Sprayable Microencapsulated Sex Pheromone Formulations for Mating Disruption of Four Tortricid Species: Effects of Application Height, Rate, Frequency, and Sticker Adjuvant

L. L. STELINSKI,[1,2] P. MCGHEE,[1] M. HAAS,[1] A. L. IL'ICHEV,[3] AND L. J. GUT[1]

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ABSTRACT Several application parameters of microencapsulated (MEC) sex pheromone formulations were manipulated to determine their impact on efficacy of disruption for codling moth, *Cydia pomonella* (L.); oriental fruit moth, *Grapholita molesta* (Busck); obliquebanded leafroller, *Choristoneura rosaceana* (Harris); and redbanded leafroller, *Argyrotaenia velutinana* (Walker). Depending on the experiment, the formulations evaluated were those formerly manufactured by 3M Canada (London, ON, Canada) or those that are currently available from Suterra LLC (Bend, OR). The efficacy of MEC formulations applied by air-blast sprayer evenly throughout the entire canopy of 2–3-m-tall apple (*Malus* spp.) trees was equivalent to treatments in which targeted applications of MECs were made to the lower or upper 1.5 m of the canopy (at equivalent overall rates) for oriental fruit moth and both leafroller species. The realized distribution of deposited microcapsules within the tree canopy corresponded well with the intended heights of application within the canopy. The additional coapplication of the pine resin sticker Nu-Film 17 increased efficacy but not longevity of MEC formulations for oriental fruit moth; this adjuvant had no added effects for codling moth or leafroller formulations. Increasing the rate of active ingredient (AI) per hectare by 20–30-fold (range 2.5–75.0 g/ha) did not improve the disruption efficacy of MECs for codling moth or either leafroller species when both low and high rates were applied at equivalent frequencies per season. A low-rate, high-frequency (nine applications per season) application protocol was compared with a standard protocol in which two to three applications were made per season, once before each moth generation for each species. The low-rate, high-frequency protocol resulted in equivalent or better disruption efficacy for each moth species, despite using two-fold less total AI per hectare per season with the former treatment. The low-rate, frequent-application protocol should make the use of MEC formulations of synthetic pheromone more economical and perhaps more effective.

KEY WORDS mating disruption, sprayable microencapsulated pheromone, Tortricidae

Disruption of moth mating by broadcasting synthetic pheromone formulations into crops has been successfully integrated into management programs for tortricid moth species in the Western (e.g., Gut and Brunner 1998) and Eastern (e.g., Atanassov et al. 2002) United States, Canada (e.g., Trimble et al. 2001), Australia (e.g., Il'ichev et al. 2002), and Europe (e.g., Louis et al. 2002). With increased reliance on "reduced risk" chemistries (Wise et al. 2003, 2004) in the face of restricted broad-spectrum options and widely developing resistance to organophosphates (Chapman and Barrett 1997, Pree et al. 1998, Kanga et al. 2003, Reuveny and Cohen 2004), mating disruption may become an increasingly important component of integrated management programs for tortricid pests. In fact, application of pheromone-based mating disruption has proven to reduce the number of required coapplied broad-spectrum insecticide sprays for adequate control of codling moth, *Cydia pomonella* (L.), and oriental fruit moth, *Grapholita molesta* (Busck) (Rice and Kirsch 1990, Gut and Brunner 1998, Walker and Welter 2001).

In Michigan, there is a complex of mainly four tortricid species infesting commercially grown apples (*Malus* spp.), including codling moth; oriental fruit moth; obliquebanded leafroller, *Choristoneura rosaceana* (Harris); and redbanded leafroller, *Argyrotaenia velutinana* (Walker). This complicates the implementation of mating disruption given the need for multispecies control. Polyethylene tube dispensers have proven moderately to highly effective for disruption of all four of these pests (Deland et al. 1994, Knight et al. 1998, Evenden et al. 1999, Trimble et al. 2001, Atanassov et al. 2002, Trimble and Appleby 2004, Stelinski

[1] Department of Entomology, Michigan State University, East Lansing, MI 48824.
[2] Current address: Entomology and Nematology Department, Citrus Research and Education Center, University of Florida, 700 Experiment Station Rd., Lake Alfred, FL 33850 (e-mail: stelinski@ufl.edu).
[3] Department of Primary Industries, Primary Industries Research Victoria, Tatura, 3616, Victoria, Australia.

et al. 2005b, Epstein et al. 2006); however, hand application of this technology renders it cost-prohibitive for many Michigan growers (Gut et al. 2004).

Sprayable formulations in which synthetic pheromone is encapsulated in microscopic polymer capsules offers a possible solution to the labor cost associated with hand-applied dispensers given that microencapsulated (MEC) pheromones are applied to crops via standard air-blast sprayers. Another advantage of these formulations is their compatibility with other orchard management chemicals, such as pesticides and fertilizers. The idea of applying microencapsulated pheromones for mating disruption is more than three decades old (Cardé et al. 1975, Taschenberg and Roelofs 1976), and research toward improvement of this technology persists today. Recent investigations of microencapsulated pheromones have consistently shown effective disruption of oriental fruit moth (Trimble et al. 2004, Kovanci et al. 2005, Il'ichev et al. 2006). Although efficacy of such formulations has been limited for codling moth (Epstein et al. 2003, Stelinski et al. 2005a), improved disruption has been reported with development of a low-volume application method (Knight and Larsen 2004). A recent evaluation of a microencapsulated formulation for disruption of obliquebanded leafroller revealed poor to moderate (50–80%) efficacy; addition of the microencapsulated pheromone treatment to a conventional insecticide program did not improve fruit protection compared with the insecticide program without pheromone (Trimble and Appleby 2004).

The objective of the current study was to investigate the effect of several application parameters of sprayable microencapsulated formulations on 1) disrupting orientation of codling moth, oriental fruit moth, obliquebanded leafroller, and redbanded leafroller to pheromone traps; and 2) preventing fruit damage. Factors investigated included 1) height of application within the tree canopy, 2) rate of active ingredient (AI) applied per hectare of crop, 3) coapplication with a sticker adjuvant (Nu-Film 17), and 4) the application frequency of low versus high rates of AI throughout the season. The overall goal of the study was to identify factors that may lead to improved efficacy of microencapsulated pheromones for disruption of the tortricid pest complex in Michigan.

Materials and Methods

Pheromone Formulations. The MEC pheromone formulations from 3M Canada (London, ON, Canada) were MEC-OFM Phase V, MEC-CM Phase IVe, and MEC-LR Phase V for oriental fruit moth, codling moth, and both the oblique and redbanded leafrollers, respectively. The MEC-OFM Phase V formulation contained 18.6% (*Z*)-8-dodecen-1-yl-acetate, 1.2% (*E*)-8-dodecen-1-yl-acetate, 0.2% (*Z*)-8-dodecen-1-ol, and 80% inert ingredients. The MEC-CM Phase IVe formulation contained 10% (*E,E*)-8,10-dodecadien-1-ol and 90% inert ingredients. The MEC-LR Phase V formulation contained 20% (*Z*)-11-tetradecenyl acetate and 80% inert ingredients. In addition, Checkmate OFM-F and CM-F (Suterra LLC, Bend, OR) were tested for oriental fruit moth and codling moth, respectively. The OFM-F contained 21.9% (*Z*)-8-dodecen-1-yl-acetate, 1.5% (*E*)-8-dodecen-1-yl-acetate, 0.3% Z-8-dodecen-1-ol, and 76.4% inert ingredients. The CM-F contained 14.3% (*E,E*)-8,10-dodecadien-1-ol and 85.7% inert ingredients.

Effect of Application Height. This experiment tested the hypothesis that disruption efficacy of MEC pheromones is affected by the height at which microcapsules are applied within the tree canopy. The experiment was conducted at the Trevor Nichols Research Complex (TNRC) of Michigan State University in Fennville, MI, in apple trees with ≈2–3-m canopy heights and described by Stelinski et al. (2004). Orchard plots were maintained according to grower standard maintenance protocols in Michigan, but they did not receive applications of insecticides. The treatments compared were 1) MEC applied by a standard air-blast sprayer (model 1029, FMC Corp., Lakeland, FL) with six nozzles directed toward the entire tree canopy, 2) MEC applied by the FMC air-blast sprayer with two operating nozzles directed toward the bottom 1.5 m of the tree canopy and the orchard floor, 3) targeted application of MEC to the upper 1.5 m of tree canopy with a Protec sprayer (Proptec, Bath, MI), and 4) a no pheromone control. All sprays were applied with water at ≈240 liters/ha; application pressures did not exceed 150 psi. For each height treatment evaluated, the MEC-OFM and -LR formulations were applied at the start of each moth generation by using 37.0 and 74.0 g AI/ha, respectively. Treatments for oriental fruit moth and the leafroller species were applied to separate sets of plots. The experimental designs were randomized complete blocks with four 0.4-ha replicates per treatment. Treatments were spaced by 0.4-ha buffers. The test was conducted for 24 d after application of MEC pheromones by monitoring moth catch in pheromone-baited delta traps (LPD Scenturian Guardpost, Suterra LLC) deployed in the central trees of treated plots. For the oriental fruit moth treatment, one trap was placed in the upper third of the tree canopy per replicate plot. For the leafroller treatment, two traps (one for each species) were deployed in each plot at least 6 m apart at the same height as oriental fruit moth traps. For oriental fruit moth, traps were baited with red rubber septa loaded with 0.1 mg of (*Z*)-8-dodecenyl acetate:(*E*)-8-dodecenyl acetate: Z-8-dodecen-1-ol in a 100:6:10 blend. For obliquebanded leafrollers, rubber septa were loaded with 0.485 mg of (*Z*)- and 0.015 mg of (*E*)-11-tetradecenyl acetates (92.2:3.0 ratio of *Z*:*E*) and 0.026 mg of (*Z*)-11-tetradecenol. For redbanded leafrollers, rubber septa were loaded with 0.93 mg of (*Z*)- and 0.07 mg of (*E*)-11-tetradecenyl acetates (93:7 ratio of *Z*:*E*) and 2.0 mg of dodecyl acetate. Moths captured in traps were counted and removed weekly.

In addition to evaluating the disruption efficacy of the three height treatments, we confirmed the realized distribution of deposited microcapsules within the tree canopy. MEC-LR was coapplied with 10.0 g of fluorescent tracer dye per hectare (Saturn Yellow

EPX-17, Day-Glo Color Corp., Cleveland, OH) to the entire canopy, upper canopy, or lower canopy of 0.4-ha plots as described above. One hundred leaves were collected from the top, middle, and bottom 1.5-m portions of the tree canopy for each application height treatment. UV illumination was used to visualize and count the number of microcapsules adhering to leaves after application of each treatment with a dissecting microscope (50× magnification and a 14-mm^2 field of view). The proportions of leaves containing microcapsules in the top, middle, and lower 1.5 m of the tree canopy was determined for each application height treatment.

Effect of Application Rate. This experiment tested the hypothesis that disruption efficacy of MEC pheromones is affected by rate of AI applied per hectare of crop. This experiment was conducted with both MEC-CM Phase IVe and MEC-LR Phase V formulations for codling moth and leafroller disruption, respectively, at the TNRC. The MEC-CM dosages compared were 0, 2.5, and 50.0 g AI/ha and the MEC-LR dosages compared were 0, 2.5, 37.5, and 75.0 g AI/ha. All treatments were applied with a standard air-blast application (as per treatment 1 under Effect of Application Height). Treatments for codling moth and the leafroller species were applied to separate sets of plots. The experimental designs were randomized complete blocks with four 0.14-ha replicate plots per treatment. Treatments were spaced by 0.4-ha buffers. For codling moth, the MEC applications were made once before the first (11 May) and second (26 June) generations of moth flight. Applications of MEC for leafrollers were made on 11 June and 17 August, which corresponded to the beginning of the first and second generations of obliquebanded leafroller flight. Male moth catch in pheromone-baited delta traps deployed centrally in plots in the upper third of the tree canopy was monitored season-long with one codling moth trap per plot in the MEC-CM experiment and one trap for each leafroller species per plot (spaced 6 m apart) in the MEC-LR experiment. Traps for codling moth were baited with red septa loaded with 1.0 mg of (*E,E*)-8,10-dodecadien-1-ol, and leafroller traps for each species were baited as described above. Moths captured in traps were counted and removed weekly. In addition, mid-season and harvest damage evaluations were conducted by inspecting 30 randomly selected fruit (15 high and 15 low in the canopy) from each of 12 trees per treatment replicate for codling moth and leafroller damage.

An additional experiment was conducted in a larger plot setting evaluating the efficacy of both MEC-CM and MEC-LR applied simultaneously. Treatments were applied to 1.5-ha plots of commercially maintained apples in Douglas, MI. Both treatments were applied at 50.0 g AI/ha and compared against a no pheromone control. Plot maintenance protocols for MEC-treated and control plots were otherwise identical. The experiment was conducted as a randomized complete block with three replicates. MEC-CM was applied on 14 May, 23 July, and 23 August. MEC-LR was applied on 20 June and 23 August. Catches of male codling moth, obliquebanded leafrollers, and redbanded leafrollers were monitored weekly with two pheromone traps for each species deployed per plot placed in trees as described above. Traps were deployed at least 15.2 m away from plot borders and at least 6 m apart from one another. In addition, a mid-season evaluation of 30 randomly selected fruit as described above from each of 20 randomly selected trees per treatment replicate was conducted.

Effect of Nu-Film 17 Addition. This experiment tested the hypothesis that application of Nu-Film 17 (di-1-*p*-menthene, Miller Chemical and Fertilizer Corporation, Hanover, PA) in concert with MEC-OFM, -CM, -LR (3M Canada) or Checkmate OFM-F and CM-F (Suterra LLC) would improve disruption efficacy over standard applications. Nu-Film 17 is a sticker-spreader designed to extend the length of efficacy of foliar-applied insecticides and fungicides by promoting product adherence and rainfastness. This experiment was conducted at the TNRC. The treatments compared were 1) MEC treatments applied without Nu-Film 17, 2) MEC treatments coapplied with Nu-Film 17, and 3) check plots not receiving sprays. Nu-Film 17 was applied at 0.6 liters/ha. MEC-OFM and CM with and without Nu-Film 17 were applied at 37.5 and 50.0 g AI/ha, respectively, on 10 May, 2 July, and 2 August. Also, on 25 July, an additional application of MEC-CM was deployed with and without Nu-Film 17. OFM-F with and without Nu-Film 17 was applied at 37.5 g AI/ha on 3 May, 2 July, and 7 August and CM-F at 50.0 g AI/ha on 15 May, 7 June, and 25 July. The 3M Canada and Suterra formulations were applied to separate sets of plots. The experimental designs were randomized complete blocks with four 0.4-ha replicates per treatment. Treatments were spaced by 0.4-ha buffers. One pheromone trap for each species was deployed per plot in a central tree. Treatment efficacy was assessed with weekly counts of male moth catch in pheromone traps according to the protocols described above.

Effect of Application Rate and Frequency. This experiment tested the hypothesis that disruption efficacy of MEC formulations could be maintained or increased by spraying frequent applications of a lower rate of AI per season (nine total applications) compared with fewer applications of a higher (standard) rate per season (two to three total applications), once before the onset of each moth generation. The experiment was conducted at two commercial orchards in the fruit ridge apple production region north of Grand Rapids, MI, and one commercial orchard in southwestern Michigan. The treatments compared for each species were 1) a low rate of MEC applied every 10–14 d during each flight, 2) a high rate of the same MEC formulation applied once at the start of each moth flight, and 3) a no pheromone control. All plots on each farm were treated identically with insecticide programs to prevent unacceptable levels of fruit damage at harvest. The low-rate MEC-CM and -OFM treatments were applied at 6.3 g AI/ha every 10–14 d throughout the season for a total of nine applications (56.7 g AI/season). The low-rate MEC-LR treatment

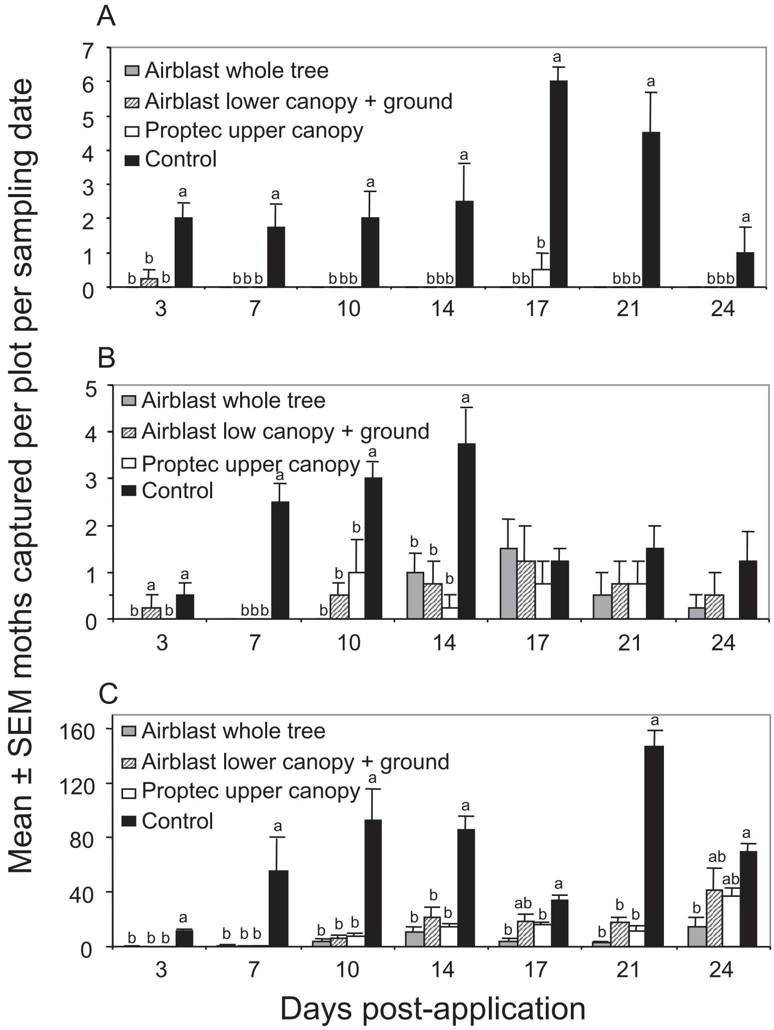

Fig. 1. Mean ± SEM weekly captures of male redbanded leafroller (A), obliquebanded leafroller (B), and oriental fruit moth (C) in pheromone traps in plots treated with MEC-LR or MEC-OFM applied by air-blast sprayer to the entire tree canopy, toward the bottom 1.5 m of the tree canopy and the orchard floor, targeted to the upper 1.5 m of tree canopy, or not treated with pheromone (control). Means followed by the same letter within a sampling date are not significantly different ($P > 0.05$; ANOVA followed by LSD).

was applied at 12.5 g AI/ha every 10–14 d throughout the season nine times in total (112.5 g AI/season). The high-rate MEC-CM, -OFM, and -LR treatments were applied at 37.5, 50.0, and 75.0 g AI/ha, respectively, at the start of each moth generation (13 May and 17 June for codling moth; 29 April, 25 June, and 12 August for oriental fruit moth; and 10 June and 29 July for leafrollers). MEC treatments were applied with a standard air-blast application (as per treatment 1 under Effect of Application Height). Replicate plots were 2–4 ha, and they were spaced by 0.5-ha buffers at minimum. The three MEC formulations for the four species were applied to plots simultaneously at either low and frequent or high and infrequent application protocols. Moth catch using two pheromone traps for each species deployed per plot as described above was monitored weekly throughout the season. Traps were distributed evenly throughout blocks at least 15.2 m away from plot borders, and they were spaced by at least 6 m. Mid-season and harvest assessments of fruit injury were conducted by evaluating 30 randomly selected fruit as described above from each of 20 randomly selected trees per plot.

Statistical Analyses. Trapping data were transformed to $\ln(x + 1)$ (to normalize the distributions and homogenize variance), and then they were subjected to analysis of variance (ANOVA). Fruit injury data were arcsine transformed before ANOVA. Differences in pairs of means were separated using Fisher least significant difference (LSD) tests (SAS Institute 2000). In all cases, the significance level was $\alpha < 0.05$. Percentage of orientational disruption was calculated as $1 -$ (mean moth catch per trap in the pheromone-treated block/mean moth catch per trap in the control block) $\times$ 100.

Table 1. Effect of microencapsulated pheromone (MEC-CM, 3M Canada) rate per hectare on catches of codling moth males in pheromone traps and fruit injury

Plot size (ha)	AI (g/ha)	Mean ± SEM moth capture		Mean ± SEM fruit injury	
		First generation	Second generation	Mid-season	Harvest
0.14	0.0	23.8 ± 6.7a	70.7 ± 10.2a	3.9 ± 1.2a	14.4 ± 2.4a
0.14	2.5	14.5 ± 2.3b	40.3 ± 7.2b	2.4 ± 0.9a	17.6 ± 3.1a
0.14	50.0	14.8 ± 1.9b	39.2 ± 9.1b	4.8 ± 1.1a	14.4 ± 0.8a
1.5	0.0	29.8 ± 5.1a	34.0 ± 7.6a	5.1 ± 0.3a	
1.5	50.0	8.8 ± 2.1b	6.0 ± 0.9b	4.2 ± 0.7a	

Means within columns followed by the same letter are not significantly different ($P > 0.05$; ANOVA followed by LSD).

Table 2. Effect of microencapsulated pheromone (MEC-LR, 3M Canada) rate per hectare on catches of obliquebanded and redbanded leafroller males in pheromone traps and fruit injury

Plot size (ha)	AI (g/ha)	Mean ± SEM moth capture		Mean ± SEM fruit injury	
		Redbanded leafroller	Obliquebanded leafroller	Mid-season	Harvest
0.14	0.0	40.7 ± 8.2a	27.7 ± 3.1a	1.9 ± 0.3a	15.7 ± 2.7a
0.14	2.5	12.7 ± 1.7b	17.2 ± 4.2b	2.2 ± 0.9a	6.9 ± 1.1b
0.14	37.5	12.7 ± 0.9b	11.5 ± 2.6b	2.4 ± 1.1a	9.0 ± 1.7ab
0.14	75.0	9.3 ± 1.4b	19.7 ± 1.8b	3.4 ± 0.8a	8.5 ± 1.2b
1.5	0.0	185.3 ± 23.8a	9.8 ± 2.2a	1.7 ± 0.9a	
1.5	50.0	15.8 ± 4.7b	1.0 ± 0.8b	4.1 ± 1.0a	

Means within columns followed by the same letter are not significantly different ($P > 0.05$; ANOVA followed by LSD).

Results

Effect of Application Height. For redbanded leafrollers, only two and five moths were captured during the 24-d experiment in plots sprayed with MEC low and high in the tree canopy, respectively; none were captured for the duration of the experiment in the whole-canopy application treatment (Fig. 1A). With the exception of the upper canopy treatment on day 3, captures of male obliquebanded leafrollers were significantly ($F = 22.1$; df = 3, 15; $P < 0.001$) reduced by all three treatments for the initial 14 d of the test; thereafter, moth catch between all three application height treatments and the control were not significantly ($F = 1.7$; df = 3, 15; $P = 0.1$) different (Fig. 1B). For the initial 14 d of the test, there was no significant ($F = 0.9$; df = 3, 15; $P = 0.2$) difference in efficacy between the three application height treatments for obliquebanded leafroller (Fig. 1B). Catch of male oriental fruit moth in pheromone traps was significantly ($F = 17.6$; df = 3, 15; $P < 0.001$) disrupted by all three height treatments compared with the control for the initial 21 d of the experiment (Fig. 1C). By day 24, only the whole canopy application maintained significant ($F = 12.4$; df = 3, 15; $P = 0.02$) disruption compared with the control (Fig. 1C). For 21 d, there was no significant ($F = 1.1$; df = 3, 15; $P = 0.4$) difference in disruption efficacy of oriental fruit moth between the three application height treatments (Fig. 1C).

Of those leaves that contained adhered microcapsules, an average of 2.4 ± 0.7 was counted per cm^2 of leaf surface area. In the whole canopy air-blast application treatment with six nozzles, the percentage of leaves found with microcapsules from the upper (30.6%), middle (36.4%), and lower (32.9%) 1.5-m portions of the tree canopy was nearly identical. For the Proptec-directed application to the upper one third of the tree canopy, 66.7, 28.6, and 0.05% of the leaves collected high, middle, and low in the canopy contained microcapsules, respectively. For the air-blast treatment with two nozzles directed at the lower 1.5 m of the tree canopy and the orchard floor, 0.03, 19.3, and 77.3% of leaves collected high, mid, and low in the canopy contained microcapsules, respectively. No microcapsules were found in untreated control plots.

Effect of Application Rate. In the small plot experiment, captures of male codling moth in pheromone traps were significantly (F's = 45.1 and 36.3; df = 2, 13, P's < 0.001) reduced by both 2.5 and 50.0 mg AI/ha treatments of MEC-CM compared with untreated plots; however, there was no significant ($F = 1.6$; df = 3, 15; $P = 0.2$) difference between the two rate treatments during both generations (Table 1). Percentage of disruption ranged between 39 and 43 and 38 and 45 for the 2.5- and 50.0-mg AI/ha treatments, respectively. In the large plot experiment, significantly ($F = 15.5$; df = 2, 5; $P = 0.01$) fewer male codling moth were captured in traps in plots treated with the 50.0 mg AI/ha treatment compared with the control and percentage of disruption ranged between 71 and 82 (Table 1). There were no significant differences in fruit injury detected at mid-season ($F = 1.7$; df = 2, 13; $P = 0.2$) and harvest ($F = 1.9$; df = 2, 13; $P = 0.2$) in the small plot experiment and at mid-season in the large plot experiment ($F = 0.9$; df = 2, 5; $P = 0.4$) (Table 1).

Captures of both obliquebanded (F's = 25.1 and 15.7; df = 3, 15; P's < 0.001) and redbanded leafroller (F's = 55.1 and 19.2; df = 3, 15; P's < 0.001) males were significantly reduced at each rate per hectare tested compared with untreated plots over the course of the season (Table 2). However, there was no significant ($F = 1.3$; df = 3, 15; $P = 0.3$) difference in disruption efficacy between the three application rates per hectare tested for either species (Table 2). Percentage of disruption for redbanded and obliquebanded leafrollers ranged between 69 and 77 and 29 and 58, respectively. In the large plot trial, significantly fewer redbanded leafrollers ($F = 13.4$; df = 2, 5; $P = 0.02$) and obliquebanded leafrollers ($F = 15.1$; df = 2, 5; $P = 0.01$) were captured in MEC-LR-treated blocks compared with untreated controls (Table 2). Percentage of disruption for these two species was 91 and 90, respectively. During the first generation, there were no significant (F's = 1.5 and 1.7; df = 3, 15; P's = 0.1) differences in leafroller damage in the small plot and large plot experiments. However, fruit injury due to leafroller was significantly (F's = 11.7 and 9.8; df = 3, 15; P's = 0.04 and 0.05) reduced at harvest in the small plot trial for the 2.5 and 75.0 g AI/ha treatments compared with the control treatment (Table 2).

Table 3. Effect of coapplied Nu-Film 17 on efficacy of 3M microencapsulated pheromone formulations (MEC-OFM, -CM, and -LR) on catches of oriental fruit moth, codling moth, and obliquebanded leafroller, respectively, in pheromone traps

Species	Date applied	Monitoring period	No pheromone	MEC-OFM, -CM, or -LR without Nu-Film 17	MEC-OFM, -CM, or -LR with Nu-Film 17
Oriental fruit moth		Before first spray		69.6 ± 13.2a	48.1 ± 9.6a
	10 May	10–27 May	96.1 ± 18.5a	30.8 ± 9.6b	8.6 ± 1.7c
		27 May–2 July	252.9 ± 13.1a	163.4 ± 16.7b	112.0 ± 9.2c
	2 July	2–24 July	476.6 ± 34.6a	173.1 ± 21.4b	57.0 ± 12.1c
		24 July–7 Aug.	139.6 ± 22.0a	60.8 ± 13.1b	37.8 ± 9.2b
	2 Aug.	7–28 Aug.	847.9 ± 48.2a	328.4 ± 18.0b	170.9 ± 16.4c
		28 Aug.–23 Sept.	982.1 ± 45.0a	96.4 ± 16.8b	144.4 ± 23.4b
Codling moth		Before first spray	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	15 May	22 May–7 June	97.9 ± 13.8a	38.8 ± 7.8b	39.5 ± 9.0b
	7 June	7–28 June	73.3 ± 8.3a	3.8 ± 1.2b	4.0 ± 0.9b
		28 June–25 July	118.0 ± 19.2a	27.9 ± 5.9b	34.9 ± 7.8b
	25 July	25 July–7 Aug.	133.6 ± 14.2a	45.4 ± 8.3b	37.3 ± 5.1b
		7 Aug.–18 Sept.	104.1 ± 11.1a	27.1 ± 5.4b	13.3 ± 1.9b
Obliquebanded leafroller		Before first spray	2.5 ± 0.7a	3.8 ± 0.8a	5.0 ± 1.1a
	24 June	24 June–18 July	10.6 ± 1.6a	0.4 ± 0.2b	0.0 ± 0.0b
		18 July–14 Aug.	14.0 ± 4.9a	4.8 ± 3.9a	9.3 ± 2.8a
	14 Aug.	14 Aug.–20 Sept.	9.9 ± 1.7a	0.9 ± 0.4b	0.9 ± 0.2b

Means within rows followed by the same letter are not significantly different ($P > 0.05$; ANOVA followed by LSD).

Effect of Nu-Film 17 Addition. MEC-OFM with or without coapplied Nu-Film 17 significantly ($F = 22.7$; df = 2, 11; $P < 0.001$) disrupted orientation of oriental fruit moth males to traps for the duration of the study (Table 3). Addition of Nu-Film 17 to MEC-OFM significantly (F's = 12.3 and 17.2; df = 2, 11; P's = 0.05) improved disruption 10 May–24 July and again 7–28 August (Table 3). Percentage of disruption achieved by MEC-OFM with and without coapplied Nu-Film 17 ranged between 56 and 91 and 35 and 90, respectively, throughout the experiment. MEC-CM and -LR with or without Nu-Film 17 significantly (F's = 18.7 and 31.6; df = 2, 11; P's = 0.01 and <0.001) disrupted male codling moth and obliquebanded leafroller, respectively, for the duration of the test; there was no significant (F's = 0.7 and 2.1; df = 2, 11; P's = 0.1 and 0.5) increase in disruption with coapplied Nu-Film 17 in both cases (Table 3). Percentage of disruption achieved by MEC-CM with or without Nu-Film 17 ranged between 60 and 95. Disruption achieved by MEC-LR with and without Nu-Film 17 ranged between 34 and 100 and 66 and 96, respectively, throughout the experiment.

Checkmate OFM-F without Nu-Film 17 significantly ($F = 11.7$; df = 2, 11; $P = 0.02$) disrupted orientation of male oriental fruit moth for the duration of the test (Table 4). There was a significant ($F = 27.2$; df = 2, 11; $P < 0.001$) improvement in disruption with coapplied Nu-Film 17 during 2 July–23 September (Table 4). Percentage of disruption of oriental fruit moth with and without Nu-Film 17 ranged between 78 and 99 and 66 and 99, respectively. Disruption of male codling moth with Checkmate CM-F without coapplied Nu-Film 17 was significant (F's = 13.4 and 17.2; df = 2, 11; P's = 0.05 and 0.02) during 7–28 June and 25 July–7 August compared with control plots. Similarly CM-F with coapplied Nu-Film 17 was significant (F's = 22.4, 19.0, and 10.8; df = 2, 11; P's < 0.001, = 0.01, and = 0.05) during 7–28 June, 25 July–7 August, and 7 August–18 September compared with control plots. However, there was no significant ($F = 1.2$; df = 2, 11; $P = 0.3$) improvement of coapplying Checkmate MEC

Table 4. Effect of coapplied Nu-Film 17 on efficacy of Checkmate OFM-F and CM-F (Suterra LLC) microencapsulated pheromone formulations on catches of oriental fruit moth and codling moth, respectively, in pheromone traps

Species	Date applied	Monitoring period	No pheromone	MEC-OFM or -CM without Nu-Film 17	MEC-OFM or -CM with Nu-Film 17
Oriental fruit moth		Before first spray	1.7 ± 0.3a	1.5 ± 0.3a	1.5 ± 0.1a
	3 May	4–21 May	132.5 ± 12.7a	1.8 ± 0.5b	2.2 ± 0.4b
	2 July	21 May–2 July	471.0 ± 23.4a	107.8 ± 15.1b	105.8 ± 18.3b
		2–24 July	546.2 ± 43.2a	30.6 ± 5.6b	4.4 ± 0.2c
		24 July–7 Aug.	164.5 ± 13.5a	56.3 ± 7.9b	14.9 ± 2.1c
	7 Aug.	7–28 Aug.	360.5 ± 31.6a	83.0 ± 7.0b	23.7 ± 3.1c
		28 Aug.–23 Sept.	358.8 ± 21.8a	103.5 ± 13.2b	61.8 ± 7.2c
Codling moth		Prior to first spray	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	15 May	22 May–7 June	59.9 ± 9.2a	99.5 ± 10.5a	76.9 ± 19.3a
	7 June	7–28 June	88.1 ± 10.0a	16.1 ± 3.1b	17.5 ± 2.5b
		28 June–25 July	39.9 ± 9.4a	28.3 ± 5.2a	23.1 ± 7.6a
	25 July	25 July–7 Aug.	20.8 ± 4.2a	2.8 ± 0.7b	1.0 ± 0.2b
		7 Aug.–18 Sept.	23.5 ± 2.2a	16.1 ± 1.0ab	11.9 ± 0.5b

Means within rows followed by the same letter are not significantly different ($P > 0.05$; ANOVA followed by LSD).

Table 5. Effect of application rate and frequency of 3M microencapsulated pheromone formulations (MEC-OFM, -CM, and -LR) on catches of oriental fruit moth, codling moth, obliquebanded leafroller, and redbanded leafroller, respectively, in pheromone traps

Species	Mean (SE) captures of male moths per trap per sampling period					
	First generation			Second and third generations[a]		
	High-rate, low-frequency	Low-rate, high-frequency	No pheromone	High-rate, low-frequency	Low-rate, high-frequency	No pheromone
Oriental fruit moth	6.9ab (3.0)	1.4b (0.8)	28.4a (12.8)	5.3ab (4.4)	0.6a (0.2)	63.3b (23.9)
Codling moth	9.3ab (1.2)	4.0b (3.2)	34.0a (18.0)	7.3a (2.2)	9.3a (5.2)	35.6a (19.0)
Obliquebanded leafroller	24.3b (19.9)	39.0ab (25.7)	104.7a (23.8)	16.0b (12.2)	19.7b (14.8)	36.3a (14.5)
Redbanded leafroller	37.0b (22.1)	23.3b (16.4)	69.0a (35.0)	1.3b (1.3)	0.0b (0.0)	27.6a (12.9)

Means within rows followed by the same letter are not significantly different ($P > 0.05$; ANOVA followed by LSD).
[a] Second generation for codling moth; combination of second and third generation flights for oriental fruit moth.

with Nu-Film 17 for this species (Table 4). Percentage of disruption with and without Nu-Film 17 ranged between 0 and 95 and 0 and 87, respectively.

Effect of Application Rate and Frequency. Catch of oriental fruit moth males in traps was significantly (F's = 11.5 and 17.6; df = 2, 5, P's = 0.05 and 0.02) disrupted by the low-rate, high-frequency application protocol compared with untreated control plots during both the first and combined second and third generations of moth flight; there was no significant difference ($F = 0.9$; df = 2, 5; $P = 0.4$) in disruption between the two pheromone application protocols (Table 5). Percentage of disruption of oriental fruit moth achieved by the low- and high-rate applications protocols was 95 and 76, respectively, for the first generation and 99 and 92, respectively, for the combined second and third generations. During the first generation, male codling moth catch in traps was significantly ($F = 12.7$; df = 2, 5; $P = 0.05$) disrupted only by the low-rate, frequent-application protocol; however, there was no significant ($F = 1.7$; df = 2, 5; $P = 0.6$) difference between either protocol and the control treatment during the second generation (Table 5). Percentage of disruption of codling moth with the low- and high-rate application protocols was 73 and 88, respectively, for the first generation and 79 and 74, respectively, for the second generation. For obliquebanded leafroller, there were no significant (F's = 1.7 and 1.4; df = 2, 5; P's = 0.1) differences in disruption between the low- and high-rate protocols for both generations (Table 5). For this species, the low-rate, frequent-application protocol was not significantly ($F = 1.3$; df = 2, 5; $P = 0.2$) different from the control during the first generation flight (Table 5). Percentage of disruption of obliquebanded leafroller with the low- and high-rate application protocols was 77 and 63, respectively, for the first generation and 56 and 46, respectively, for the second generation. For redbanded leafroller, both application protocols significantly disrupted male catch in traps during the first (F's = 23.7 and 19.7; df = 2, 5; P's < 0.001 and = 0.01) and second (F's = 17.7 and 36.7; df = 2, 5; P's = 0.01 and <0.001) generations compared with the control; however, there was no significant ($F = 2.7$; df = 2, 11; $P = 0.2$) difference between the two treatment protocols (Table 5). Percentage of disruption of redbanded leafroller with the low- and high-rate application protocols was 66 and 46, respectively, for the first generation and 100 and 95, respectively, for the second generation.

There were no statistically significant reductions in fruit injury for oriental fruit moth and codling moth (F's = 2.1 and 1.7; df = 2, 5; P's = 0.1) and the two leafroller species (F's = 0.2 and 1.2; df = 2, 5; P's = 0.4 and 0.1) for the first and second generations, respectively (Table 6). However, internal fruit injury was eliminated by the low-rate frequent-application protocol during the first generation, and it was reduced ≈6- and 19-fold by the high- and low-rate protocols, respectively, during the second generation (Table 6). External injury by leafrollers was reduced 4- and 11-fold by the high- and low-rate protocols, respectively, during the first generation, and both treatments reduced injury by approximately two-fold during the second generation (Table 6).

Discussion

The experiments described herein have revealed that certain application parameters of MEC phero-

Table 6. Effect of application rate and frequency of 3M microencapsulated pheromone formulations (MEC-OFM, -CM, and -LR) on fruit injury

Species	Mean (SE) fruit injury per sampling period					
	First generation			Second and third generations[a]		
	High-rate, low-frequency	Low-rate, high-frequency	No pheromone	High-rate, low-frequency	Low-rate, high-frequency	No pheromone
Oriental fruit moth and codling moth	0.2a (0.2)	0.0a (0.0)	0.5a (0.2)	0.9a (0.9)	0.3a (0.2)	5.8a (4.4)
Oblique and redbanded leafrollers	0.2a (0.2)	0.07a (0.07)	0.8a (0.2)	1.8a (0.4)	1.8a (0.5)	3.0a (1.1)

Means within rows followed by the same letter are not significantly different ($P > 0.05$; ANOVA followed by LSD).
[a] Second generation for codling moth; combination of second and third generation flights for oriental fruit moth.

mones impact disruption efficacy, whereas others have no effect. Collectively, we have demonstrated that efficacy is 1) unaffected by application height for oriental fruit moth and the two leafroller species; 2) not improved by increasing the rate of AI applied per hectare when low and high rates are applied at the same frequency for codling moth, obliquebanded leafroller, and redbanded leafroller; 3) improved for oriental fruit moth with the coapplication of the adjuvant Nu-Film 17 but not so for codling moth or the two leafroller species; and 4) equivalent or better for each species when MEC pheromones are applied with a low-rate, frequent-application protocol versus a high-rate, infrequent-application protocol, despite using approximately two-fold less AI per season with the former protocol. Disruption of oriental fruit moth and redbanded leafroller was typically superior to that achieved with codling moth or obliquebanded leafroller throughout the various experiments in the current study. This result is highly congruent with other studies evaluating a broad-range of pheromone dispenser technologies (for review, see Gut et al. 2004).

The effect of application height on efficacy of hand-applied pheromone dispensers has been investigated previously for tortricid pest species. For codling moth, it has been shown that efficacy increases with increasing height of dispenser placement within the tree canopy (Weissling and Knight 1995). A recent similar investigation with oriental fruit moth suggested that vertical positioning of hand-applied dispensers within the tree canopy does not affect disruption efficacy of this species (deLame and Gut 2006). In the current investigation, the two targeted (lower and upper canopy) and whole-canopy application treatments of MEC pheromone correlated well with realized microcapsule deposition based on the leaf evaluations conducted after spraying. However, microcapsules sprayed low or high in the canopy were not less or more effective in disrupting oriental fruit moth and both leafroller species than when applied evenly throughout the 2–3-m-tall tree canopies. These results suggest that application height of MEC formulations has little impact on efficacy of disruption for these three species in modern tree plantings; thus, small differences between air-blast sprayer models should not impact disruption efficacy. Additionally, development of applicators for targeted deposition of microcapsules to the upper canopy of trees, such as the Proptec applicator tested here, does not seem to hold promise for improving efficacy of sprayable pheromones. This finding needs to be confirmed with MEC formulations for codling moth.

Nu-Film 17 is a pine resin sticker developed to increase the rainfastness and associated longevity of efficacy of foliar-applied chemicals. In the current investigation, there was evidence of increased efficacy, but not longevity of both 3M and Suterra MEC formulations for oriental fruit moth; however, there was no added benefit of this adjuvant detected with formulations for codling moth or obliquebanded leafroller. Thus, the increased efficacy for oriental fruit moth is likely explained by increased deposition of microcapsules during application with additional Nu-Film 17 rather than by increased retention of capsules after application. This hypothesis is supported by the results of Waldstein and Gut (2004), who found that retention of microcapsules on leaves dipped in 3M MEC-OFM was not affected by addition of Nu-Film 17. Our results with codling moth are congruent with a laboratory investigation conducted by Knight et al. (2004) using simulated rainfall. Those authors found that coapplication of Nu-Film 17 with an experimental MEC formulation containing 15.7% (*E,E*)-8,10-dodecadien-1-ol AI neither influenced deposition nor retention of microcapsules. The current results suggest that Nu-Film 17 may improve efficacy of MEC formulations for some species, such as oriental fruit moth, but it is unlikely to improve the effectiveness of MEC formulations in general. Other types of adjuvants, such as latex stickers (Knight et al. 2004), may hold greater promise.

Increasing the rate of AI per hectare by 20–30-fold did not improve the disruption efficacy of MEC formulations for codling moth or either leafroller species when both low and high rates were applied at equivalent frequencies. Similar results were obtained with a 3M MEC formulation tested against *Sparganothis sulfureana* (Clemens) (Polavarapu et al. 2001). In that study, application rates ranging between 25 and 187.5 g AI/ha yielded equivalent disruption efficacy. Thus, an emerging general trend is that efficacy of MEC pheromones does not increase with increasing AI per hectare as might be expected with a toxicant. However, a key finding from the current study was that the amount of AI per season of MEC pheromones could be reduced two-fold, while maintaining equivalent or increased efficacy, when applying MEC pheromones at a higher frequency per season (nine applications) compared with a standard two to three applications or once per moth flight. A high-frequency application protocol is highly compatible with Michigan orchard management practices, which require frequent applications of fungicides and insecticides due to prevalent rain events and abundant pest complex. A low-rate, frequent-application protocol should make the use of MEC formulations of synthetic pheromone more economical and perhaps more effective for moth pests in general.

The current investigation evaluated various parameters of MEC pheromone application protocols on disruption efficacy by using formulations from both 3M Canada and Suterra LLC; however, the studies were not designed to compare efficacy of formulations between these two manufacturers. Although, the specific formulations by 3M Canada are no longer manufactured, the results of the current investigation should be applicable to the use of MEC formulations in general, including those currently available from Suterra LLC and those that may be developed in the future.

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