Monitoring Codling Moth (Lepidoptera: Tortricidae) in Apple with Blends of Ethyl (*E*, *Z*)-2,4-Decadienoate and Codlemone

A. L. KNIGHT,[1] R. HILTON,[2] AND D. M. LIGHT[3]

Yakima Agricultural Research Laboratory, Agricultural Research Service, USDA, 5230 Konnowac Pass Rd., Wapato, WA 98951

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ABSTRACT Studies evaluated blends of the pear-derived kairomone ethyl (*E*, Z)-2,4-decadienoate and codlemone, loaded in gray halobutyl septa, as attractants for adult codling moth, *Cydia pomonella* L. Studies were conducted in apple orchards, *Malus domestica* Borkhausen, treated with or without sex pheromone dispensers for mating disruption (MD). Septa were loaded with either one or both compounds at rates of 0.0, 0.3, and 3.0 mg pear ester and 0.0 and 3.0 mg codlemone in the first series of tests. Traps baited with a 3.0/3.0-mg blend caught significantly more males and total number of codling moths than traps baited with either compound alone in both types of orchards. Traps baited with two lures loaded individually with pear ester (3.0 mg) and codlemone (3.0 mg) caught significantly fewer males and total moths than traps baited with the dual lure (3.0/3.0 mg). The addition of 3.0 mg codlemone to pear ester did not significantly affect the capture of female moths. However, increasing the loading of pear ester from 0.3 to 3.0 mg in the dual lure significantly increased female moth catch in the untreated orchard but not in the sex pheromone MD orchard. Increasing the loading of pear ester to 20.0 mg in a dual lure with 3.0 mg codlemone significantly increased total codling moth catch compared with a 3.0 mg codlemone lure, but female catch was significantly lower compared with traps baited with a 3.0 mg pear ester lure. Adding a 3.0 mg pear ester lure to traps baited with a 42.0 mg sex pheromone lure significantly reduced male moth catch compared with the sex pheromone lure alone but did not reduce the catch of female moths compared with traps baited with a 3.0 mg pear ester lure alone.

KEY WORDS *Cydia pomonella*, apple, pear ester, monitoring

MONITORING CODLING MOTH, *Cydia pomonella* L., in orchards treated with sex pheromone mating disruption (MD) is a key prerequisite for its effective management (Knight 1995). Moth catches in traps are used to initiate models that predict the start of egg hatch and to establish action thresholds (Vickers and Rothschild 1991). The standard protocol for using sex pheromone–baited traps (Riedl et al. 1986) is often modified within sex pheromone MD orchards by placing traps high in the canopy and/or on the borders of orchards, increasing the lure loading, and increasing the density of traps (Gut and Brunner 1996). Unfortunately, the placement of traps at distances <0.3 m from year-old and new MD dispensers is common in apple orchards and can significantly reduce moth catch (Knight et al. 1999). The failure of sex pheromone–baited traps to detect late-season moth populations continues to be a major problem associated with sex pheromone MD (Gut and Brunner 1996).

Ethyl (*E*, Z)-2,4-decadieonate isolated from ripe pears is a potent kairomone attractant for both male and female codling moths (Light et al. 2001). Studies in walnut, *Juglans regia* L. (Light et al. 2001), pear, *Pyrus communis* L. (Knight et al. 2005), and apple, *Malus domestica* Borkhausen (Thwaite et al. 2004), orchards under sex pheromone MD have shown that kairomone lures can be equal to or more attractive than sex pheromone lures for codling moth. To date, field studies with pear ester have not used a standard lure and have tested a range of lure loadings from 1.0 to 40.0 mg (Light et al. 2001, Knight and Light 2004, 2005, Knight et al. 2005).

The optimal loading of pear ester for capture of codling moth in MD apple orchards likely depends on the specific objectives of the monitoring program (Knight and Light 2005). Lures loaded with 40.0 mg pear ester were more effective than a 3.0-mg loading in detecting the start of male emergence in the spring in pear and were equal to a sex pheromone lure (Knight and Light 2004). Pear ester lures loaded with 1.0–40.0 mg caught equivalent numbers of male codling moth during the season; however, the 1.0- and 3.0-mg lures were the most effective in capturing fe-

[1] Corresponding author: USDA–ARS, 5230 Konnowac Pass Rd., Wapato, WA 98951 (e-mail: aknight@yarl.ars.usda.gov).

[2] Southern Oregon Research and Extension Center, Oregon State University, 569 Hanley Rd., Central Point, OR 97502.

[3] USDA–ARS WRRC, 800 Buchanan St., Albany, CA 94710.

male moths (Knight and Light 2005). The 3.0-mg lure also caught the highest proportion of virgin female moths. Developing predictive models for the start of egg hatch and establishing action thresholds based on the capture of female moths with a 3.0-mg lure has been effective (Knight 2002).

Monitoring females instead of only male codling moths may have certain benefits, especially in orchards treated with sex pheromone MD. Capture of female versus male moths should be a more direct correlative measure of resulting egg density and timing of egg hatch. Assessing the risk of crop damage by monitoring only males in these orchards can be subject to errors associated both with the capture of males flying into orchards because they are treated with sex pheromone MD and because of the disruption of male orientation to sex pheromone–baited traps within these orchards (Witzgall et al. 1999). Unfortunately, many pest managers do not sex the moths caught in traps baited with pear ester and are only interested in the total number of moths captured (A.L.K., unpublished data). Further improvements in correlating codling moth catches in traps with population densities in sex pheromone MD orchards are needed.

Testing of host plant volatiles in combination with codlemone can be a useful approach to improve monitoring of codling moth (Light et al. 1993). The pear ester is one of a group of three host plant volatiles that have been shown to be effective in field trapping both sexes of codling moth when used as single components (Light et al. 2001, Coracini et al. 2004). However, the other two host plant compounds, (*E*)-β-farnesene and (*E, E*)-farnesol, have been shown to attract primarily males, and their attractiveness has not been compared with codlemone (Coracini et al. 2004). The addition of other host plant volatiles such as linalool, (Z)-jasmone, (*E, E*)-α-farnesene, caryophyllene, germacrene-D, (Z)-3-hexanol, (Z)-3-hexenyl 2-methylbutanoate, and 4,8-dimethyl-1,(*E*)3,7-nonatriene in various blends did not improve the performance of these compounds (Coracini et al. 2004). Interestingly, the codling moth female attractant (*E, E*)-α-farnesene did not exhibit any field attraction when loaded in red rubber septa (Coracini et al. 2004) and exhibited only low attraction for both sexes when loaded in gray halobutyl elastomer septa in walnut and apple orchards (Light and Knight 2005). The poor performance of (*E, E*)-α-farnesene in field trials is attributed to its chemical instability (Anet 1969).

Host plant volatiles can synergize the response of male moths to their sex pheromone (Landolt and Phillips 1997). Individual blends of three host plant volatiles, linalool, (*E*)-β-farnesene, and (Z)-3-hexen-1-ol, with codlemone at a 100:1 ratio synergized the responses of male codling moth in flight tunnel assays (Yang et al. 2004). In addition, a blend of green leaf volatiles significantly increased codling moth male catch when added to codlemone (Light et al. 1993). In contrast, field studies with pear ester have not found any synergistic effect when added at a ratio of 1:10 with 1.0 mg codlemone or at a ratio of 7:1 ratio with 3.0 mg codlemone in apple and pear orchards not treated with sex pheromone MD (Ioriatti et al. 2003). However, these two lures did not have optimal loading rates of pear ester (Knight and Light 2005). In a second study, lures loaded with 0.5 mg of pear ester and 0.5 mg of codlemone did not significantly increase moth catches compared with codlemone-loaded lures in pome fruit trials in orchards treated or not treated with sex pheromone MD (Il'ichev 2003). Unfortunately, the codlemone loading in this test was not similar between lure types.

Here we report studies that evaluated the attractiveness of the pear ester and codlemone alone versus combinations of 0.3 and 3.0 mg pear ester with 3.0 mg codlemone, loaded on gray halobutyl elastomer septa, to codling moth in apple orchards treated or not treated with sex pheromone MD. Subsequent studies evaluated the combinations of 20.0 mg pear ester with 3.0 mg codlemone and 3.0 mg pear ester with 42.0 mg codlemone in orchards treated with sex pheromone MD.

Materials and Methods

General Study Protocol. Studies in 2001 were conducted in two mature apple orchards, 'Delicious' interplanted with 'Golden Delicious' on 5.0 by 6.0-m spacing, situated near Moxee, WA. One orchard was treated with Isomate-C PLUS dispensers (Pacific Biocontrol, Vancouver, WA) applied at a rate of 1,000 dispensers/ha. Dispensers were loaded with 182.3 mg of a 60:33:7 blend of (*E, E*)-8–10-dodecadien-1-ol, dodecanol, and tetradecanol. Dispensers were attached to branches in the upper third of the canopy. Both orchards received multiple applications of 1.0% horticultural oil, and no other insecticides were applied during the season. Codlemone and pear ester were loaded either individually or together into gray halobutyl elastomer septa by personnel at Trécé (Adair, OK). Lures were placed inside diamond-shaped traps (Pherocon IIB; Trécé). Traps were attached to PVC poles and placed in the upper third of the canopy. One replicate of each lure treatment was randomized within an orchard row and traps within the replicate were spaced 30.0 m apart. Rows with traps were 20.0 m apart. Moths were sexed, counted, and removed from traps on each trap check date. Traps were replaced when cumulative moth catch exceeded 20, and lures were removed and placed in new traps with a clean metal trowel. Traps baited with solvent-loaded lures ($n = 5$) were placed in both orchards at the start of each test and checked weekly to detect possible contamination of trapping materials. Moth catch in these traps were trivial in both orchards, and these data are not reported.

Studies in 2002 were conducted in a 'Golden Delicious' orchard situated near Medford, OR and in a 'Delicious' orchard situated near Moxee, WA. Both orchards were treated with sex pheromone dispensers placed in the upper third of the canopy. The Medford orchard was treated with Nomate CM dispensers (Scentry Biologicals, Bozeman, MT) at 500/ha. Dispensers were loaded with 130 mg (*E, E*)-8–10-dode-

cadien-1-ol. The Moxee orchard was treated with Isomate-C PLUS at 1,000 dispensers/ha. Lures were placed in delta-shaped traps (Pherocon VI; Trécé) in the Medford orchard. Personnel handling all traps wore latex gloves to minimize the potential for cross-contamination.

Orchard Not Treated with Sex Pheromone MD, 2001. Traps were placed in the orchard on 18 May and checked six times at 5- to 10-d intervals until 5 July. Six replicates of six lure treatments were evaluated. The following combinations were evaluated with single lures: 3.0/0.0, 0.0/3.0, 0.3/3.0, and 3.0/3.0 mg pear ester/codlemone, respectively. In addition, two treatments (0.3/3.0 and 3.0/3.0 mg) evaluated the use of two lures with the pear ester and codlemone loaded separately and placed together within a trap.

Orchard Treated with Sex Pheromone MD, 2001. Studies were conducted from 13 July to 2 August. Four lure types with both pear ester and codlemone loaded into a single lure were evaluated: 3.0/0.0, 0.0/3.0, 0.3/3.0, and 3.0/3.0 mg pear ester/codlemone, respectively. Five replicates were included per treatment, and traps were checked weekly for 3 wk.

Orchards Treated with Sex Pheromone MD, 2002. Three lure treatments were evaluated in the Medford orchard: 3.0/0.0, 0.0/3.0, and 20.0/3.0 pear ester and codlemone, respectively. Four replicates of each treatment were included in this study. Traps were placed in the orchard on 10 April and checked weekly until 1 October. Lures were changed on 11 June and 7 August, and trap liners were replaced as needed. The Moxee study evaluated three lure types: 3.0/0.0, 0.0/42.0, and 3.0/42.0 pear ester and codlemone, respectively. Ten replicates of each lure type were included in this study. Traps were placed on 17 July and checked on three dates until 16 August.

Statistical Analysis. Counts of male, female, and total adult codling moths were square-root transformed ($x + 0.01$) and subjected to a repeated measures analysis of variance (ANOVA) across dates within an orchard. The date by treatment term was used as the error term in these analyses. When the ANOVA was significant, means were separated with Fishers least significant difference (LSD) test ($P < 0.05$) (Analytical Software 2000).

Results

Orchard Not Treated with Sex Pheromone MD, 2001. Significant differences were found among lures for the mean catch of male, female, and total number of codling moths (Table 1). Traps baited with only a 3.0 mg pear ester lure caught significantly fewer total moths than traps with a 3.0/3.0-mg loading when loaded either into one or two lures. Traps with only the 3.0 mg pear ester lure caught significantly fewer male codling moths than any trap baited with codlemone. Traps baited with lures containing 3.0 mg pear ester all caught significantly more females than traps baited with only codlemone. Traps baited with the combination 3.0/3.0-mg lure had significantly higher catches of females than traps with the 0.3/3.0-mg lure. There was no difference in moth catches when the pear ester and codlemone were loaded together into one lure versus separate lures for the 0.3 mg pear ester loading. However, significantly more males and total moths were caught in traps baited with the single lure versus two lures with the 3.0/3.0-mg loading.

Table 1. Comparison of mean moth catches in traps baited with lures loaded with either pear ester or codlemone or a blend of the two

Lure loading (mg)		Mean ± SEM moth catch per trap per time interval		
Pear ester	Codlemone	Males	Females	Total
3.0	0.0	1.5 ± 0.4a	1.9 ± 0.4c	3.4 ± 0.7a
0.0	3.0	3.1 ± 0.5b	0.1 ± 0.1a	3.2 ± 0.5ab
0.3[a]	3.0	3.9 ± 0.7b	1.0 ± 0.3bc	4.9 ± 0.9ab
0.3	3.0	3.4 ± 0.9b	0.6 ± 0.2ab	4.1 ± 1.0ab
3.0[a]	3.0	4.4 ± 0.8b	1.5 ± 0.5bc	5.9 ± 1.3b
3.0	3.0	6.9 ± 1.2c	1.9 ± 0.5c	8.8 ± 1.6c
ANOVA		$F = 11.60$	$F = 3.95$	$F = 6.83$
df = 5,25		$P < 0.0001$	$P < 0.01$	$P < 0.001$

The study was conducted in an apple orchard not treated with sex pheromone dispensers, 18 May to 5 July, 2001.

Means were transformed and subjected to a repeated measures ANOVA. Means were separated with an LSD test ($P < 0.05$). Column means followed by a different letter are significantly different.

[a]Pear ester and codlemone were loaded into individual lures.

Orchard Treated with Sex Pheromone MD, 2001. Significant differences were found among lures in the catch of male, female, and total codling moths (Table 2). Traps baited with the combination lures caught significantly more males and total moths than traps baited with either the pear ester or codlemone alone. Traps baited with the codlemone lure caught significantly more males than traps baited with the pear ester lure, but the total number of moths caught was similar. Traps with the pear ester alone caught significantly more females than traps with the codlemone lure alone.

Orchards Treated with Sex Pheromone MD, 2002. Significant differences in male, female, and total moth catches occurred among treatments in both the Medford and Moxee orchards (Table 3). At the Medford orchard, the highest total moth catch occurred in traps

Table 2. Comparison of mean moth catches in traps baited with one lure containing pear ester, codlemone, or a blend of the two

Lure loading (mg)		Mean ± SEM moth catch per trap per time interval		
Pear ester	Codlemone	Males	Females	Total
3.0	0.0	3.7 ± 0.8a	5.4 ± 1.5b	9.1 ± 2.2a
0.0	3.0	8.1 ± 1.7b	0.1 ± 0.1a	8.1 ± 1.7a
0.3	3.0	15.3 ± 3.3c	1.8 ± 0.4ab	17.1 ± 3.4b
3.0	3.0	15.9 ± 2.1c	6.3 ± 1.4b	22.2 ± 2.9b
ANOVA		$F = 28.30$	$F = 7.99$	$F = 13.50$
df = 3,6		$P < 0.001$	$P < 0.05$	$P < 0.01$

Studies were conducted in an apple orchard treated with sex pheromone dispensers on 13 July to 2 Aug. 2001.

Means were transformed and subjected to a repeated measures ANOVA. Means were separated with an LSD test ($P < 0.05$). Column means followed by a different letter are significantly different.

Table 3. Evaluation of mean moth catch in traps baited with pear ester and codlemone at ratios of 7:1 and 1:14 in apple orchards treated with sex pheromone dispensers in Medford, OR, and Moxee, WA, 2002

Lure loading (mg)		Mean ± SEM catch per time interval		
Pear ester	Codlemone	Males	Females	Total
		Medford		
3.0	0.0	0.9 ± 0.2a	1.8 ± 0.3c	2.7 ± 0.4a
0.0	3.0	13.0 ± 1.6b	0.0 ± 0.0a	13.0 ± 1.6b
20.0	3.0	21.0 ± 1.8c	0.8 ± 0.1b	21.7 ± 1.9c
ANOVA		$F = 66.01$	$F = 19.10$	$F = 48.61$
df = 2,48		$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
		Moxee		
3.0	0.0	4.9 ± 0.6a	2.4 ± 0.4b	7.4 ± 0.7a
0.0	42.0	72.7 ± 2.8c	0.0 ± 0.0a	72.7 ± 2.8c
3.0	42.0	52.3 ± 4.0b	1.8 ± 0.4b	54.1 ± 4.1b
ANOVA		$F = 92.25$	$F = 12.24$	$F = 117.49$
df = 2,4		$P < 0.001$	$P < 0.05$	$P < 0.001$

Means were transformed and subjected to a repeated measures ANOVA. Means were separated with an LSD test ($P < 0.05$). Column means within each study site followed by a different letter are significantly different.

baited with the combination lure loaded with 20.0 mg pear ester and 3.0 mg codlemone. Traps with 3.0 mg codlemone lures caught significantly more males and total moths than traps baited with a 3.0 mg pear ester lure. Traps with the pear ester lure caught significantly more females than traps baited with a combination lure containing 20.0 mg pear ester and 3.0 mg codlemone. Traps baited with either concentration of pear ester caught significantly more females than traps containing codlemone alone.

Significant differences in moth catch were found in traps baited with the three lure types in the Moxee orchard (Table 3). Traps baited with codlemone caught significantly more males and total moths than traps baited with only pear ester. The 42.0 mg codlemone lure caught significantly more males and total moths than either the 3.0 mg pear ester lure or the combination lure with 3.0 mg pear ester and 42.0 mg codlemone. Traps baited with pear ester caught significantly more females than traps baited with only codlemone. No difference in the number of female moths trapped occurred between traps baited with pear ester or the combination pear ester and codlemone lure.

Discussion

Pear ester is a potent kairomonal attractant for both sexes of codling moth. Total moth catches in traps baited with pear ester can be equivalent to codlemone in walnut (Light et al. 2001) and in pome fruit orchards treated with sex pheromone MD (Light et al. 2001, Thwaite et al. 2004, Knight and Light 2005, Knight et al. 2005). Yet a variety of factors can influence the effectiveness of pear ester to monitor codling moth. Both cultivar (Thwaite et al. 2004) and crop phenology (Light et al. 2001, Knight and Light 2005) can significantly impact the attractiveness of pear ester in pome fruit, and these factors influence the development of reliable monitoring guidelines based on this lure (Knight 2002).

Development of an improved lure that combines pear ester with codlemone has had mixed results. In our study reported here, the 3.0/3.0-mg combination lures significantly increase male and total moth catch in orchards treated or not treated with sex pheromone MD. However, in other studies, the combination lures were not more attractive than codlemone alone (Ioriatti et al. 2003, De Cristofaro et al. 2004). The poor results in these trials can likely be explained by the use of nonoptimal loadings of pear ester (0.1 and 20.0 mg). We found that lures loaded with 0.1 mg pear ester caught significantly fewer codling moths than similar lures loaded with 1.0–40.0 mg (Knight and Light 2005). We also found that increasing the loading of pear ester in lures to 20.0 (current study) or 40.0 mg (Knight and Light 2005) significantly reduced the catch of female moths. However, the reduction in moth catch when a 3.0 mg pear ester lure was added to traps baited with a high load codlemone lure cannot be similarly explained by the loading rate. Apparently, at these lure loadings the behavioral response of moths to traps is mediated by some interaction of these compounds.

The sensory physiology of male and female codling moths' antennae to codlemone (Roelofs et al. 1971, Ebbinghaus et al. 1998, De Cristofaro et al. 2004) and to various plant-based volatiles (Bäckman et al. 2001, Bengtsson et al. 2001, Light et al. 2001, De Cristofaro et al. 2004) has been well studied. Two olfactory receptor neurons in the sensilla trichodea of the male antennae were found to be sensitive to codlemone (Ebbinghaus et al. 1998). Female codling moth antennae can also detect codlemone but show a much lower response than males (Ansebo et al. 2004, De Cristofaro et al. 2004). In contrast, the electroantennogram (EAG) amplitude of codling moth's antennal response to pear ester was similar between sexes, between mated and virgin moths of both sexes, and for moths collected from several hosts (De Cristofaro et al. 2004). A small sensillum auricullum cell type was found to be specific for the pear ester and insensitive to codlemone (D.M.L., unpublished data). De Cristofaro et al. (2004) found that antennae of both sexes possess individual receptor cell types sensitive only to codlemone, only to pear ester, or to both compounds in nearly equal proportions. They hypothesized that the behavioral responses of codling moth to both the pear ester and codlemone are partially mediated through a common sensory channel.

Our field trapping data suggest that the sensory interaction of codlemone and pear ester defines a blend that is optimal for monitoring codling moth. The optimal loading of gray elastomer septa for females has been shown to be between 1.0 and 10.0 mg (Knight and Light 2005). Higher or lower loadings of pear ester in this lure substrate reduce the capture of females (Table 2; De Cristofaro et al. 2004, Knight and Light 2005). The effect on male moth catches of adding pear ester on male moth catches depends on the loading

rate of codlemone. Within sex pheromone MD orchards we found that adding 3.0 mg pear ester to lures with relatively low loading of codlemone (3.0 mg) increased male capture. Conversely, adding 3.0 mg pear ester to a lure with a high codlemone loading (42.0 mg) reduced male capture. The influence of sex pheromone MD on the optimal lure loading may also be important. Adding 3.0 mg pear ester to 3.0 mg codlemone significantly increased male catch in both treated and untreated orchards. However, the 20.0/3.0-mg combination lure significantly increased male and total moth count in a sex pheromone MD orchard but had no additive effect in an orchard not treated (Ioriatti et al. 2003). Additional lure studies with blends of pear ester and codlemone should also address possible influences from crop phenology or cultivar.

Developing a lure with an optimal blend of pear ester and codlemone will have significant impact on efforts to improve monitoring of codling moth and to develop more effective attract and kill programs (Knight et al. 2002). At present, the 3.0-mg gray elastomer septa loaded with pear ester is the most effective lure for trapping female codling moth. This lure has outperformed a variety of codlemone lures in apple and pear orchards treated with sex pheromone MD under specific conditions such as in 'Granny Smith' apples (Thwaite et al. 2004), 'Bartlett', 'D'Anjou', and 'Comice' pears (Knight et al. 2005), or during specific time periods during the season (Knight and Light 2005). The 3.0/3.0-mg combination lure tested here can significantly increase the catch of male moths in apple orchards. Further studies are needed to assess the correlation of moth catches with levels of egg density or fruit injury. Determining the active space of pear ester lures and some of the biological and operational factors that influence the performance of baited traps should be useful in developing a more effective monitoring program for codling moth.

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