

Sterile Insect Technique (SIT) combined with Mating Disruption for Management of Codling Moth in Pear Orchards

Cindy Kron, UC Cooperative Extension IPM Advisor

Charles Burks, Research Entomologist, USDA-ARS

Nathan Moses-Gonzales, Chief Executive Officer, M3 Agriculture Technologies

Houston Wilson, UC Cooperative Extension Specialist

Clebson Goncalves, UC Cooperative Extension Advisor

Broc Zoller, Pest Control Advisor

ABSTRACT

A series of 20 weekly releases of sterile codling moth (CM) in 2023 and 2024 were used to examine the potential for use of sterile insect technique (SIT) to augment present pest management tactics, including mating disruption (MD), used to control codling moth in mature California pear orchards. Three orchard blocks under MD were divided into two adjacent plots, with one plot receiving a weekly release of 800 sterile codling moth per acre while the other received all other pest management treatments used in the SIT block. Release and control blocks were switched in 2024. The ratio of sterile to wild moths in traps was variable between weeks and locations, with a season-long trap overflooding ratio of 2x to 15.9x in 2023 and 0.8x to 7.3x in 2024. Recovery in the traps of all sterile moths released ranged from 0.18% to 0.88%. Dispersal was documented by captures in the comparison block of 19% to 37% of the sterile CM released over the 2 years. The proportion of wild females mated was greater in the SIT in 2023 but not in 2024. These findings confirm that mass-release sterile codling moth performed well in California, demonstrate spatial and temporal variability in performance, and suggest that sterile mass-release CM males bred with wild females in these orchards in the presence of mating disruption.

INTRODUCTION

Sterile insect technique and mating disruption have been used successfully against a variety of moth pests (Simmons et al. 2021). Codling moth (CM) is one of three long-term successful moth SIT programs (Simmons et al. 2021, Thistlewood and Judd 2019). Sterile insect technique is often referred to as "sterile male" technique by the general public, and male only releases are practical and preferred for many dipteran targets. In Lepidoptera, however, both sexes have been sterilized and released in all large-scale cases of SIT for Lepidoptera (Simmons et al. 2021). There is evidence that overflooding with both sexes can, in some instances, be more effective than overflooding with males only (Saour et al. 2022, Ikegawa et al. 2021).

Mating disruption is also widely used against moth pests (Miller and Gut 2015), including codling moth (McGhee et al. 2014). Mating disruption can work by competitive, non-competitive, or hybrid mechanisms (Miller and Gut 2015). Mating disruption against the codling moth works by a competitive mechanism (Miller and Gut 2015, McGhee et al. 2014). Mating disruption against the codling moth has been technically and economically successful, but mating disruption is not as effective for the codling moth as it is for some target pests such as the oriental fruit moth (Miller and Gut 2015). Choices for monitoring codling moth in the presence of mating disruption include a combination of pheromone and pear ester (optionally with acetic acid to increase female capture)(CMDA + AA), or pear ester, nonatriene, linalool oxide, and acetic acid (4K) (Knight et al. 2019, Knight et al. 2022). CMDA + AA is approved for use in organic orchards, whereas 4K is not.

On first consideration, combining mating disruption and SIT as control techniques can meet skepticism, since the former depends primarily on prevention of mating whereas the latter depends on mating between mass-release sterile and wild moths for effectiveness. The counter argument is that the effects may still be added if mating is equally reduced for sterile mass-release and wild moths, and that this effect might be even more likely if both sexes are released. In practice, mating disruption and sterile insect technique (SIT) both have successfully been used together to control codling moth (Horner et al. 2020, Judd and Garner 2005). The present proposal tests vigor and dispersal of codling moth from the Okanagan Kootenay Sterile Insect Release Program (British Columbia, Canada), imported into the U.S. and transported and released by a private contractor (M3 Agriculture, Omak WA). Impact on wild CM populations will also be assessed. Crop damage at harvest was not assessed is not directly reported, but codling moth damage is assessed via sampling of cut fruit (Zoller and Zoller 2001).

OBJECTIVES

- Determine if overflooding is achieved, the sterile:wild ratio, and if the number of wild moths decrease over the 20 weeks
- Determine dispersal: if sterile moths stay on the release side or disperse evenly across the site.
- Spermatophores — Baseline probability of capturing an unmated vs. a mated Codling moth female in a trap

PROCEDURES

Orchard sites Three orchard sites served as replicate blocks for this experiment in both 2023 and 2024. The west (presumably upwind) half of each of these orchards served as a release plot, while the east half of the orchards served as a grower standard (i.e., a plot

receiving identical cultural and pest management treatments exception sterile moth release). The plots serving as release and grower standard were reversed in 2024. Each of these orchards was under mating disruption for codling moth.

Table 1. Characteristics of the orchard sites used as the three replicate blocks

Orchard Block	County	Latitude	Longitude	Release area (ha)	Comparison area (ha)	Mating Disruption
1	Sacramento	38.34	-121.55	4	4	Aerosol
2	Lake	39.00	-122.85	4	4	Aerosol
3	Lake	39.01	-122.85	2.4	2.4	Hand-applied

Block and plot characteristics are shown in Table 1. Block 1 was established ca. 100 years ago and additional interplanted trees were added ca. 60 years ago, so current spacing is 18 ft rows by 9 ft tree and 16 ft rows by 8 ft tree spacing. Mating disruption was provided by 2 aerosol dispensers (Suterra CheckMate Puffer CM-OFM Standard, Bend OR USA) per acre, and 200 hand dispensers/ acre in the 3 rows adjacent Highway 160 on the North side (Isomate CTT, Pacific Biocontrol, Vancouver, WA USA) placed the week of 20 March, 2023. Insecticides active against CM included Spinosad (Entrust, Corteva Agriscience, Indianapolis IN USA) applied on 10 June. In 2024 the same aerosol mating disruption product and timing was used. Methoxyfenozide was applied on 26 April, and cyantraniliprole was applied on 13 June and 25 June.

Block 2 was established ca. 60 years ago and spacing is 16 ft rows by 8 ft tree spacing. Mating disruption was provided by 2 aerosol dispensers (Suterra CheckMate Puffer CM-OFM Standard, Bend OR USA) per acre, placed on 6 April, 2023. No hand applied dispensers were placed in rows along windward edges in this block. Insecticides active against CM included esfenvalerate (Asana, Valent USA LLC, San Ramon CA USA) applied on 28 April, methoxyfenozide applied on 30 May, and spinetoram (Delegate, Corteva Agriscience) applied on 28 June and 12 July. In 2024 aerosol mating disruption (Isomate CM/OFM Mist Plus, Pacific Biocontrol) was applied on 1 April. Abamectin and methoxyfenozide were applied on 8 May, methoxyfenozide was applied on 29 May, and cyantraniliprole was applied on 19 June, 2 July, and 20 July.

Block 3 was established ca. 90 years ago and additional interplanted trees were added ca. 25 years ago, so current spacing is 21ft rows by 10.5 ft tree spacing. Mating disruption was provided by 200 hand-applied dispensers with 2 dispensers/tree applied in 1 row along all edges (Isomate CTT, Pacific Biocontrol, Vancouver WA USA) per acre, placed on 1 April, 2023. The only insecticides active against CM was Spinosad (Entrust, Corteva Agriscience) applied on 9 May and Pyrethrin (PyGanic, MGK, Minneapolis MN USA) on 10 August, 2023. Block 3 was certified organic. In 2024 Isomate CTT mating disruption dispensers were again applied at 200 per acre on 1 April, and spinosad was applied on 1 June and 12 July.

Sterile moth releases Sterile codling moth (800 adults per acre) were released each Tuesday for 20 weeks, from 18 April to 29 August, 2023 and from 16 April to 27 August 2024. Releases were shifted a day later due to holidays for the weeks of 30 May and 4 July. Mixed-sex sterile codling moth were sourced from the Okanagan Kootenay Sterile Insect Release (OKSIR) Program (Kelowna, British Columbia, Canada). Adults were exposed to 150 Gy using a Cobalt Irradiator and imported into the United States by M3 Agriculture Technologies (Omak WA, USA). Codling moth from OKSIR are routinely fed a diet containing a lipophilic red dye (calco oil red) that is retained internally by adults and that permits distinguishing sterile released adults from wild codling moth. Moths were shipped from the US port of entry via parcel overnight express to Sacramento, where they were picked up and applied to fields the following day. Moths were kept at 2°C using pre-chilled refrigerant gel bags while in shipping, or temperature-controlled coolers while transported in vehicles to the field. Field release was conducted using the Hermes V.2 Unmanned Aircraft Systems (UAS)(Esch et al. 2021, Moses-Gonzales et al. 2021). Way points programmed into the UAS provided for release above each of the 9 monitoring points in the release plot (described in the paragraph).

Adult Monitoring Capture of wild and sterile codling moth was examined using 9 sticky traps per plot, arranged in grids of 3 traps in each of 3 orchard rows (Fig. 1). Orange wing traps (Suterra LLC, Bend OR, USA) were modified using bent wire spacers as described elsewhere (Kuenen et al. 2005, Burks et al. 2020). In each orchard traps were \geq 32 ft from the edge of the orchard. Traps in Block 1 were approximately 400 feet apart within east-west rows, with trap rows were 230 to 256 ft apart. In block 2 traps were 260 to 300 ft apart within east-west rows and trap rows were 290 ft apart. In the smaller block 3 traps were 100 to 170 ft apart within east-west rows and trap row were 270 to 280 feet apart. Block 3 was wider (more row) in the eastern half than in the western half of the orchard, and there was a 250 ft-wide area on the southeast (non-SIT release area) in which monitoring traps were not placed. Monitoring traps were baited with pear ester (Light and Henrick 2001, Knight et al. 2019) and acetic acid (Landolt et al. 2007) because this combination attracts codling moth in the presence of mating disruption (Knight et al. 2019)

and is more effective at capturing females than other attractants currently used (Evan Esch, personal communication). The pear ester and acetic acid bait formulation is not currently produced commercially, but was provided by Trece Inc. (Adair, OK, USA). The lures were changed every 6 weeks. Trap liners were changed weekly and examined in the laboratory to obtain counts of wild and sterile males and females, and to dissect spermatophores in the females to determine mating status.

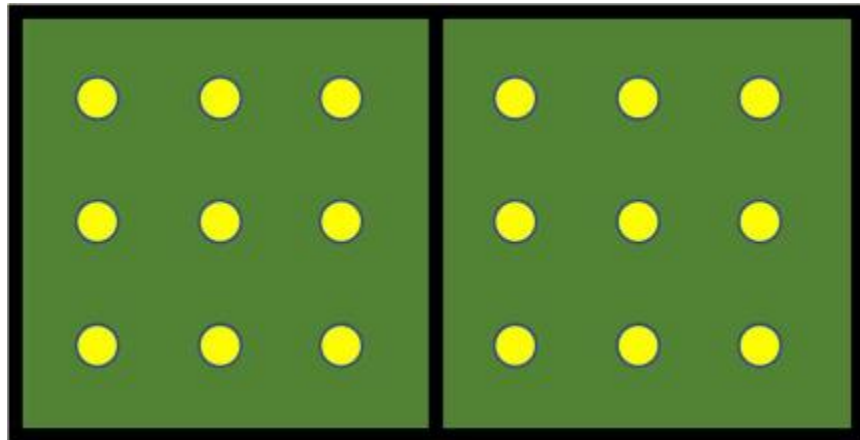


Figure 1. Schematic diagram of the trap arrangement in adjacent treatment and grower standard plots in each of the three replicate blocks.

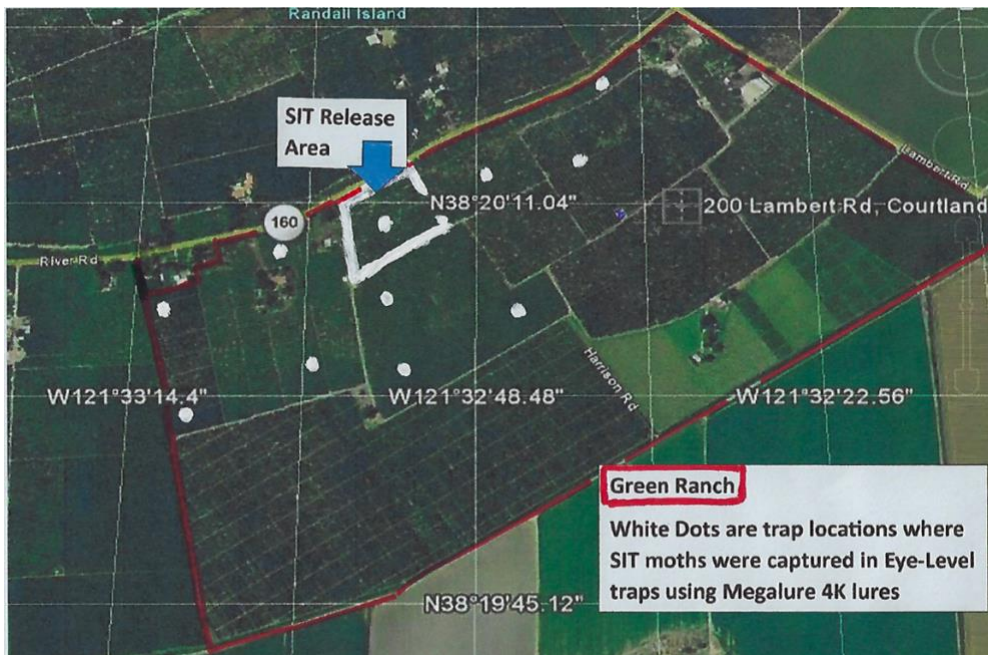


Figure 2. Trap locations where SIT moths were captured in eye-level traps using Megalure 4K lures.

Adult Monitoring Capture of wild and sterile codling moth was also tracked using eye-level trap using Megalure 4K lures (Trece', Adair OK) in 2 blocks and CM pheromone DA+AA lures in one block. A trap was positioned in the center of the release area and in the center of the control area of each block. In addition, 22 other locations with these traps were in the block 1 ranch. The results of this trapping are not reported here, except in Fig. 2, showing the proximity of all sterile moth captured adjacent to the test block 1. The other 2 of the three test blocks were not adjacent to other orchard areas with eye-level traps.

Egg Monitoring Weekly egg searches of fruit clusters using the cut fruit technique were conducted (Zoller and Zoller 2001) 3 cut fruits per trap per orchard = 54 total cut fruit per week per orchard plot, cut 1 week prior to egg searches} were maintained as well as random samples of uncut fruit in clusters (306 total uncut fruit per week per orchard plot).

Data analysis Moths captured in pear ester/day traps were pooled by block, plot, and monitoring interval to examine trap overflooding (defined here as the ratio of dyed to non-dyed moths in traps), percent of sterile moths recovered, and the percent of sterile moths that were recovered in the non-release comparison plot adjacent to the release plot. For analysis the weeks from approximately April 15 to the end of August were examined, i.e., the weeks when SIT releases were performed. Response variables were based on pooled sums from traps in a plot on sampling interval (i.e., 9 traps). There was no missing data in 2023, but data were missing in some plots in 2024. To keep balanced comparisons, plots with missing values on 1 week were discarded in both years prior to analysis. Data were analyzed using R 4.4.1 (R Core Team 2024). The distribution of wild and sterile moths between plots in an orchard block was examined using paired t-tests. The proportion of released moths recaptured and the proportion of sterile vs. wild moths on trap liners was examined using a generalized linear model (GLM) with a negative binomial distribution. Predictors (Year-Block and Treat-Sex combinations) were analyzed as factorial variables in an ANOVA-like test using the car package (Fox and Weisburg 2019), and posthoc tests were performed using the package emmeans (Length 2024). Chi-square contingency table analysis was used to examine differences in mating of wild females for all blocks and years, based on either SIT treatment (release vs. comparison) or plot location (west vs. east).

RESULTS

Over the two-year study, there was no consistent difference in the number of wild CM captures in the pear-ester trap grips in the west vs. the east side of the orchard blocks (Table 2). However, significantly more mass-release sterile moths were captured in the release plot vs. the comparison plot (Table 3). The proportion of sterile moths recaptured in the comparison plot ranged from 19 to 37.

Table 2. Distribution of wild moths between the two plots with each orchard replicate in 2023 and 2024

Year	Orchard Block	East Plot	West Plot
2023	1	23	41
	2	79	110
	3	29	34
2024	1	80	20
	2	330	383
	3	53	50

No difference between plots. Paired t-test, $t = 0.7995$, $df = 5$; $P = 0.4603$

Table 3. Distribution of released sterile moths between the two plots with each orchard replicate in 2023 and 2024

Year	Orchard Block	East Plot	West Plot	% Moths in Comparison Plot
2023	1	130	559	19
(release on west)	2	75	217	26
	3	248	539	32
2024	1	167	93	36
(release on east)	2	253	77	23
	3	288	232	37

Significantly more dyed moths captured in release plots (paired t-test, $t = -4.0496$, $df = 5$; $P = 0.0098$)

The proportion of all mass-release sterile moths recapture in all 18 traps in the block (both plots) varied significantly between years and orchard blocks (Table 4). Recapture rates ranged from 0.18 to 0.88% of the sterile moths released.

Table 4. Recapture of sterile moths by year and orchard block

Year	Orchard Block	Sterile moths	Recapture as percent released
2023	1	689	0.46b
	2	292	0.21cd
	3	787	0.88a
2024	1	260	0.18d
	2	330	0.24c
	3	620	0.81a

GLM with binomial distribution. Chi-squared = 1151, df= 5; $P < 0.0001$

A graph of the ratio of sterile to wild CM capture in the release block only revealed wide variation from week to week, between blocks, and between years (Fig. 3). The overall season-long trap ratio for the release block only range from 0.8 to 15.9 sterile:wild.

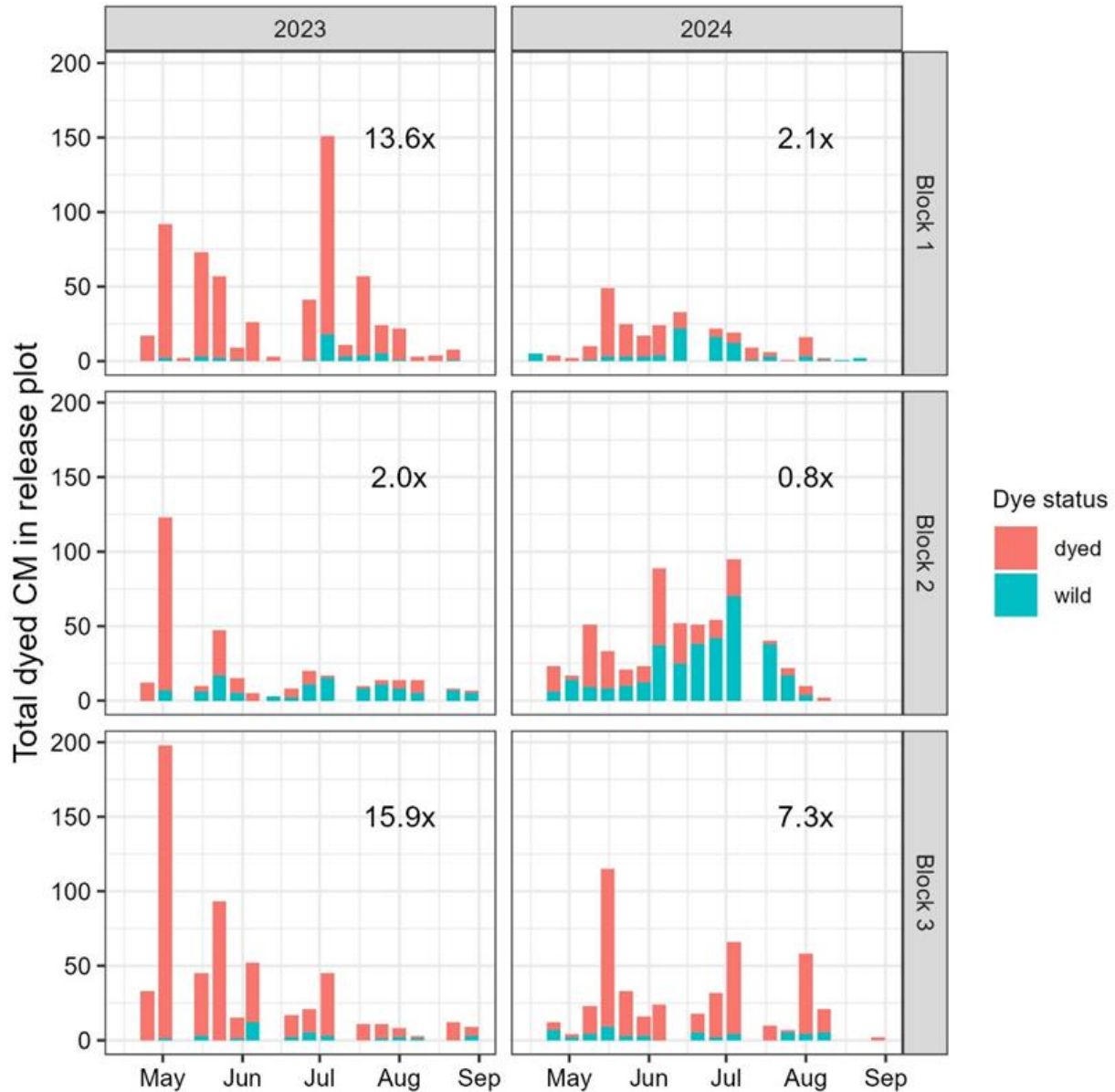


Figure 3. Weekly capture of sterile (dyed) and wild moths in pear ester traps in the release plots only. The ratio of the year-long sum of sterile to the year-long sum of wild moths is indicated by the numeral in the field of the panel.

Captures from all blocks and both years were combined to compare the sterile:wild ratio between treatment blocks (SIT release vs. comparison) and by sex (male or female) (Table 5). Both within the SIT treatment and the comparison plot, the ratio of sterile:wild on the pear-ester traps was greater for males than for females (Table 5).

Table 5. Overall trap ratio sterile-to-wild males and females, all years and orchard blocks

Treatment Plot	Sex	Sterile	Wild	Trap ratio
Release	Male	1,438	397	3.62a
	Female	684	251	2.73b
Comparison	Male	621	346	1.79c
	Female	234	238	0.98d

GLM with binomial distribution. Chi-squared = 169.23, df= 3; $P < 0.0001$

Egg monitoring data with locations of eggs detected in Table 6. Statistical analysis of egg monitoring data was not performed, as many locations had no eggs.

		2023 Trap Locations					
		2024 Trap Locations					
1 B Block	Sacramento County	36 Cut Fruit per trap location (3/week)					
		30 Cut Fruit per trap location (3/week)					
		SIT Area (10 acres, W side)		No SIT Area (10 acres, E side)			
		No SIT Area (10 acres, W side)		SIT Area (10 acres, E side)			
		..... North Border.....				North Border.....	
		0 0	0 3.3	0 0	0 0	0 0	0 0
		0 0	0 0	2.8 0	0 0	0 3.3	0 0
		0 0	0 0	0 0	0 0	0 0	0 0
		..... South Border.....				South Border.....	
	2 Hedge	Lake County	42 Cut Fruit per trap location (3/week)				
		39 Cut Fruit per trap location (3/week)					
		SIT Area (10 acres, W side)		No SIT Area (10 acres, E side)			
		No SIT Area (10 acres, W side)		SIT Area (10 acres, E side)			
		..... North Border.....				North Border.....	
		2.4 0	0 0	0 0	0 0	0 0	0 0
		0 0	11.9 0	0 0	0 0	0 0	2.4 0
		7.1 35.9	2.4 12.8	0 7.7	0 2.6	0 0	0 0
		..... South Border.....				South Border.....	
Notes: SW corner of the Hedge block is the upwind corner during frequent SW coastal wind drift in the afternoons. There are 2 abandoned pear trees on neighbor's property line just north of NW Trap.							
3 Rickabaugh	Lake County	42 Cut Fruit per trap location (3/week)					
		39 Cut Fruit per trap location (3/week)					
		SIT Area (5.8 acres, W side)		No SIT Area (8.2 acres, E side)			
		No SIT Area (5.8 acres, W side)		SIT Area (8.2 acres, E side)			
		..... North Border.....				North Border.....	
		0 0	0 0	0 0	0 2.6	0 0	0 0
		0 2.6	0 0	0 0	0 0	0 0	0 0
		0 0	0 2.6	0 0	0 5.1	0 2.6	0 0
		..... South Border.....				South Border.....	
		..... South Border.....				South Border.....	

Table 6. Location of sampled fruit (percent) with codling moth eggs using the cut fruit technique.

DISCUSSION

The lack of significant difference in wild moths captured between the sides of the orchard block (Table 2) suggests that there was not a systematic difference in abundance of CM between the west (presumably upwind) and the east (presumably downwind) halves of the orchard. In contrast, a majority of sterile codling moth were recaptured on the release side of the orchard both when the release was on the upwind side in 2023, and when it was on the downwind side in 2024.

Variation in results between the orchard sites serving as replicate blocks might be explain in part by differences in the pest management practices used. For example, in block 2 where both overflooding and recovery were much lower, there was greater use in 2023 of insecticides with contact activity such as esfenvalerate and spinetoram. In block 2 the former was used at the end of April, and the latter was used at the end of June and mid-July. In contrast, Spinosad was used only on 10 June 2023 in Block 1 and only on 9 May in Block 2023. Another notable feature in which Block 2 differed from the others was the absence of a windbreak on southwest part of the orchard (in the SIT block). Higher damage has been noted just in this area over several years. The other blocks have windbreak trees and buildings on the windward edges (Broc Zoller, personal observation). In 2024 the number of wild CM capture was numerically greater in all three blocks, more insecticides were used, and the overflooding rate was lower (Fig. 3). Methoxyfenozide, used on blocks 1 and 2 in 2024, is a growth regulator and should not have affected the adult sterile CM. However, abamectin, used with methoxyfenozide in Block 2, has contact activity, and cyantraniliprole, used in both blocks 1 and 2, also has activity against adult Lepidoptera.

Generally, the ratio of sterile to wild CM in the monitoring traps suggested that substantial overflooding was achieved with the weekly releases. Since the pink bollworm SIT was closed following the eradication of pink bollworm in the US, the OKSIR SIT program for CM, which provided the sterile CM for the present study, is the most well-established Lepidopteran SIT program in North America (Thistlewood et al. 2019, Simmons et al. 2021). The overall overflooding rate and dispersal is consistent with robust and competitive performance of the sterile mass-release moths in the present study. The variation in overflooding rate and the modest recovery are therefore likely illustrative of expected performance of moths in an SIT program. This type of variation was also noted in a recent study of trapping area for CM using a pheromone-pear ester lure (Horner et al. 2020, Curtiss et al. 2023). In the maximum dispersive distance suggested that traps baited with pheromone and pear ester drew CM males from an area of 10 and 15 acres, respectively, the plume reach (area over which CM actively followed scent trails from attractants) was <15 ft. This is consistent with the modest overall recovery observed in

the present study. Moreover, while an average of 20% of CM recovered were captured in traps in the comparison plot, these grids only captured CM that dispersed in one direction. The modest recovery rate reported here is therefore consistent with adequate performance to provide control by SIT.

Sterile CM have previously been used with mating disruption, both as a means of providing additive crop protection (Judd and Gardiner 2005, Horner et al. 2020) and as a means of testing efficacy and examining mechanisms of mating disruption (Welter et al. 2005, McGhee and Miller 2014, Miller and Gut 2015). Traps baited with pear ester can capture unmated as well as mated CM (Knight 2006), and use of acetic acid with pear ester increases the ratio of females to males captured (Knight 2010). Traps baited with pear ester therefore have the potential to assess the impact of mating disruption treatments on CM females.

In 2023, when sterile CM was released on the upwind side of the orchards, there was greater mating of wild CM in the release plots compared to the comparison plots. In 2024, however, this trend vanished when sterile CM were released on the downwind side of the orchard. Data pooled for both years supported greater mating of wild CM in the upwind side of these blocks under MD, but not on the side where SIT CM were released when data for releases on both sides of the orchard were included. This is consistent with data from multiple studies indicating that protection of edges is of particular concern for mating disruption for CM.

In summary, the present data demonstrate that the sterile CM released for SIT in this study achieved trap overflowing. Variation in performance was similar to that observed in previous studies. Mating in wild CM females in the SIT blocks was consistent with mating between sterile mass-release males and wild females. These data indicate that CM SIT is compatible with MD but is complicated by insecticide programs with products with adult activity. Future studies should examine whether SIT can assist with areas of weakness for CM MD, such as upwind edges.

LITERATURE CITED

Curtiss, R.T., Nottingham, L., and Gut, L.J. (2023). Estimating plume reach and trapping radii for male and female *Cydia pomonella* (Lepidoptera: Tortricidae) captured in pheromone–kairomone baited traps in Washington State apple orchards under mating disruption. *Journal of Economic Entomology*, 116(5), 1592-1603. <https://doi.org/10.1093/jee/toad167>

Fox, J., and Weisburg, S. (2019). *An R Companion to Applied Regression*, 3rd ed. Sage, Thousand Oaks CA. <https://www.john-fox.ca/Companion/>

Horner, R. M., Lo, P. L., Rogers, D. J., Walker, J. T. S., & Suckling, D. M. (2020). Combined effects of mating disruption, insecticides, and the sterile insect technique on *Cydia pomonella* in New Zealand. *Insects*, 11(12), 837. <https://doi.org/10.3390/insects11120837>

Ikegawa, Y., Ito, K., Himuro, C., & Honma, A. (2021). Sterile males and females can synergistically suppress wild pests targeted by sterile insect technique. *Journal of Theoretical Biology*, 530, 110878. <https://doi.org/10.1016/j.jtbi.2021.110878>

Judd, G. J. R., & Gardiner, M. G. T. (2005). Towards eradication of codling moth in British Columbia by complimentary actions of mating disruption, tree banding and sterile insect technique: Five-year study in organic orchards. *Crop Protection*, 24(8), 718–733. <https://doi.org/10.1016/j.cropro.2004.12.009>

Knight, A. (2006). Assessing the mating status of female codling moth (Lepidoptera: Tortricidae) in orchards treated with sex pheromone using traps baited with ethyl (E, Z) - 2,4-decadienoate. *Environmental Entomology*, 35(4), 894-900. <https://doi.org/10.1603/0046-225X-35.4.894>

Knight, A. (2010). Improved monitoring of female codling moth (Lepidoptera: Tortricidae) with pear ester plus acetic acid in sex pheromone-treated orchards. *Environmental Entomology*, 39(4), 1283-1290. <https://doi.org/10.1603/EN10034>

Knight, A. (2022). Knight: The prescription for effective monitoring of codling moth. *Good Fruit Grower*. <https://www.goodfruit.com/knight-the-prescription-for-effective-monitoring-of-codling-moth/>

Knight, A. L., Mujica, V., Herrera, S. L., & Tasin, M. (2019). Addition of terpenoids to pear ester plus acetic acid increases catches of codling moth (Lepidoptera: Tortricidae). *Journal of Applied Entomology*, 143(8), 813–821. <https://doi.org/10.1111/jen.12646>

Length, R. V. (2024). *emmeans: Estimated Marginal Means, aka Least-Squares Means*. R package version 1.10.5 <https://CRAN.R-project.org/package=emmeans>

McGhee, P. S. (2014). *Impact of High Releasing Mating Disruption Formulations on (male) Codling Moth, Cydia pomonella L., Behavior*. Ph.D. Dissertation, Michigan State University.

McGhee, P. S., Gut, L. J., & Miller, J. R. (2014). Aerosol emitters disrupt codling moth, *Cydia pomonella*, competitively: Competitive disruption of codling moth by aerosol emitters. *Pest Management Science*, 70(12), 1859–1862. <https://doi.org/10.1002/ps.3732>

Miller, J. R., & Gut, L. J. (2015). Mating disruption for the 21st century: Matching technology with mechanism. *Environmental Entomology*, 44(3), 427–453. <https://doi.org/10.1093/ee/nvv052>

Moses-Gonzales, N., Conway, H., Krompetz, D., Rodriguez, R, Adams, C. G., Baez, I., Milam, M. (2021). The Use of Multiple Unmanned Aircraft Systems as a Swarm to Release Sterile Mexican Fruit Fly (Diptera: Tephritidae) Into South Texas Citrus Groves. *Journal of Economic Entomology*, 114(5): 1857-1866. <https://doi.org/10.1093/jee/toab024>

R Core Team. (2024). A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Australia. <https://www.R-project.org/>

Saour, G., Hashem, A., & Jassem, I. (2022). Mating competitiveness of irradiated *Lobesia botrana* (Lepidoptera: Tortricidae) in male-only and both sex release strategies under laboratory cage conditions. *Insects*, 14(1), 18. <https://doi.org/10.3390/insects14010018>

Simmons, G. S., Bloem, K. A., Bloem, S., Carpenter, J. E., & Suckling, D. M. (2021). Impact of moth suppression/eradication programmes using the sterile insect technique or inherited sterility. In *Sterile Insect Technique* (2nd ed.). CRC Press. <https://www.taylorfrancis.com/chapters/oa-edit/10.1201/9781003035572-31/impact-moth-suppression-eradication-programmes-using-sterile-insect-technique-inherited-sterility-simmons-bloem-bloem-carpenter-suckling>

Thistlewood, H. M. A., & Judd, G. J. R. (2019). Twenty-five years of research experience with the sterile insect technique and area-wide management of codling moth, *Cydia pomonella* (L.), in Canada. *Insects*, 10(9), 292. <https://doi.org/10.3390/insects10090292>

Welter, S. C., Pickel, C., Millar, J., Cave, F., Van Steenwyk, R. A., & Dunley, J. (2005). Pheromone mating disruption offers selective management options for key pests. *California Agriculture*, 59(1), 16-22. <https://escholarship.org/uc/item/2tc8k3gc>

Zoller, B.G. and Zoller, A.M. 2001. Biased sampling of codling moth oviposition using a cut fruit technique to monitor mating disruption in Bartlett pears. Proceedings, 75th Annual Western Orchard Pest and Disease Management Conference p 14-15. January 10-12, Portland, Oregon; [2001OPDMC-Abstracts.pdf](#)