in that more pheromone will be released when evaporative losses from the crop are greatest. Analysis of individual emissions from the microsprayers by gas chromatography after 3 mo of field operation has demonstrated that the pheromones retained their chemical identity in the canister (R.I., unpublished data).

By characterizing the performance of the microsprayer under a range of environmental conditions, we have tried to understand the physical constraints on the operation of this technology. Measurement of dispenser performance is essential if advances are to be made in development of new technologies for mating disruption. For example, deployment of pheromone rope dispensers has become more sophisticated since the pheromone release characteristics have been quantified (Leonhardt 1988, Brown et al. 1992, McDonough et al. 1992). If the expected weather conditions for an orchard are known, release rates can be modeled to provide an estimate of the volume of pheromone solution required for season-long mating disruption. During the season, the same model can be used to estimate the amount of pheromone solution

remaining in the canister, based on degree-day accumulations at the site.

The spatial distribution of pheromone released into a crop will affect the likelihood of behavioral response by male moths (Cardé and Minks 1995), but the effect of release method on pheromone distribution throughout the crop environment is currently not well understood. For pheromone released at high rates from sparse point sources, primary release rates will be high, but it is expected that for this approach to be effective, subsequent downwind movement and adsorption onto foliage will be necessary to provide sufficient pheromone distribution for effective mating disruption. Given that moth sex pheromones have relatively high molecular weights, we expect them to condense readily on foliage and other surfaces upon contact following a given evaporative event. Rather than being rapidly swept out of an orchard after evaporation, we postulate that pheromone partitions between air and solid surfaces in the chromatographic sense. Although the partitioning coefficient is expected to highly favor solid surfaces over air, evaporated pheromone could travel substantial distances before recondensing out of the mobile phase (air) onto the stationary phase (foliage). Extended evaporative rerelease of pheromone from apple foliage (Karg et al. 1994, Suckling et al. 1996), will act as secondary release sites of pheromone after changes in the wind direction shift the position of the primary release pheromone plume. We assume that variability of wind direction as pheromone partitions between air and foliage will, over time, lead to its redistribution throughout the crop and produce many disparate point sources of pheromone release. This type of buffering would expand the active space of low-density release devices, and may partly explain the effectiveness recently reported for this approach to pheromone release in field and orchard crops (Shorey et al. 1996; Shorey and Gerber 1996a, b; Baker et al. 1997).

In light of the expected mechanisms of pheromone redistribution through the orchard, microsprayer control circuits were set to release pheromone throughout the day and night cycle. By using constant release, the pheromone is more likely to move throughout the orchard to condense onto leaf, bark, and ground surfaces as the wind direction varies. Similar concerns have been addressed for the MSTRS device through the use of a pad to capture the discharge from the reservoir bottle, creating a long-term point-source emission for generating pheromone plumes (Mafra-Neto and Baker 1996, Baker et al. 1997). As demonstrated herein, by propelling the pheromone solution from the nozzle, the microsprayer produced primary deposition throughout the foliage of the tree in which it was positioned, and primary volatilization into the air (Fig. 5). Most droplets were <0.1 mm in diameter, with low settling velocities. Thus, the release distribution consists of local primary and distant secondary pheromone deposition with associated volatile pheromone release into the air across a large area. Future research will investigate the impact of release technology and crop architecture on pheromone distribution over time.

The microsprayer was designed and operated with the partitioning model of pheromone dispersion in mind. By selecting and deploying equipment for excellent vertical distribution of pheromone droplets on and around a source tree at primary release, it was anticipated that appropriate vertical distribution would be maintained thereafter during dispersal by partitioning. Additionally, it was judged appropriate that microsprayers released many microliter-quantity bursts throughout the day and night to diversify primary deposition by taking advantage of even minor shifts in wind direction and turbulence. The data from weather stations within the test orchards indicated this strategy was justified. The efficacy of this release technology for insect mating disruption will be discussed further in light of the field trials conducted in 1998 (unpublished data), in which effective mating disruption of 2 tortricid apple pest species was achieved by microsprayers releasing pheromone at a density of 2 units/acre.

The device reported herein is a research prototype that permits loading without needing to access specialized aerosol equipment. Commercial models of this device will comprise an aerosol can containing pheromone mixture and propellant, connected to the fuel injector nozzle and powered by a small plug-in circuit. A simplified system for mounting the microsprayer in the crop will result in a practical and cost-effective alternative for pheromone release for pest control in situations lending themselves to pheromone dispersal by partitioning between the air and foliage.

Acknowledgments

We thank Andrew Erickson, Sara Varty, and Amy Meeker for their technical assistance in the laboratory. The field assistance of Peter McGhee, Anne-Marie Wissman, Brian Dixon, Melanie Kaeb, Ben Kaeb, and Aaron Kaeb is gratefully acknowledged. We thank John Wise and the staff of Trevor Nichols Research Complex and Clarksville Horticultural Research Station for making their expertise and field sites available. This project was supported by Grant No. 97-06472 from the USDA Pest Management Alternatives Program to R.I., J.R.M., and L.J.G., and by Gerber Products Company, Ford Motor Company, MI, Apple Research Committee, and an enhancement grant from the Pesticide Research Center at Michigan State University.

References Cited

Baker, T. C., T. Dittl, and A. Mafra-Neto. 1997. Disruption of sex pheromone communication in the blackheaded fireworm in Wisconsin cranberry marshes by using MSTRS devices. J. Agric. Entomol. 14: 449–457.

Brown, D. F., A. L. Knight, J. F. Howell, C. R. Sell, J. L. Krysan, and M. Weiss. 1992. Emission characteristics of a polyethylene pheromone dispenser for mating disruption of codling moth (Lepidoptera: Tortricidae). J. Econ. Entomol. 85: 910–917.

Cardé, R. T., and A. K. Minks. 1995. Control of moth pests by mating disruption: successes and constraints. Annu. Rev. Entomol. 40: 559–585.

Fadamiro, H. Y., A. A. Cosse, T. Dittl, and T. C. Baker. 1998. Suppression of mating by blackheaded fireworm (Lepidoptera: Tortricidae) in Wisconsin cranberry marshes using MSTRS™ devices. J. Agric. Entomol. 15: 377–386.

Karg, G., D. M. Suckling, and S. J. Bradley. 1994. Absorption and release of pheromone of *Epiphyas postvittana* (Lepidoptera: Tortricidae) by apple leaves. J. Chem. Ecol. 20: 1825–1841.

Leonhardt, B. A., W. A. Dickerson, R. L. Ridgway, and E. D. Devilbiss. 1988. Laboratory and field evaluation of controlled release dispensers containing grandlure, the pheromone of the boll weevil (Coleoptera: Curculionidae). J. Econ. Entomol. 81: 937–943.

Lopez, J. D. Jr., B. A. Leonhardt, and T. N. Shaver. 1991. Performance criteria and specifications for laminated plastic sex pheromone dispenser for *Helicoverpa zea* (Lepidoptera: Noctuidae). J. Chem. Ecol. 17: 2293–2305.

Mafra-Neto, A., and T. C. Baker. 1996. Timed, metered sprays of pheromone disrupt mating of *Cauda cautella* (Lepidoptera: Pyralidae). J. Agric. Entomol. 13: 149–168.

McDonough, L. M., W. C. Aller, and A. L. Knight. 1992. Performance characteristics of a commercial controlled-release dispenser of sex pheromone for control of codling moth (*Cydia pomonella*) by mating disruption. J. Chem. Ecol. 18: 2177–2189.

Millar, J. G. 1995. Degradation and stabilization of *E*8,*E*10-dodecadienol, the major component of the sex pheromone of the codling moth (Lepidoptera: Tortricidae). J. Econ. Entomol. 88:1425–1432.

Shorey, H. H, C. B. Summers, C. B. Sisk, and R. G. Gerber. 1994. Disruption of pheromone communication in *Spodoptera exigua* (Lepidoptera: Noctuidae) in tomatoes, alfalfa, and cotton. Environ. Entomol. 23: 1529–1533.

Shorey, H. H., and R. G. Gerber. 1996a. Use of puffers for disruption of sex pheromone communication among navel orangeworm moths (Lepidoptera: Pyralidae) in almonds, pistachios, and walnuts. Environ. Entomol. 25: 1154–1157.

Shorey, H. H., and R. G. Gerber. 1996b. Use of puffers for disruption of sex pheromone communication of codling moths (Lepidoptera: Tortricidae) in walnut orchards. Environ. Entomol. 25: 1398–1400.

Shorey, H. H., C. B. Sisk, and R. G. Gerber. 1996. Widely separated pheromone release sites for disruption of sex pheromone communication in two species of Lepidoptera. Environ. Entomol. 25: 446–451.

Suckling, D. M., G. Karg, and S. J. Bradley. 1996. Apple foliage enhances mating disruption of light-brown apple moth. J. Chem. Ecol. 22: 325–341.

Vickers, R. A., and G.H.L. Rothschild. 1991. Use of sex pheromones for control of codling moth, p. 339–354. *In* L.P.S. van der Geest and H. H. Evenhuis [eds.], Tortricid moths: their biology, natural enemies and control. Elsevier, Amsterdam.

Received for publication 1 March 1999; accepted 8 June 1999.