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Efficacy and mode of action of female-equivalent dispensers of pheromone for mating disruption of codling moth

L. L. Stelinski, P. McGhee*, M. Grieshop*,†, J. Brunner† and L. J. Gut*

*Entomology and Nematology Department, Citrus Research and Education Center, University of Florida, Lake Alfred, FL 33850 and*Department of Entomology, Michigan State University, East Lansing, MI 48824 and †Tree Fruit Research and Extension Center, Washington State University, Wenatchee, WA 98801, U.S.A.*

Abstract

1 We evaluated the efficacy and mode of action of commercially available female-equivalent dispensers of pheromone for mating disruption of codling moth *Cydia pomonella* (L.) (Lepidoptera Tortricidae).

2 Scentry fibres, but not Hercon flakes, were consistently as or more effective than Isomate C Plus dispensers when applied by hand at 50 dispensers per tree.

3 Individual Scentry fibres were slightly more attractive to male codling moth than Hercon flakes.

4 Efficacy of aerially applied Scentry fibres was equivalent to that of Isomate dispensers in disrupting male codling moth in 4-ha commercial apple plots.

5 Initial deposition and retention of aerially applied fibres were inefficient with approximately 44% formulation loss at application, poor rainfastness and a gradual loss of dispensers from tree canopies after application.

6 Male codling moths were captured in traps baited with lures containing 0.1 mg of pheromone and mated with tethered virgin females that were surrounded by eight fibres placed 30 cm away or 16 fibres placed 45 cm away in untreated plots and plots treated with a background of 50 Isomate dispensers per hectare.

7 A plausible explanation for mating disruption of codling moth by female-equivalent dispensers is competitive attraction without associated habituation and thus improving the effectiveness of these technologies will depend on maximizing the attractiveness of individual dispensers as well as the application density of dispensers per area of crop.

Keywords *Cydia pomonella*, fibres, flakes, reservoir dispensers, Tortricidae.

Introduction

The codling moth *Cydia pomonella* (L.) (Lepidoptera Tortricidae) is one of the leading pests driving the research and development programmes of the global semiochemical industry with approximately 162 000 ha of pome fruit treated with synthetic formulations of pheromone for codling moth worldwide (Witztgall *et al.*, 2008). Subsequent to its registration in the U.S.A. in 1991, the polyethylene Isomate reservoir dispenser has become an industry standard (Thomson *et al.*, 1999; Witztgall *et al.*, 2008). Such dispensers contain approximately 200 mg of a three-component codling moth pheromone blend and are deployed by hand once per season at densities of 500–1000 units/ha. Effectiveness of Isomate dispensers has been variable (Cardé & Minks, 1995; Witztgall *et al.*, 2008); however, area-wide applications have been successful and have reduced reliance on broad-spectrum insecticides (Waldner, 1997; Brunner *et al.*, 2002). The main drawbacks of reservoir dispenser technology are the need for hand application and the economic limitation of a point source density of approximately 1000 units/ha, which typically results in only one or two dispensers per tree (Epstein *et al.*, 2006).

Several technologies have been investigated as possible alternatives to reservoir dispensers for mating disruption of codling moth. Microencapsulated formulations of pheromones are deployed with standard agricultural air-blast sprayers, replacing the need for hand application. Although such sprayable formulations are highly desirable from a practical standpoint, their efficacy has been inconsistent and short-lived in the field (Epstein *et al.*, 2003; Knight & Larsen, 2004). A recently developed low volume application method, which yields high densities of clusters comprised

Correspondence: Lukasz Stelinski. Tel: +1 863 956 1151; fax: +1 863 956 4631; e-mail: stelinski@ufl.edu

of hundreds of microcapsules on tree foliage, has improved efficacy and increased longevity of sprayable formulations for codling moth (Knight & Larsen, 2004). Another alternative to reservoir dispensers are aerosol devices. These are deployed at very low densities (approximately 2–3) per hectare of crop (Knight, 2004). Current aerosol devices are mechanized and remotely-controlled delivering metered sprays of solvent-diluted pheromone at regular intervals (Knight, 2004). Initial tests with codling moth demonstrated high efficacy (95–98% disruption) by deploying 2.3 aerosol devices per hectare of walnut (Shorey & Gerber, 1996). However, a more recent investigation of commercially available aerosol devices deployed at 2.5 units/ha of apples reported poor efficacy of codling moth disruption (24–75%) (Stelinski *et al.*, 2007).

Female-equivalent dispensers represent a third alternative to hand-applied reservoir dispensers. These include Hercon Disrupt CM flakes (Hercon, Emigsville, Pennsylvania) and Scentry NoMate CM fibres (Scentry, Billings, Montana) (Swenson & Weatherston, 1989). These dispensers are also machine-applied to crops but as tens of thousands of point sources of pheromone per hectare of crop. They are applied via custom applicators and are amendable to aerial application. The presumable advantages of these technologies are machine application and deployment of many thousands of point source per hectare. Increasing point source density above 1000 dispensers per hectare has been shown to improve codling moth disruption (Epstein *et al.*, 2006; Stelinski *et al.*, 2006a; Angeli *et al.*, 2007). A proof-of-concept investigation of an early hollow fibre dispenser (Conrel), deployed as 1700 points of ten fibres/ha, also showed excellent disruption (96–100%) of codling moth (Cardé *et al.*, 1977).

In the present study, we evaluated the efficacy and mode of action of commercially available female-equivalent dispenser formulations for mating disruption of codling moth. The specific objectives were: (i) to compare the efficacies of two commercially available female-equivalent dispenser formulations with the industry standard reservoir dispenser formulation; (ii) to investigate the efficacy, pattern of deposition within the crop, and longevity of adherence of an aerially applied, female-equivalent dispenser formulation; (iii) to determine the attractiveness of individual and clusters of female-equivalent dispensers relative to monitoring lures; (iv) to determine the effect of fibre density on the attractiveness of a centrally mounted monitoring trap or virgin female; and (v) to determine the effect of fibre distance away from a monitoring trap or virgin female on disruption of male codling moths orienting to the trap or female.

Materials and methods

Pheromone formulations

Isomate C Plus dispensers (Pacific Biocontrol Co., Vancouver, Washington) were reported to contain 205 mg of 53.0% codlemone [(*E*,*E*)-8,10-dodecadien-1-ol], 29.7% 12OH, 6.0% 14OH and 11.3% inert ingredients per dispenser with a recommended application rate of 500–1000 units/ha. The Scentry fiber formulation contained 10.8% codlemone and 89.2% inert ingredients (approximately 260 μg of codlemone/fibre) with a recommended application rate of 38–375 g of fibres/ha. The Hercon flake formulation contained 5.97% codlemone and 94.03% inert ingredients (approximately 190 μg of codlemone/flake) with a recommended application rate of 827 g of flakes/ha.

Small plot comparison of hand-applied female-equivalent dispensers with hand-applied reservoir dispensers

This experiment compared the effectiveness of hand-applied female-equivalent dispensers with hand-applied reservoir dispensers in disrupting sexual communication of codling moth in experimental orchard plots. It was conducted at the Trevor Nichols Research Complex (TNRC) of Michigan State University in Fennville, Michigan. in a 4-ha orchard of 20-year-old 'Delicious' apple trees, approximately 2–3 m tall. Trees were planted in 3 × 6 m tree/row spacing. Orchard plots were maintained with standard fungicide and fertilizer treatments but did not receive applications of insecticides. The treatments compared were: (i) two Isomate C Plus dispensers per tree (approximately 815 per hectare); (ii) 50 Scentry fibres/tree (approximately 20 375 per hectare); (iii) 50 Hercon flakes per tree (approximately 20 375 per hectare); and (iv) a no pheromone control. Female-equivalent dispensers were applied at 50 per tree based on previous research showing this to be an effective density (Epstein *et al.*, 2006). Isomate dispensers were attached to tree branches in the upper portions of the tree canopy. Likewise, both fibres and flakes were hand-applied to branches and leaves in the upper portions of tree canopies. Applications were made by first completely submerging either fibres or flakes in Bio-Tak (Scentry Biologicals Inc., Buckeye, Arizona), an adhesive sticker additive that is applied with Scentry fibres for adhesion to foliage, and then carefully placing the fibre or flake flat against the surface of tree leaves or stems using laboratory forceps. Fibres and flakes were applied in this fashion so as to promote retention of applied dispensers. The experimental design was a randomized complete block with four 0.04-ha (nine tree) replicates per treatment. Treatments were separated by 54-m buffers. Treatments were monitored with pheromone-baited delta traps (LPD Scenturian Guardpost; Suterra, Bend, Oregon) baited with Suterra CM 1X (1 mg of codlemone) red septum lures. Each plot received a total of five traps, with one trap placed in the central tree and the other trap placed on the interior portion of each corner tree. Traps were hung approximately 2–3 m above ground level in the upper third of the tree canopy. Traps were positioned as far away as possible from pheromone dispensers (at least 60 cm). Moths captured in traps were counted and removed weekly. The experiment was conducted from 27 May to 23 July 2004.

Large plot comparison of aerially applied Scentry fibres with hand-applied Isomate C Plus

This experiment compared the effectiveness of aerially applied Scentry fibres with hand-applied Isomate C Plus in disrupting codling moth in commercial apple orchard plots in Grand Rapids, Michigan. Orchards were planted on a 4.6 × 5.5 m tree/row spacing (441 trees per hectare) and with 4.9–5.5 m tall 'Delicious' apples. Replicate plots were 4 ha in size and were spaced by 0.5 ha buffers at a minimum. The treatments compared were: (i) Isomate C Plus at 1000 dispensers/ha; (ii) aerially applied fibres at 160 g/ha (approximately 89 910 fibres/ha); and (iii) a no pheromone control. Isomate C Plus was applied by hand to the upper third of the tree canopies. Fibres were applied from a fixed wing aircraft equipped with Ecogen aerial application pods (Ecogen Inc., Goodyear, Arizona), which is specifically designed for the application of agricultural products. The pods dispense a calibrated amount of product from a central hopper containing both fibres and Bio-Tak adhesive into a spinning cone that distributes fibres onto the crop. Fibres were dispensed with 2.3 L of Bio-Tak adhesive per hectare. An application of fibres was made at the beginnings of both the first (5–6 May 2004) and second (12–13 July 2004) generation codling moth flights. The experimental design was a randomized complete block with four replicates per treatment. All plots on each farm were also treated with identical insecticide programmes to prevent unacceptable levels of fruit damage at harvest. During the first generation, there were two applications of azinphos-methyl at 2.2 kg/ha and during the second generation there were two applications of thiocloprid at 0.43 L/ha. Disruption was evaluated with ten pheromone traps baited with Trécé CM L2 (3 mg of codlemone) lures (Trécé, Adair, Oklahoma) deployed per plot. Traps were placed in plots at least 15.2 m away from plot borders and spaced by at least 6 m away from each other. Mid-season and harvest assessments of fruit injury were conducted by evaluating 30 randomly-selected fruit (15 high and 15 low in the canopy) from each of 20 randomly-selected trees per plot. The experiment was conducted from 12 May to 20 July 2004.

Deposition of aerially applied fibres

The pattern of fibre deposition was quantified during the two aerial applications of fibres made to the four 4-ha commercial apple orchard plots described above. Thirty white cardboard panels (0.4 m^2) were distributed within each orchard immediately prior to application. Ten panels were placed on the ground in each of three locations: (i) between trees in a row; (ii) between rows; and (iii) under tree canopies. The number of fibres adhering to panels in each location was assessed immediately after aerial application. Based on the mean numbers of fibres counted on the panels at each location, the number of fibres adhering to each tree was estimated using the formula: (89 910 fibres applied per hectare – estimated number of fibres landing between tree canopies – estimated number of fibres landing under trees per hectare)/441 trees per hectare.

Retention of aerially applied fibres

After each aerial application of fibres, we also attempted to quantify the longevity of fibre retention on the tree canopies. Data were collected only during the second generation because a heavy rain event (17.8 cm), 1 week after the first generation application dislodged 100% of applied fibres. Immediately after application, trees were inspected for fibres. Fibres were found to either completely adhere flat against the surface of tree wood and leaves or to partially adhere and also partially hang off of the substrate. Twenty-five completely and 25 partially adhering fibres were tagged and monitored weekly per replicate from 13 July to 28 September 2004.

Attractiveness of point source dispensers

Two experiments were conducted to determine the attractiveness of Scentry fibres or Hercon flakes to codling moth males. All treatments were evaluated by moth catch in plastic delta traps described above. In the first experiment, conducted from 14 May to 15 July 2004, the dispenser treatments compared were: one, eight or 24 fibres or flakes. These were compared with traps baited with either one Trécé CM L2 lure or one Suterra CM 1X red septum lure (Suterra, Bend, Oregon) pinned to the upper ceiling of delta traps. Fibres and flakes were placed onto double-sided sticky tape and affixed to the ceiling of traps. All treatments were deployed in 0.4-ha plots of 20-year-old 'Delicious' apples 2–3 m tall and planted on a 3 × 6 m tree/row spacing at the TNRC. These plots did not receive applications of insecticides or pheromone disruption treatments. The experiment was arranged in a randomized complete block with six replicates. Traps were hung approximately 1.5–2 m above ground level in the upper third of tree canopies. Treatments were separated by at least 26 m and rotated weekly. Moths captured in traps were counted and removed weekly. In a second experiment, conducted from 19 July to 16 September 2004, the same protocol was followed except that the 24 flakes and 24 fibres treatments were eliminated.

Effect of fibre position on disruption of male moths

Studies were conducted to evaluate the effects of fibre density and distance away from a centrally located monitoring trap or virgin female on orientation of codling moth males to the trap or female. Fibres were hand-applied to apple leaves surrounding delta traps or 8 × 16 cm horizontal platforms upon which a virgin female was tethered. In the first experiment, eight fibres were deployed in a sphere pattern 30, 45 or 60 cm away from a central trap or tethered virgin female. In the second experiment, the distance from the trap or virgin female was maintained constant at 45 cm and three densities of fibres (four, eight or 16) were compared. For each experiment, a trap or virgin female without surrounding fibres served as a control and the experimental designs were randomized complete blocks with five replicates. Treatments were deployed in the upper canopy of trees in plots identical to those described for the study 'Attractiveness of point source dispensers'.

Each tree contained only one treatment and treatments were separated by at least 15 m. Each treatment was initially set up with a delta trap baited with a 0.1 mg codlemone lure. The traps were inspected twice weekly by counting and removing captured male moths. Once per week, traps were removed and treatments were monitored by deploying tethered virgin females. Codling moth pupae were obtained from the USDA-ARS Yakima Agricultural Research Laboratory in Wapato, Washington. Pupae were sorted by sex and adults emerged in 1-L plastic cages containing 5% sucrose in plastic cups with cotton dental wicks protruding from their lids. Females (2–3 days old) were tethered on 8 · 16 cm plastic platforms mounted centrally approximately 2.5 m above ground level within the canopy of 2–3 m apple trees. Females were collected from the field approximately 18–20 h after deployments. Dissections were conducted to determine mating status by removal of the bursa copulatrix and inspection for the presence of a spermatophore. In the first generation (16 May to 8 July 2005), treatments were deployed in orchards otherwise not treated with pheromone. During this first generation, disruption of male moth orientation to traps and prevention of virgin female mating was judged to be poor. We hypothesized that a background concentration of pheromone, which may be achieved by the label-rate application of fibres, would improve disruption. Thus, in the second generation (13 July to 1 September 2005), all treatments (including the control) were deployed in orchards treated with 50 Isomate C-Plus dispensers/ha. The Isomate dispensers were placed at least 6 m from the nearest fibre density or distance location. A total of 420 females were deployed in each generation with 209 and 201 recovered and dissected during the first and second generations, respectively.

Analyses

Trapping data were transformed to ln $(x + 1)$ (to normalize the distributions and homogenize variances) and then subjected to analysis of variance (ANOVA). Fruit injury data were arcsin transformed prior to ANOVA. For the fibre deposition study, the number of fibres per ten panels per location (between trees in a row, between rows, or under tree canopies) was averaged for each of the four orchards where the study was conducted, which were considered as blocks for the ANOVA. When ANOVA was significant, Tukey's honestly significant difference test was used to compare treatment means (SAS Institute, Cary, North Carolina).

Results

Small plot comparison of female-equivalent dispensers with hand-applied reservoir dispensers

During the first generation moth flight, significantly ($F = 9.1$, d.f. = 3,9, $P = 0.009$) fewer male codling moths were captured in monitoring traps in plots treated with each pheromone treatment compared with the control plots; however, there was no significant difference between the two female-equivalent dispenser treatments and Isomate C Plus (Table 1). In the second generation, significantly ($F = 6.8$, d.f. = 3,9, $P = 0.01$) fewer male codling moths were captured in plots treated with Scentry fibres compared with control plots; however, catches in plots treated with Hercon flakes and Isomate C Plus dispensers were not significantly different from the control (Table 1).

Table 1 Effect of two female-equivalent dispenser technologies and Isomate C plus on disruption of male codling moth orientation to pheromone traps

	Mean ± SEM moth capture/trap	
Treatment	First generation (14 May to 23 July)	Second generation (26 July to 16 September)
Control	8.2 ± 2.5^{a}	31.7 ± 16.1^{a}
Isomate C Plus	4.1 ± 0.9^{b}	$15.2 \pm 5.4^{a,b}$
Scentry fibres	3.1 ± 0.8^{b}	7.6 ± 3.7^{b}
Hercon flakes	3.1 ± 1.9^{b}	$16.8 \pm 15.4^{a,b}$

Means within a column followed by the same superscript letter are not significantly different (Tukey's tests, $P > 0.05$).

Large plot comparison of aerially applied Scentry fibres with hand-applied Isomate C Plus

There was a significant effect of the blocking factor during the first generation ($F = 20.5$, d.f. = 3,6, $P = 0.01$), but not during the second generation ($F = 0.32$, d.f. = 3,6, $P = 0.13$). During both the first ($F = 18.3$, d.f. = 2,6, $P = 0.008$) and second ($F = 6.3$, d.f. = 2,6, $P = 0.05$) generations, significantly fewer males were captured in plots treated with Isomate C Plus compared with control plots; however, moth catch in plots treated with aerially applied fibres was not different from the control (Table 2). In the first generation, moth catch in Isomate-treated plots was significantly lower than in fibre-treated plots; however, there was no significant difference between these two treatments during the second generation (Table 2). Fruit injury at mid-season ($F = 1.0$, d.f. = 2,6, $P = 0.44$) and at harvest ($F = 2.1$, d.f. = 2,6, $P = 0.19$) in the two pheromone treatments and the control did not differ significantly (Table 2).

Deposition of aerially applied fibres

The mean ± SE number of fibres landing between tree rows (1.71 ± 0.31) was significantly ($F = 13.1$, d.f. = 2,6, $P = 0.01$) greater than the mean number between trees within rows (0.83 ± 0.19) or beneath trees (0.35 ± 0.11); however, there was no difference between the latter two locations. Given that approximately 89 910 fibres were applied to 441 trees/ha, we calculate that an estimated 39 333 fibres/ha fell to the orchard floor whereas approximately 50 578 fibres/ha landed on trees. Thus, approximately 115 fibres were deposited per tree.

Retention of aerially applied fibres

Thirty eight days after the aerial application of fibres, which was approximately mid-way through the second moth generation, 68% and 51% of completely and partially adhering fibres, respectively, were found remaining on foliage (Fig. 1). At 72 days post-application, approximately 38 and 21% of completely and partially adhering fibres, respectively, remained attached to canopies (Fig. 1).

Table 2 Effect of aerially applied Scentry fibres and Isomate C Plus codling moth catch in pheromone traps and fruit injury

	Mean ± SEM moth capture/trap		Mean ± SEM % fruit injury	
Treatment	First generation	Second generation	Mid-season	Harvest
Control	40.3 ± 10.0^{a}	51.7 ± 22.1^{a}	0.27 ± 0.18^{a}	0.48 ± 0.43^{a}
Isomate C Plus	13.4 ± 2.5^{b}	1.9 ± 1.3^{b}	0.47 ± 0.37^{a}	1.0 ± 3.2^{a}
Scentry fibres	38.8 ± 7.1^{a}	$15.3 \pm 6.7^{a,b}$	0.17 ± 0.09^{a}	0.27 ± 0.16^{a}

Means within a column followed by the same superscript letter are not significantly different (Tukey's tests, $P > 0.05$).

Attractiveness of point source dispensers

Delta traps baited with Trécé L2 lures and Suterra 1X red septum lures captured significantly ($F = 10.7$, d.f. = 7,35, $P < 0.0001$) more male codling moth than any of the Scentry fibre or Hercon flake treatments during the first generation flight (Table 3). Traps baited with one, eight and 24 Scentry fibres and those baited with one or eight Hercon flakes captured statistically equivalent numbers of moths (Table 3). Significantly fewer males were captured in traps baited with 24 Hercon flakes than in traps baited with one, eight or 24 Scentry fibres (Table 3).

During the second generation, significantly ($F = 15.5$, d.f. = 5,25, $P = 0.01$) more males were captured in traps baited with Trécé L2 and Suterra 1X red septum lures than in traps baited with 1 or 8 Hercon flakes; however, there was no significant difference between catch in traps baited with the two lure types and those baited with one or eight Scentry fibres (Table 4).

Effect of fibre position on disruption of male moths

In plots otherwise not treated with pheromone, significantly ($F = 7.4$, d.f. = 3,16, $P = 0.01$) fewer male *C. pomonella* were captured in traps baited with 0.1-mg lures when eight surrounding fibres were placed 30, 45, or 60 cm away from the trap compared with traps not surrounded with fibres (Fig. 2A). There was no significant difference in male catch between the three distance treatments (Fig. 2A). In plots treated with a low rate of Isomate C Plus, there was no significant ($F = 0.8$, d.f. = 3,16, $P = 0.9$) difference between moth catch in control traps and those surrounded by fibres at the three distances tested (Fig. 2A).

In untreated plots, significantly ($F = 17.3$, d.f. = 3,16, $P = 0.0001$) fewer male moths were captured with four, eight and 16 surrounding fibres placed 45 cm away from a central trap compared with control traps without surrounding fibres (Fig. 2B). However, in plots treated with a background treatment of Isomate C Plus, there was no significant ($F = 1.1$, d.f. = 3,16, $P = 0.3$) difference in moth catch between untreated traps and those surrounded by four, eight or 16 fibres placed 45 cm away from traps (Fig. 2A).

In otherwise untreated plots, mating was significantly ($F = 6.2$, d.f. = 3,16, $P = 0.04$) reduced when eight fibres were deployed 30 and 45 cm away from tethered virgin females compared with controls; however, mating was not significantly reduced compared with the control when fibres were placed 60 cm away from females (Fig. 3A). In plots treated with a low density of Isomate C Plus, mating was significantly ($F = 8.8$, d.f. = 3,16, $P = 0.03$) reduced only when fibres were 30 cm away from females (Fig. 3A).

In both untreated plots ($F = 7.1$, d.f. = 3,16, $P = 0.04$) and plots treated with a background of pheromone ($F = 10.4$, d.f. = 3,16, $P = 0.01$), mating was significantly reduced compared with the control when eight and 16 fibres were placed 45 cm away from a central tethered virgin females; however, four fibres 45 cm away from females did not significantly reduce mating compared with control females (Fig. 3B).

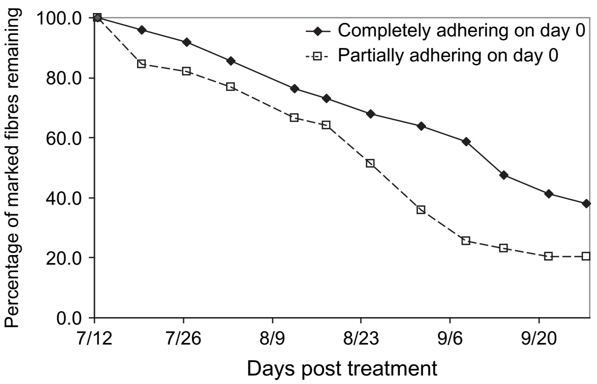

Figure 1 Percentage of fibres remaining on tree wood and foliage at various intervals after aerial application of 160 g of fibres/ha (approximately 89 910 fibres/ha).

Table 3 Cumulated captures of male codling moth in traps baited with various dispensers or lures during the first generation moth flight (14 May to 15 July)

Dispenser or lure type	Mean ± SEM moth capture/trap
Trécé L2 lure	76.3 ± 11.5^{a}
Suterra 1X Red Septum	53.8 ± 10.5^{a}
One Scentry fibre	24.8 ± 4.6^{b}
Eight Scentry fibres	30.3 ± 11.1^{b}
24 Scentry fibres	26.0 ± 4.6^{b}
One Hercon flake	$19.0 \pm 6.4^{b,c}$
Eight Hercon flakes	$16.0 \pm 5.3^{b,c}$
24 Hercon flakes	11.2 ± 3.6^{c}

Means followed by the same superscript letter are not significantly different (Tukey's tests, $P > 0.05$).

Table 4 Cumulated captures of male codling moth in traps baited with various dispensers or lures during the second generation moth flight (19 July to 26 August)

Dispenser or lure type	Mean ± SEM moth capture/trap
Trécé L2 lure	101.8 ± 38.0[a]
Suterra 1X Red Septum	92.0 ± 10.5[a]
One Scentry fibre	51.2 ± 21.4[a,b]
Eight Scentry fibres	34.0 ± 13.3[a,b]
One Hercon flake	27.3 ± 12.7[b]
Eight Hercon flake	27.8 ± 14.5[b]

Means followed by the same letter are not significantly different (Tukey's tests, $P > 0.05$).

Discussion

The present study demonstrated that the efficacy of female-equivalent dispensers can be equivalent to that of polyethylene-tube reservoir tubes in disrupting codling moth. However, practical drawbacks of aerial application and poor retention of the applied formulation limit the effectiveness of Scentry fibres. When applied to tree foliage by hand to maximize the potential of retention, Hercon flakes were not as effective in disrupting codling moth orientation to traps as were Scentry fibres, which were equivalent to Isomate dispensers in efficacy. This may be explained by the slightly greater attractiveness of Scentry fibres than Hercon flakes as determined by the trapping study (Tables 3 and 4). In addition, clusters of eight and 24 Scentry fibres and eight and 24 Hercon flakes were as attractive as individual dispensers of each type, indicating that clusters of multiple dispensers should also function as attractive point sources when deployed from mechanized spray equipment.

When applied aerially to 4-ha blocks of commercial apple, Scentry fibres were as effective as hand-applied Isomate dispensers in disrupting male orientation to traps during the second generation of moth flight. Fruit injury was also equivalent between plots treated with Scentry fibres and Isomate dispensers; however, this result was probably affected by concurrent applications of insecticides under commercial growing standards. The lack of effective disruption during the first generation was due to a heavy rain event 1 week after application, which dislodged 100% of the applied formulation. During the second generation, 70% of applied fibres remained on tree foliage 5 weeks after application and half of the fibres were still present on the seventh week. This corresponds to approximately 50 fibres/tree after 7 weeks based on an

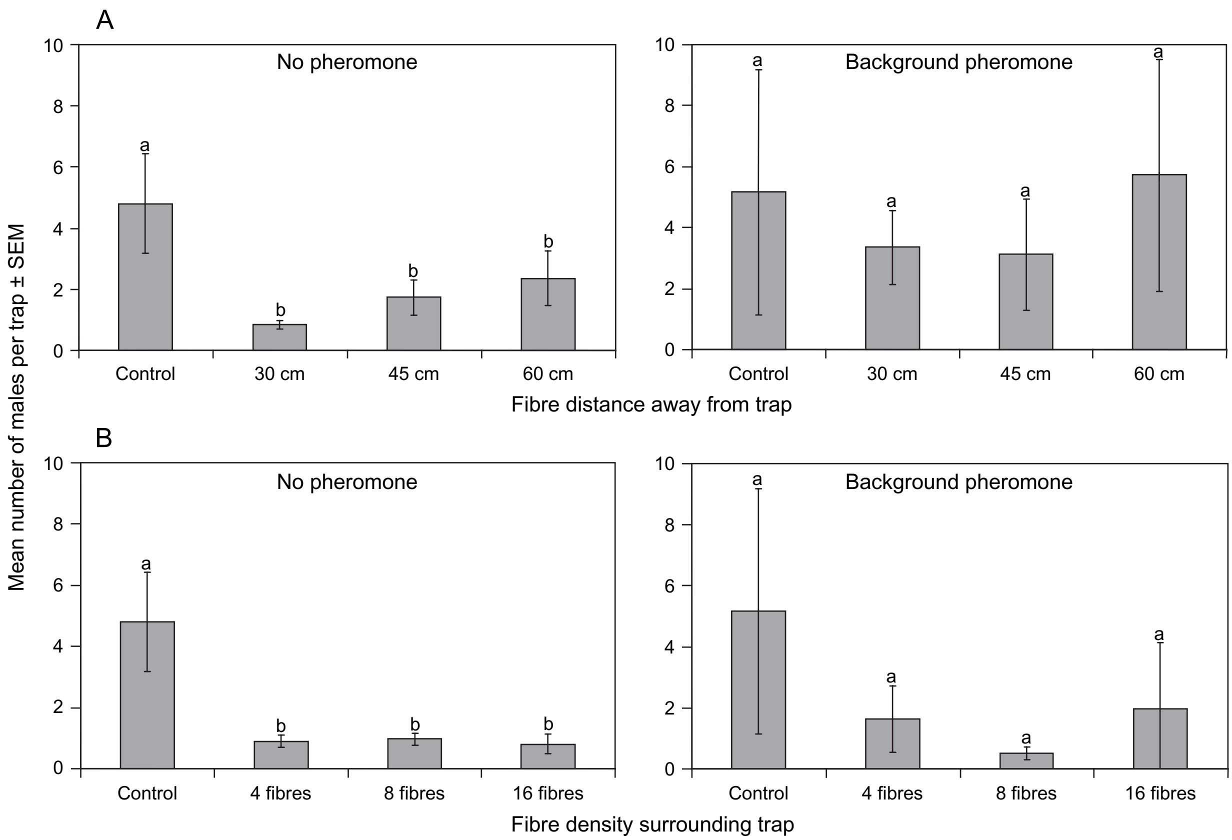

Figure 2 Mean number ± SE of male codling moths captured in pheromone traps baited with 0.1-mg lures surrounded by (A) 8 fibres placed 30, 45, or 60 cm away from the trap or (B) four, eight or 16 fibres placed 45 cm away from the trap in plots not treated with pheromone or treated with 50 Isomate C plus dispensers per hectare. Means followed by the same letter are not significantly different (Tukey's tests, $P > 0.05$).

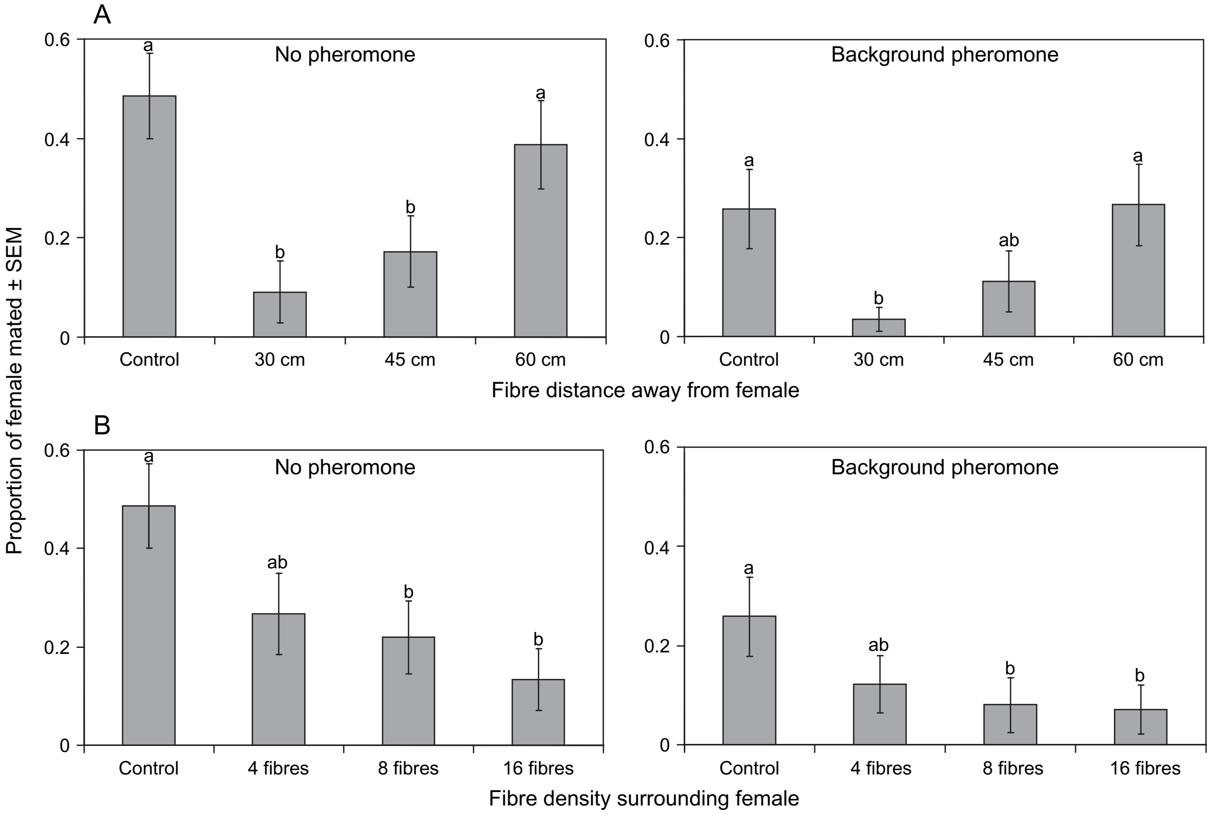

Figure 3 Mean proportion ± SE of tethered virgin female codling moths that were mated after one night in the field when surrounded by (A) eight fibres placed 30, 45, or 60 cm away from the female or (B) four, eight or 16 fibres placed 45 cm away from the female in plots not treated with pheromone or treated with 50 Isomate C plus dispensers per hectare. Means followed by the same letter are not significantly different (Tukey's tests, $P > 0.05$).

estimated 115 fibres realized per tree on the day of application. The aerial application of fibres was highly inefficient with almost 44% of the formulation falling to the orchard floor where it does not contribute to disruption. Recently, a tractor-mounted mechanical applicator was developed for Scentry fibres similar to the one described by Stelinski *et al.* (2006b), which may improve efficiency of fibre deposition onto trees. However, even with 50 fibres/tree, only 62–76% and 70% disruption were obtained in the small and large plot experiments, respectively, suggesting that this density of fibres per area of crop was not sufficient for effective disruption under the codling moth population densities observed in these studies.

Another drawback of this technology, in addition to low efficiency of product adherence to crop foliage, was poor rainfastness. Heavy rains rendered the first generation application completely ineffective and the formulation was also progressively lost over the course of the second generation (Fig. 1). Increasing the effectiveness of the Bio-Tak sticker adhesive is a potential solution; however, a highly effective sticker during a second generation application when apples are present may be unacceptable if fibres remain on harvested fruit. This may be a particularly difficult problem to overcome for a fibre formulation targeting codling moth, given the phytotoxicity of the codlemone active ingredient (Giroux & Miller, 2001).

Male codling moths were captured in monitoring traps and mated with tethered virgin females that were surrounded by eight fibres 30 cm away or 16 fibres 45 cm away. Although disruption was improved by increasing the number of fibres surrounding a monitoring trap or a tethered virgin female, as well as by decreasing the distance between the fibres and traps or females, realized disruption was never above 82%. Male oriental fruit moths, *Grapholita molesta* (Busck), are capable of efficiently discriminating between multiple overlapping pheromone plumes (Valeur & Löfstedt, 1996). Moreover moths are known to efficiently discriminate the boundaries of pheromone plumes within homogenous background concentrations of pheromone (Sanders, 1996; Schofield *et al.*, 2003). The current results obtained with the codling moth are consistent with these previous findings and imply that feral male codling moth were capable of discriminating among multiple plumes (i.e. those emanating from the trap or female as well as those from surrounding fibres). It appears that persistent searching behavior exhibited by a portion (approximately 13%) of those moths having oriented to traps or females surrounded by fibres resulted in successful location of the central trap or female. In both otherwise untreated and Isomate-treated plots, 4–39% of females surrounded with four to 16 fibres were mated. Therefore, calling females perched at least 30 cm away from fibres are vulnerable of being mated. It is possible that the female's natural multi-component pheromone (Witzgall *et al.*, 2001) is more attractive to males than the synthetic codlemone alone released from fibres.

Effective disruption of codling moth appears to be dependent on both competitive attraction of males to plumes of synthetic pheromone and subsequent central nervous system habituation of male response due to overexposure (Witzgall *et al.*, 2008). Isomate C Plus dispensers are known to both attract male codling moths (Barrett, 1995; Knight *et al.*, 1999; Stelinski *et al.*, 2004, 2005) and brief exposure within metres of such dispensers strongly habituates the males' central nervous system (Stelinski *et al.*, 2006a). Given their release rate of approximately 0.1 μg/h (Weatherston *et al.*, 1985), fibres probably disrupt male orientation by competitive attraction without associated habituation (Stelinski *et al.*, 2006a) and, thus, the efficacy of this formulation will be highly dependent on codling moth density. Future improvements to female-equivalent technologies that may improve efficacy include: (i) improving mechanical application so a greater proportion of applied formulation adheres to tree canopies; (ii) increasing attractiveness of individual dispensers; and (iii) increasing release rate per dispenser (which may require decreasing point source density per area of crop) to increase the likelihood of sensory habituation.

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