Journal of Economic Entomology, XX(XX), 2021, 1–10
doi: 10.1093/jee/toaa297
Research

Management of Navel Orangeworm (Lepidoptera: Pyralidae) Using Four Commercial Mating Disruption Systems in California Almonds

David R. Haviland,[1,5] Jhalendra P. Rijal,[2] Stephanie M. Rill,[1] Bradley S. Higbee,[3] Charles S. Burks,[4] and Chelsea A. Gordon[1]

[1]University of California Cooperative Extension, Kern County, 1031 South Mount Vernon, Bakersfield, CA 93307, [2]University of California Statewide Integrated Pest Management Program, 3800 Cornucopia Way #A, Modesto, CA 95358, [3]Trece Inc., P.O. Box 129, Adair, OK 74330, [4]USDA, Agricultural Research Service, San Joaquin Valley Agricultural Sciences Center, 9611 South Riverbend Ave, Parlier, CA 93648, and [5]Corresponding author, e-mail: dhaviland@ucdavis.edu

Disclaimer: Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

Subject Editor: Jana Lee

Received 14 July 2020; Editorial decision 25 November 2020

Abstract

The navel orangeworm, *Amyelois transitella* (Walker), is the most significant pest of California almonds. Direct feeding on the kernel by the larvae causes reductions in salable crop, crop quality, and exportability. Pheromone mating disruption (MD) targeting navel orangeworm is a relatively new technique with the potential to improve management. In 2017, we used replicated ~16-ha plots to compare the efficacy of four commercial MD systems (CheckMate, Cidetrak, Isomate, and Semios) for their relative impacts on the number of navel orangeworm in monitoring traps and crop quality. From 2017 to 2018, we conducted nine direct comparison studies in 16 to 40 ha almond orchards to compare conventional pest management programs to programs incorporating pheromone MD systems. Across all studies, MD reduced male moth captures in pheromone traps by >94%. In the efficacy study, use of mating disruption led to 35% and 53% reductions in kernel damage in Nonpareil and pollinizer cultivars, respectively, and an average increase in crop value of \$370 ha^{-1}. In the direct comparison, kernel damage to Nonpareil and pollinizer cultivars was reduced by 65% and 78%, respectively, resulting in an average increase in crop value of \$357 ha^{-1}. Economic analyses showed that increases in crop returns exceeded the costs of implementing MD systems with the break-even point ranging from 0.86 to 1.06% of kernel damage. These results suggest that adding MD to an existing navel orangeworm management program is a cost-effective way to reduce damage while promoting sustainable pest management practices.

Key words: mating disruption, almond, *Amyelois transitella*, pheromone, monitoring

Mating disruption (MD) is widely used as part of integrated management for several moth species of global importance as pests of horticultural crops (Welter et al. 2005, Witzgall et al. 2010, Miller and Gut 2015, Abd El-Ghany 2019). Formulations containing some or all of the female sex pheromone blend are used to prevent or delay mating; thus controlling oviposition and preventing damage by larval feeding while minimizing impacts on beneficial arthropods, the environment, workers, and consumers (Witzgall et al. 2010, Miller and Gut 2015, Abd El-Ghany 2019).

An MD system acts by one or more of a variety of mechanisms (Miller and Gut 2015, Evenden 2016). These mechanisms are often categorized as either competitive or noncompetitive (Miller and Gut 2015, Evenden 2016). The variety of methods used to dispense pheromones for mating disruption range from microencapsulated formulations that blanket the treated area with a very dense grid of release points of low concentration; to hand-applied devices that typically emit at a much higher concentration than calling females but are placed in dense grids of hundreds per ha; to electronically controlled aerosol emitters that release pheromone at much higher concentrations than hand-applied devices but from only a few points per ha (Benelli et al. 2019). The term meso-dispenser is used to describe passive hand-applied dispensers with intermediate emission rates and intermediate release point densities (Light et al. 2017) (dozens per ha compared to hundreds for other hand-applied dispensers and several for aerosol dispensers).

The mechanism(s) by which MD mating disruption occurs depends both on the physiology of the target species and the pheromone formulation and manner in which pheromone is dispensed. For example, the mating of the oriental fruit moth, *Grapholita molesta* Busk (Lepidoptera: Tortricidae), is disrupted by competitive mechanisms when presented with many point sources of low concentration, but by a noncompetitive mechanism when presented with more concentrated pheromone sources than those actually used for MD for that species (Reinke et al. 2014). In contrast, the codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae) is disrupted by a competitive mechanism even when disruption occurs using widely spaced high concentration aerosol dispensers (McGhee and Gut 2014).

MD is a relatively new component of pest management for the navel orangeworm (NOW), *Amyelois transitella*, (Walker) (Pyralidae). NOW is a key insect pest of major tree nut crops in California, including almonds (Wade 1961; Haviland et al. 2016; Haviland et al. 2020a, 2020b). Larvae feed directly on almond kernels, rendering them unmarketable and also impacting incentives paid to growers for high crop quality if the damage exceeds a certain level. Additionally, damaged kernels are susceptible to the fungus, *Aspergillus flavus*, which produces aflatoxins that limit crop exportability (Schatzki and Ong 2001, Palumbo et al. 2014).

Almonds are vulnerable to NOW infestation from the time hulls (i.e., fruit exocarp and pericarp) begin to split (i.e., hullsplit) during mid-summer until harvest, approximately 40 to 60 d later. However, due to the pollination requirements of almonds, typical orchards are planted with two to three cultivars, such that the period of time that the first cultivar becomes susceptible to NOW infestation until the last cultivar is harvested can last 3 mo. This period spans the second (late June to July), third (mainly August) and fourth (mostly September to early October) NOW flights. This prolonged period of susceptibility in combination with seasonal weather variations, variability in production practices, changes in pest pressure, variations in the quality of shell seal (Soderstrom 1977, Hamby and Zalom 2013), and a robust dispersal capability (Higbee and Siegel 2009, Sappington and Burks 2014, Rovnyak et al. 2018) make NOW damage extremely unpredictable (Rosenheim et al. 2017). In order to prevent significant economic losses, almond producers must take a comprehensive approach to NOW management.

NOW is managed through a combination of cultural and chemical controls. These include winter sanitation to remove sources of overwintering larvae (mummy nuts) from the orchard (Zalom et al. 1984, Higbee and Siegel 2009), timely harvest to remove nuts before infestation occurs, and insecticide applications (University of California 2002, Haviland et al. 2020b). Insecticides are typically scheduled to prevent infestation of the new crop from when it becomes susceptible, at the initiation of the hullsplit, through harvest (Higbee and Siegel 2012, Haviland et al. 2020b). Various monitoring methods (described subsequently) are used to time insecticide applications. Despite these control measures, industrywide percentages of inedible kernels ranged from 1.2 to 2.4% in the past 5 yr on more than one billion kg of dry kernels produced annually (Almond Board of California 2019a). Assuming a 10-yr average of 1.34% inedible harvest valued at \$5.50 kg^{-1} (Almond Board of California 2019a), this is \$75 million in grower payment losses annually, most of which can be attributed to NOW.

Monitoring and MD for NOW are influenced by the unusual sex pheromone of this species, which is a combination of conventional type I compounds (C10 to C18 unsaturated alcohols, acetates, or aldehydes) and a type II compound (unsaturated C17 to C23 straight-chain hydrocarbons) that is necessary for point-source attraction (Leal et al. 2005, Kanno et al. 2010, Kuenen et al. 2008). For monitoring, difficulty in elucidating the pheromone for use in monitoring lures (Kuenen et al. 2008, Higbee et al. 2014) meant that egg traps (Rice et al. 1976, Van Steenwyk et al. 1986, Kuenen et al. 2008, Higbee and Burks 2011) were used for NOW long after pheromone lures where available for monitoring many other orchard moth pests. Moreover, soon after a pheromone lure became available, use of MD for NOW led to a search for alternatives to pheromone lures for monitoring (Burks et al. 2016, Burks 2017, Burks et al. 2020). One of these alternatives, phenyl propionate (PPO), has been offered commercially for this purpose (Burks et al. 2020).

MD for NOW uses the principle type I aldehyde component, (11Z,13Z)-hexadecadienal (Z11,Z13:16-Ald) (Higbee et al. 2017). Early efforts used Z11,Z13:16-Ald when it was the only known component and showed some promise, but technical and economic impediments prevented practical use (Landolt et al. 1981, Curtis et al. 1985). Aerosol dispensers (Shorey and Gerber 1996, Benelli et al. 2019) offered improved performance and economy using Z11,Z13:16-Ald (Higbee and Burks 2008). The mechanism of MD for NOW using Z11,Z13:16-Ald involves a noncompetitive or hybrid mechanism, and males remain unable to orient to a female- or monitoring-strength pheromone source for the rest of the night after exposure (Burks and Thomson 2020). Studies suggest that use of a more complete pheromone blend could improve MD (Higbee et al. 2017). However, differences in registration requirements and costs for type II vs. type I pheromone component have kept MD formulations based on a more complete pheromone blend off the market (Higbee et al. 2017).

Since the commercial availability of CheckMate Puffer NOW in 2008, three additional products have become available to growers in California (Table 1). These include Isomate NOW Mist, Semios NOW Extra, and Cidetrak NOW Meso. Each product releases the single-component non-attractive pheromone (Z11,Z13-16:Ald) with variations on how it is dispensed. Active dispersal systems (CheckMate, Isomate, Semios) use 2.5 to 5 dispensers per ha, emitting pheromones nightly from aerosolized cans. Release rates can be static (CheckMate, Isomate) or variable (Semios). The variable system uses networked dispensers that adjust release rates according to the programmer's interpretation of data from automated camera traps, weather monitoring stations, and degree-day

Table 1. Characteristics of mating disruption products evaluated during 2017 and 2018

Product	Manufacturer	Dispensers per Acre	Dispenser type	Variable release rates	a.i. per ha (g)
CheckMate Puffer NOW	Suterra LLC, Bend, OR	2	Pressurized can	No	18.7
Isomate NOW Mist	Pacific Biocontrol, Vancouver, WA	1	Pressurized can	No	17.8
Semios NOW Extra	SemiosBio Technologies, Inc, Vancouver, BC	1	Pressurized can	Yes	15.0
Cidetrak NOW Meso	Trécé Inc, Adair, OK	20	Passive dispenser	No	30.0

Each product contains a single component of the NOW pheromone, ((Z,Z)-11,13-hexadecadianal).

models. The final system (Cidetrak) releases pheromone passively from 'Meso' emitters that are made of a polymeric matrix designed to emit pheromone for a period of 150–180 d (Trece Inc. 2020).

Here, we present results of experiments evaluating the effects of CheckMate, Isomate, Semios, and Cidetrak MD systems on NOW management. In 2017 we compared four MD systems and their impact on NOW captures in monitoring traps and crop quality. In 2017 and 2018, we conducted nine direct comparisons of commercial NOW management practices with and without the addition of one of four different MD technologies. The costs and benefits of implementing MD systems were calculated and used to provide recommendations on the advantages and disadvantages of commercial-scale adoption by almond growers in California.

Materials and Methods

2017 Efficacy Study

Four MD products were evaluated in a randomized complete block design using three mature, commercial almond orchards in Kern County, CA, from March through the end of harvest (October) in 2017 (Table 1). The almond orchards were planted to the cultivars Nonpareil, Monterey, and Fritz in a 50:25:25 ratio at a tree spacing of 6.7–7.9 m by 4.3–5.5 m (272–325 trees ha^{-1}). Each orchard was divided into nine 16-ha plots. Five plots were assigned to one of four MD treatments or a No-MD control in a checkerboard pattern with the No-MD control assigned to the northwest corner in the direction of prevailing winds and the four MD plots assigned randomly at each orchard. The four remaining plots at each orchard served as buffers to alleviate pheromone drift from one treatment into another. Each orchard was one replication of the study and was managed according to commercial almond production practices regarding irrigation, fertilizers, disease, and weed control. Standard commercial practices for NOW management at each orchard included winter sanitation through the removal of mummy nuts to no more than an average of two mummies per tree and one or two insecticide applications of chlorantraniliprole or methoxyfexozide between the initiation of hull split and harvest.

Pheromone dispensers were deployed in the MD plots approximately 1 mo after bloom between 27 March and 6 April 2017. They were hung in the top third of the trees at the height of approximately four to five meters and were distributed along grids that allowed even spacing across the plots according to the manufacturers' suggested rates (Table 1).

Two NOW monitoring stations were established approximately 122 meters to the north and south of the center of each plot. Each station contained a wing trap (Pherocon 1C Trap, Trécé Inc, Adair, OK) baited with a NOW pheromone lure (NOW L2-H, Trécé Inc, Adair, OK) and an egg trap (Pherocon IV (NOW) Egg Trap, Trécé Inc, Adair, OK) baited with almond meal (Trécé Inc, Adair, OK). Each trap was hung on an almond branch at a height of approximately 2 meters in March or early April and evaluated weekly for male moths and eggs, respectively, through the end of September. The almond meal in egg traps was changed every 30 d. Pheromone lures were changed every 30 d, and sticky wing trap bottoms were replaced as needed to maintain a sticky surface.

The grower cooperators conducted normal harvest operations for each cultivar. When nuts were on the ground or in windrows, we collected four harvest samples from each plot by gathering approximately 300 nuts selected at random from two locations within 6–18 meters of each of the two monitoring stations. Nuts were transported to a warehouse where they were spread out and allowed to dry for approximately 2 wk, after which they were placed into cold storage until evaluation, at which time each nut was cracked open by hand to determine the presence or absence of NOW damage, including direct feeding on the kernel and the presences of NOW larvae, webbing, or frass.

2017–2018 Direct Comparison Studies

Direct comparisons between one of four MD formulations versus a No-MD control were conducted using paired orchards at nine sites in the San Joaquin Valley (SJV) of California during 2017 and 2018 using a randomized block design. These included sites in Wasco (Kern Co.), Lost Hills (Kern Co.), Maricopa (Kern Co.), Turlock (Stanislaus Co.) and Escalon (San Joaquin Co.). All sites, except for Maricopa, were used for two consecutive years with each year considered a replicate. At each site, the No-MD control was placed upwind of the paired MD treatment to avoid cross-contamination due to drifting pheromone. The No-MD control and MD orchards were managed conventionally and received the same production practices across orchards at each site regarding irrigation, fertilization, and disease and weed management. The downwind orchard at each site was treated with one of the four MD systems previously described (Table 1). At seven sites, the MD orchards received identical or slightly modified insecticide programs as their No-MD control counterparts (Supp Table S1 [online only]). In Wasco (2017, 2018), the MD orchards received similar non-chemical NOW management as their control counterparts (sanitation, early harvest, etc.), but used MD as a replacement for, and not in addition to, two insecticide sprays (Supp Table S1 [online only]). The grower cooperators defined their own conventional practices at each site, including the timing and choice of insecticides, which MD product to use, the level of winter sanitation, and dates of harvest.

Each treatment was monitored weekly for NOW activity from April through the end of harvest using two pheromone and two egg traps per orchard that were installed and maintained as previously described. In 2018, an additional pheromone trap was added to each plot that also contained an experimental phenyl propionate-based (PPO) lure to make the trap attractive to both male and female moths (Burks et al. 2016, Burks 2017). Within each orchard at harvest, 300 randomly selected almonds were collected at four locations from each cultivar, as previously described, to assess damage by NOW.

Economics

To measure the impact of NOW on crop loss we calculated weights of non-salable kernels ha^{-1}, crop value based on the percentage of kernels damaged by NOW (NOW%), and assumed yields. The potential yields (PY) of dry kernels in orchard windrows were assumed to be 3,363 kg ha^{-1} in the southern SJV and 2,802 kg ha^{-1} in the northern SJV (Haviland et al. 2019). The PY's within each orchard were distributed proportionally to the cultivars present, usually in a 2:1:1 ratio for Nonpareil (NP), the early pollenizer (P1), and late pollenizer (P2). The PYs for each cultivar were multiplied by the NOW% for that cultivar and summed to determine the total kg of damaged kernels ha^{-1} (KDK) according to the formula:

$$KDK = (PY_{NP} * NOW\%_{NP}) + (PY_{P1} * NOW\%_{P1}) + (PY_{P2} * NOW\%_{P2})$$

Grower paid weights (GPW) for each cultivar were defined as the potential yield minus the weight of damaged kernels:

$$GPW = PY - KDK$$

Crop value was calculated using 10-yr average base prices for dry kernels (PBase) of \$4.70 kg^{-1} for Nonpareil and \$4.45 kg^{-1} for pollinizers (ABC 2019a). Adjustments (PAdj) for quality were made by comparing NOW% injury values to the 2018 Blue Diamond Quality Schedule, which assigned premiums for low reject levels of up to \$0.264 kg^{-1} for Nonpareil and \$0.176 kg^{-1} for pollenizers (Blue Diamond Growers, 2018). Prior to assigning price adjustments, NOW% injury values were divided by two based on our experience that approximately one-half of damaged kernels from windrows (where we collected our samples) are removed during commercial pickup, hulling, and shelling processes before quality is assessed commercially. Total per-ha returns to the grower were calculated as follows:

$$\text{Total Grower Return} = (GPW_{NP})(PBase_{NP} + PAdj_{NP}) + (GPW_{P1})(PBase_{P1} + PAdj_{P1}) + (GPW_{P2})(PBase_{P2} + PAdj_{P2})$$

Cost-benefit analysis for the 2017 efficacy study was conducted by comparing total grower returns in plots with and without MD, after taking into account the costs of adding MD to the pest management program. Cost-benefit analysis for the 2017–2018 MD direct comparison studies was done by calculating the total cost of insecticide and MD programs in the No-MD and MD orchards, determining the cost differential, and comparing this value to the difference in total grower returns. For the calculations, an average cost of \$313 ha^{-1} for MD implementation was used, based on the average price of materials and installation for the four different MD systems used in the study, after deducting the costs for additional services that come bundled with some systems. For insecticide sprays, we assumed application costs of \$50 ha^{-1} and materials costs of \$123 ha^{-1} for methoxyfenozide, \$93 ha^{-1} for chlorantraniliprole, and \$25 ha^{-1} for bifenthrin or lambda-cyhalothrin (Haviland et al. 2019).

Statistics

For each pheromone and PPO trap the cumulative moths captured was calculated for each of the four NOW flights. Flight cutoffs were: from study initiation through 15 June (first), 16 June until 31 July (second), August (third), and September (fourth). In the northern SJV, the first week of October was included in the fourth flight. For the first flight, data from weeks prior to MD dispenser deployment were excluded from evaluation. Egg trap data were organized using the same flight cutoff dates for the four generations of NOW larvae.

For the 2017 efficacy study, cumulative moths per pheromone trap for each flight, cumulative moths per PPO trap for each flight, cumulative eggs per egg trap for each generation, NOW% for each cultivar, KDK, and grower returns were evaluated by ANOVA with means separated by Fisher's Protected LSD ($\alpha = 0.05$). Prior to analysis, data of the cumulative moths per pheromone trap, cumulative moths per PPO trap, and cumulative eggs per egg trap were transformed using the square root transformation ($\sqrt{x+0.5}$) to normalize variances (SAS Institute Inc. 2015). Further analysis of NOW% injury and KDK data were completed using planned orthogonal contrasts to compare plots with and without MD using a 4:1:1:1:1 weighting for the No-MD control and four MD treatments (SAS Institute Inc. 2015). For the 2017–2018 direct comparison studies, data of cumulative moths per pheromone trap, cumulative moths per PPO trap, cumulative eggs per egg trap, NOW% and KDK were evaluated using paired t-tests with each site serving as a replication ($n = 9$). In order to normalize variances, prior to analysis data from traps were transformed using a square root transformation and NOW% injury data were transformed using an arcsine transformation (arcsine(sqrt(x))) (SAS Institute Inc. 2015).

Cost-benefit analyses to add MD to an existing management program for NOW were performed using regression analysis for each study. For the 2017 efficacy study, the independent variable was defined as the average NOW% across varieties (weighted by percentage surface area of each variety) in each No-MD control and the independent variable was defined as the change in crop value for each MD block compared to the corresponding check, minus the cost of implementing MD, which was assumed to be \$313 ha^{-1}. For the 2017–2018 direct comparison studies, the same process was followed, except that net gain or loss calculations also included the costs of insecticides that targeted NOW in all orchards. Insecticide costs were assumed to be \$173 ha^{-1} for methoxyfenozide, \$143 ha^{-1} for chlorantraniliprole, and \$65 ha^{-1} for products whose active ingredients were pyrethroids.

Results

Efficacy Study

All four commercial MD products significantly reduced the number of male NOW captured in pheromone baited traps, with moth suppression ranging from 92.1% to 97.3% for the first flight (NS), >98.3% for the second and third flights ($P < 0.0146$), and 77.6% to 93.9% for the fourth flight ($P = 0.0009$) (Table 2). Moth captures in plots receiving the four MD products were statistically equivalent to each other for all four flights. Male captures in planned contrasts between treatments with and without MD were significantly reduced for all four flights ($P < 0.0199$), with a 94.9% reduction for

Table 2. Cumulative NOW per pheromone trap (mean ± SE) for four flights and the entire season from orchards using four mating disruption systems in 2017

	Mean (±SE) cumulative NOW moths per trap				
Treatments	Flight 1	Flight 2	Flight 3	Flight 4	Total
No-MD Control	49.0 ± 41.0	63.5 ± 39.0a	162.0 ± 37.6a	76.5 ± 33.8a	351.0 ± 146.7a
Isomate	3.5 ± 2.6	0.2 ± 0.2b	2.8 ± 0.9b	17.2 ± 13.2b	23.7 ± 13.5b
Semios	1.3 ± 0.4	0.3 ± 0.2b	3.3 ± 1.4b	4.7 ± 4.4b	9.7 ± 3.2b
Checkmate	2.0 ± 1.8	0.3 ± 0.2b	2.7 ± 1.0b	19.8 ± 9.9b	24.8 ± 12.4b
Cidetrak	3.8 ± 2.8	0.0 ± 0.0b	1.3 ± 0.3b	12.2 ± 6.8b	17.3 ± 6.8b
F (df 4,8)	2.14	6.14	59.51	4.75	15.01
P	0.1672	0.0146	<0.0001	0.0294	0.0009

Means followed by the same letter are not significantly different after ANOVA with means separated by Fisher's PLSD ($\alpha = 0.05$) after square root transformation of the data. Mean catch is reported.

Table 3. Cumulative NOW eggs per trap (mean ± SE) for four larval generations and entire season from orchards using four mating disruption systems in 2017

	Mean (±SE) cumulative NOW eggs per trap				
Treatments	Generation 1	Generation 2	Generation 3	Generation 4	Total
No-MD Control	7.3 ± 7.3	3.3 ± 3.3	0.2 ± 0.2	0.5 ± 0.5	11.3 ± 11.3
Isomate	0.5 ± 0.5	0.5 ± 0.5	5.8 ± 5.8	0.2 ± 0.2	7.0 ± 6.8
Semios	1.0 ± 0.8	5.5 ± 5.5	5.0 ± 4.8	0.0 ± 0.0	11.5 ± 10.0
Checkmate	2.3 ± 1.3	1.5 ± 1.5	2.5 ± 1.6	0.5 ± 0.5	6.8 ± 3.7
Cidetrak	4.2 ± 4.2	1.0 ± 1.0	5.8 ± 5.1	0.7 ± 0.7	11.7 ± 10.9
F (df 4,8)	0.69	1.00	1.28	0.43	0.24
P	0.6208	0.4609	0.3542	0.7846	0.9070

Table 4. Percentage almonds damaged by NOW and total kilograms of damaged kernelsper hectare (mean ± SE) for the cultivars Nonpareil, Monterey, and Fritz in plots treated with mating disruption products and the No-MD control in the 2017 growing season

Treatments	Nonpareil	Monterey	Fritz	Total kg of damaged kernels per hectare
No-MD Control	1.7 ± 0.6	3.6 ± 1.1	2.0 ± 0.6	76.7 ± 18.9
Isomate	1.0 ± 0.4	2.4 ± 0.8	0.9 ± 0.3	45.0 ± 14.0
Semios	1.5 ± 0.8	1.2 ± 0.1	0.8 ± 0.1	41.4 ± 13.6
Checkmate	0.8 ± 0.4	1.7 ± 0.9	1.2 ± 0.4	38.2 ± 7.2
Cidetrak	1.2 ± 0.6	1.7 ± 0.5	0.7 ± 0.3	41.1 ± 14.7
F (df 4, 8)	3.49	1.83	2.10	2.44
P	0.0623	0.2160	0.1731	0.1321

Means followed by the same letter are not significantly different after ANOVA with means separated by Fisher's PLSD (α = 0.05). Mean percent injury or kg of damaged kernels reported.

the entire season ($F = 59.36$; df = 1,8; $P < 0.0001$). There were no statistically significant differences for any treatment in egg captures for individual generations or for the entire season when data were analyzed by ANOVA (Table 3, $P > 0.3542$) or through planned orthogonal contrasts ($P > 0.0687$).

At harvest, the percentages of kernels damaged by NOW in the No-MD control were 1.7% for Nonpareil, 3.6% for Monterey, and 2.0% for Fritz (Table 4). Damage percentages in MD plots were numerically, but not statistically, reduced for all four MD products for all three cultivars compared to the control ($P > 0.0623$). The total weight of damaged kernels ranged from 38.2 to 44.9 kg ha^{-1} for MD plots compared to 76.7 kg ha^{-1} in the No-MD control (NS, $P = 0.1321$). Damage in planned contrasts between plots with and without MD were significant for all three cultivars (Nonpareil: $F = 7.95$; df = 1,8; $P = 0.0225$. Monterey: $F = 5.82$; df = 1.8; $P = 0.0423$. Fritz: $F = 7.14$; df = 1,8; $P = 0.0283$), with 46.0% reductions in NOW damage where MD was used ($F = 9.53$; df = 1,8; $P = 0.0150$).

Direct Comparison Studies

Orchards using MD had significant reductions in the number of male moths caught in pheromone traps during all four flights (Fig. 1a: 1st flight: $t = 3.63$; df = 8; $P = 0.0067$. 2nd flight: $t = 5.16$; df = 8; $P = 0.0009$. 3rd flight: $t = 6.86$; df = 8; $P < 0.0001$. 4th flight $t = 4.53$; df = 8; $P = 0.0019$). This included greater than 98.1% reductions during the second and third flights, and season-long reductions of 93.5% ($t = 6.86$; df = 8; $P < 0.0001$). During the first flight, prior to when MD products could affect NOW population levels, there were no significant differences in the number of moths in PPO traps (Fig. 1b, 1st flight; $t = 1.25$; df = 5; $P = 0.2661$). Subsequently, there were significant reductions in the number of moths caught in PPO traps in MD plots during the second and third flights, 68.4% and 69.5%, respectively ($t = 2.94$; df = 5; $P = 0.0322$ and $t = 8.46$; df = 5; $P = 0.0004$), but not during the fourth flight ($t = 0.79$; df = 5; $P = 0.4649$). Season-long captures in PPO traps in MD plots were reduced by 47.3% ($t = 3.83$; df = 5; $P = 0.0122$). The number of eggs captured in MD treatments was reduced by less than 4.2% compared to the control during the first and fourth flights, and by 56.7% to 64.9% during the second and third flights, respectively, though none of these reductions were statistically significant (Fig. 1c; $P > 0.3805$).

At harvest, orchards employing MD had a 65.4% reduction in the percentage of damaged Nonpareil kernels ($t = 4.02$; df = 8; $P = 0.0039$) and a 78.3% reduction for kernels of pollenizer cultivars (Fig. 2; $t = 2.74$; df = 8; $P = 0.0253$). This resulted in a 70.2% reduction in the KDK across all cultivars from 60.5 kg ha^{-1} in No-MD orchards to 18.0 kg ha^{-1} where MD was employed ($t = 4.25$; df = 8; $P = 0.0028$).

Economics

In the 2017 efficacy study, grower returns in plots using Isomate, Semios, CheckMate and Cidetrak MD systems ranged from $18,264 ± 102 to $18,314 ± 51 ha^{-1} compared to $17,915 ± 193 for the No-MD Check (NS, $F = 3.70$; df = 4, 8; $P = 0.0545$). When analyzed through planned orthogonal contrasts, grower returns in plots using MD systems were significantly higher than in the No-MD control ($F = 14.89$; df = 1, 8; $P = 0.0048$). Increases in crop value where the four MD products were used ranged from $364 to $399 ha^{-1}, with an average of $370 ha^{-1}.

In the nine direct comparison orchards, the cost of implementing MD varied according to the commercial practices of each cooperating grower (Table 5). At Lost Hills, Maricopa, and Turlock, where MD was implemented in addition to the same commercial insecticide programs as the No-MD control, NOW management costs in the MD orchard increased by $313 ha^{-1}. At Escalon, where insecticide programs varied slightly between the MD and No-MD

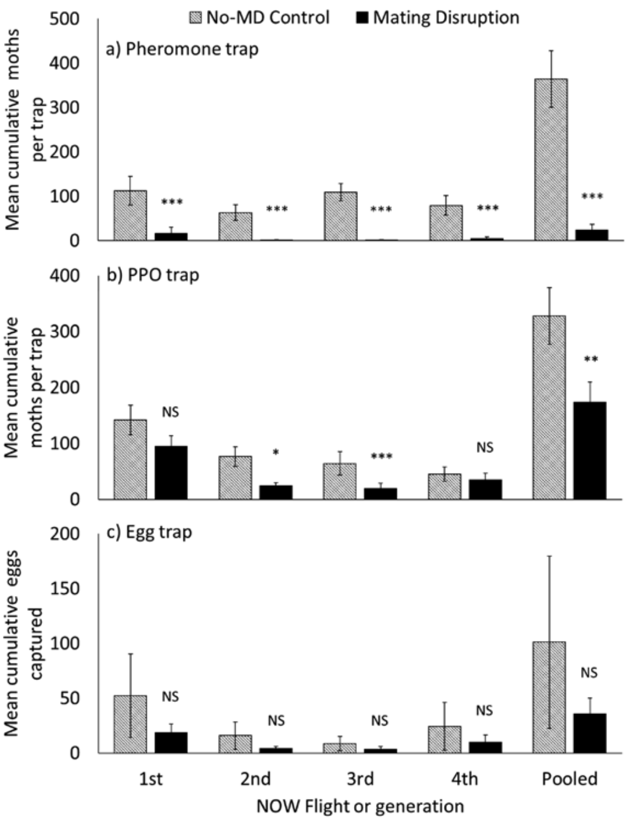

Fig. 1. Cumulative mean (±SE) NOW (a) moths per pheromone trap, (b) moths per pheromone trap baited with a phenyl proprionate (PPO) lure, or (c) eggs per egg trap during four flights and pooled for the entire season in nine pairs of almond orchards with and without mating disruption, 2017–2018. Asterisks indicate significant differences of $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***) when evaluated by *t*-test after sqrt+0.5 transformation of the data. Mean catch is reported.

orchards, the management costs in the MD orchard increased by \$188 to \$288 ha^{-1}. At Wasco, where the grower cooperator used MD as a replacement for applications of methoxyfenozide and chlorantraniliprole, NOW management costs were reduced by \$3 ha^{-1} in the MD orchard.

Grower returns were higher in MD orchards at all nine sites, averaging \$357 ha^{-1} (Table 5, $t = -2.63$; df = 8; $P = 0.0300$). After the costs for implementing MD were considered, growers' return on investment to switch to a NOW management program, including MD ranged from a \$271 ha^{-1} loss to a \$762 ha^{-1} gain, with an average gain of \$127 ha^{-1}. The point at which the costs and benefits of adding a MD system to an existing management program break-even was 1.73% of kernels damaged in windrows, or 0.86% of kernels damaged after processing at the huller (Fig. 3: $m = 454.8$; $b = 390.6$; $R^2 = 0.9974$; $P < 0.0001$). A similar analysis of data from the 2017 efficacy study showed that the average net gain of implementing MD was \$57 ha^{-1}, but ranged from a \$445 ha^{-1} gain to a \$263 ha^{-1} loss. The break-even point at which MD implementation costs were offset by increased grower returns was 2.12% of kernels damaged in windrows or 1.06% of kernels damaged at the huller (Fig. 3: $m = 494.7$; $b = 512.9$; $R^2 = 0.8079$; $P < 0.0001$).

Discussion

This is the first study to provide quantitative estimates of the impact of MD for NOW management. While there are examples of economic analysis for MD for oriental fruit moth (Pickel et al. 2002) and codling moth (Gut and Brunner 1998, Elkins et al. 2005, McGhee et al. 2011), critiques of a scarcity of such studies in economic entomology in general (Onstad and Knolhoff 2009, Naranjo et al. 2015) also seem applicable to MD. Earlier studies of MD showing that an all-insecticide program provided control of oriental fruit moth in California pears at a lower cost than MD programs for part or all of the year (Pickel et al. 2002), and contemporaneous studies with codling moth found that the cost of MD was often higher than all-insecticide programs but could be lower depending on the accounting for insecticide treatments for secondary pests flairs due to suppressed natural control (Gut and Brunner 1998). Subsequent studies of MD for codling moth found that insecticide costs and overall operating costs decreased over a multi-year area-wide program in California pears (Elkins et al. 2005), and were lower in pome fruit regions in Michigan under area-wide control as compared to isolated MD blocks or control with insecticide only (McGhee et al. 2011). A key difference between the current study and these predecessors is that the current study quantifies the economic impact of MD over a range of infestation levels and estimates a relationship between the level of infestation and the impact of MD on return to growers.

The financial benefit of MD in this study was a roughly linear function of NOW pressure as determined by damage in non-MD orchards. The range of damage in the current study was moderate, with averages across varieties ranging from 0.7 to 1.7% in the efficacy study, and from 0.3 to 2.6% in the direct comparison samples. Much higher levels of damage are not uncommon. Throughout the range of damage, the proportional difference of percent damaged kernels between MD and the No-MD control was similar. For example, for sites averaging <1% damage levels in the No-MD control, damaged kernels by weight was reduced by 58.5%. In comparison, reductions were 70.0% at sites averaging 2.4 to 5.1% total injury across cultivars. Since the cost of MD was constant, the rate of return was a roughly linear function of NOW pressure as determined by the damage in the non-MD plots. When pressure was low the rate of return was lower with MD than without it, but when it was higher net return was greater with MD.

In our study, adding MD systems to orchards with 1.6 to 2.4%, and from 4.8% to 5.2% damaged kernels, resulted in net gains of \$80.8 ha^{-1} and \$733.3 ha^{-1}, respectively. The point at which the costs of adding a MD system to an existing management program break-even was 1.73% of kernels damaged in windrows, or 0.86% of kernels damaged after processing at the huller (Fig. 3). A similar analysis of data from the 2017 efficacy study showed that the average net gain of implementing MD was \$57 ha^{-1}, ranging from a gain of \$445 ha^{-1} to a loss of \$263 ha^{-1}. The break-even point at which MD costs were offset by increased grower returns was 2.12% of kernels damaged in windrows or 1.06% of kernels damaged at the huller (Fig. 3). Statewide damage levels are similar to the break-even point for using MD systems. Over the past 10 yr, the average percentage of inedibles (off-graded kernels for which a grower does not get paid) in California almonds was 1.35% (range 0.80–2.42%, ABC 2019a). When considering that most inedible kernels are caused by NOW, with a portion attributed to hemipterans (stink bugs, leaffooted bugs), other lepidoptera larvae, and ants, the statewide average for NOW damage is comparable to the 0.86% to 1.06% estimates for break-even damage levels calculated from our efficacy and direct comparison studies. An important caveat is that a linear benefit of MD should not be extrapolated beyond the rate of damage seen in this study. It is likely that, at some point, MD will be overwhelmed.

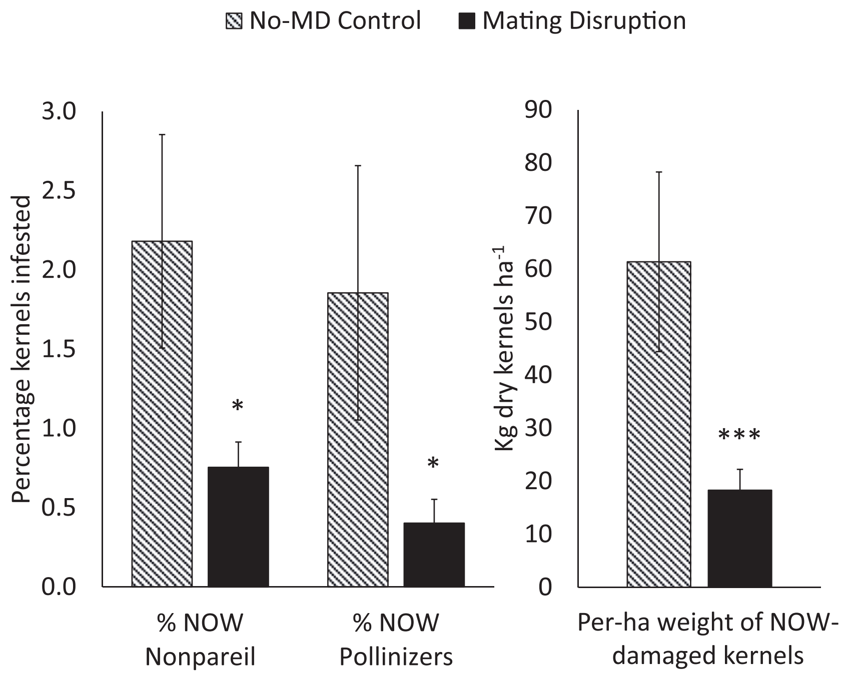

Fig. 2. Mean (±SE) percentage of Nonpareil and pollenizer cultivars of almonds damaged by NOW, and per-ha weights of damaged kernels assuming yields of 3,363 kg ha^{-1} in the southern San Joaquin Valley and 2,802 kg ha^{-1} in the northern San Joaquin Valley from nine pairs of almond orchards with and without mating disruption, 2017–2018. Asterisks indicate significant differences of $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***) when evaluated by t-test after sqrt+0.5 transformation of the data. Original means are shown.

Table 5. Economic analysis of nine direct comparison orchards using conventional management programs for NOW compared to modified programs, including mating disruption

		No-MD		MD				
Site	Year	Costs[a] ($/ha)	Returns ($/ha)	Costs[a] ($/ha)	Returns ($/ha)	Change in cost ($/ha)	Change in Returns ($/ha)	Net gain/loss to grower (ha^{-1})
Escalon	2017	198	14,223	486	15,215	288	993	705
Escalon	2018	411	15,143	629	15,395	218	253	35
Lost Hills	2017	143	17,273	456	18,348	313	1,075	762
Lost Hills	2018	489	18,363	802	18,480	313	118	−196
Maricopa	2018	579	17,845	892	18,285	313	440	127
Turlock	2017	238	15,280	551	15,410	313	130	−183
Turlock	2018	208	15,375	521	15,418	313	43	−271
Wasco	2017	316	18,448	313	18,553	−4	105	109
Wasco	2018	316	18,465	313	18,520	−4	55	59
	Mean.	322	16,713	551	17,069	229	357	127

[a]Costs associated with insecticides and mating disruption in conventionally managed orchards (No-MD) and orchards with modified conventional practices, including MD. Inputs associated with costs can be referenced in Supp Table 1 (online only). Note that at Wasco in 2017 and 2018, MD was used as a replacement for, and not as an addition to, insecticide sprays.

Efforts to understand the mechanisms behind the efficacy of MD products for NOW are still in progress. Recent studies by Burks and Thompson (2019, 2020) suggested that current MD products act via a hybrid mechanism that is not density-dependent, making it more similar to noncompetitive rather than competitive systems (Miller et al. 2006, Miller and Gut 2015). If true, this mechanism helps explain the relatively consistent relationship we found between NOW abundance (as indicated by infestation levels) and reduction in kernel damage across a range of pest densities. In its entirety, the overall benefit of MD is likely complex and multi-factorial, involving not only neurophysiological effects, but also relationships between the pest and host and immigration and emigration in the system. For example, the European corn borer *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) has an obligatory dispersal behavior prior to mating (Dorhout et al. 2008), which would complicate MD for that species. NOW has a robust dispersal capacity (Sappington and Burks 2014), but does not seem to disperse prior to mating (Rovnyak et al. 2018). It is also likely that the orchards treated with MD are a source of, rather than a sink for, NOW at the time they are harvested. Landscape effects are nonetheless important. For example, NOW abundance is typically higher in pistachio than in almond due to greater difficulty removing overwintering host material in pistachio orchards (Burks et al. 2008). There is also a significant relationship between damage in almonds and distance from the nearest pistachio orchard (Higbee and Siegel 2009). Logically, it is also evident that a very effective MD system might not be economically

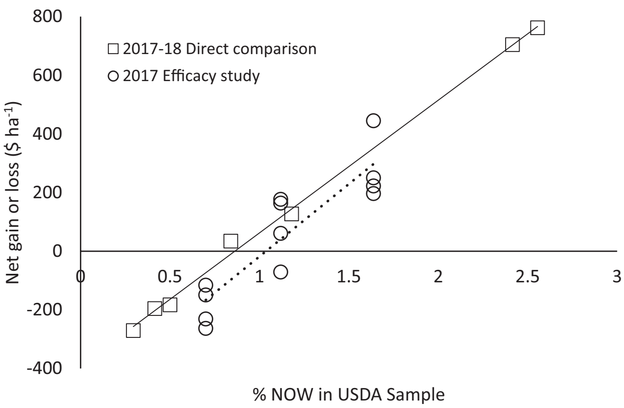

Fig. 3. Relationships between the percentages of NOW damage (USDA samples at the huller) from orchards without mating disruption and the net gain or loss if mating disruption had been implemented in addition to the existing management program. Break-even points were 1.06% for the 2017 efficacy study ($y = 0.0016x + 1.059$, $R^2 = 0.8079$) and 0.86% for the 2017–2018 direct comparison ($y = 0.0022x + 0.8634$, $R^2 = 0.99$).

viable in a cropping system with a thin profit margin, whereas a more modestly effective system might be economically viable for a higher value crop.

We used pheromone traps, egg traps, and PPO traps in the present study because those are currently used to monitor NOW by farmers and pest control advisers. Pheromone traps can reveal mechanistic aspects of MD, but for that purpose it is generally necessary to experimentally manipulate MD treatments (Miller et al. 2006, Miller and Gut 2015, Burks and Thomson 2020) and use a trap density (Miller et al. 2015, Adams et al. 2017) that is not typical of commercial practice. In previous studies MD for NOW has very effectively suppressed pheromone traps, even at points far enough from dispensers that a crop protection benefit seemed unlikely. Therefore, pheromone traps serve as a quality control measure when MD is in use. Egg traps have long been used for monitoring NOW (Rice et al. 1976, Van Steenwyk et al. 1986) and have the benefit of directly assessing female fertility, i.e., the potential for damage. However, they have the disadvantage of an overdispersed frequency distribution (many empty traps, a few high numbers), which make large samples more important for quantitative estimates (Higbee and Burks 2011). As a result, most pest control advisers who use egg traps have enough data to monitor trends for regions, but not for individual management blocks (Higbee and Burks 2011). Traps baited with pheromone and PPO capture both sexes and are attractive in both the presence and absence of MD but have not been used as long as the other trap types discussed. In the present study all MD treatments suppressed capture of NOW in pheromone traps. There were no statistically significant differences between the MD treatments regarding male NOW captured in pheromone traps. Numerical trends in the pheromone trap data, however, suggest fewer males were captured during the fourth flight in the plots treated with the passive meso-dispensers (Cidetrak) than with the two non-variable aerosols (Isomate, Checkmate); and even fewer were captured with the variable-rate aerosol system (Semios) compared to the meso-dispensers. This observation suggests that some treatments provided full suppression farther into the season than others, but further research is needed to verify this trend. The number of eggs per trap were not significantly different between the MD and No-MD orchards. Variation in egg numbers was apparently greater in the NO-MD than in the MD plots, suggesting that the failure to find statistically significant differences was due to an insufficient number of egg traps. The data also suggest a larger variance for PPO-pheromone in the absence of MD than in the presence. While a larger variance accompanying a large mean is common to count data, it is plausible that the PPO-pheromone traps in No-MD plots were attracting NOW from greater distance than those in the MD plots.

Incorporation of MD for NOW into pest management programs is a work in progress. Available data suggest that the relationship between abundance (infestation of kernels) and reduction in damage by pesticide treatments is also density-dependent, and that crop protection benefits of insecticides and MD for reduction of NOW damage are additive (Higbee, unpublished data). In-season prediction of NOW damage is complex and only moderately precise (Rosenheim et al. 2017). Pest management decisions involving both insecticide and MD are made based on orchard history, with monitoring used more typically to inform timing of insecticide application. Insecticide treatment decision might be modified by in-season factors like changing crop prices and perceived influence of weather and heat accumulation on regional NOW abundance. Industry groups, such as the Almond Board of California are concerned about the effects of externalities and perceived environmental indifference on regulations and marketability on the almond industry (Almond Board of California 2019b). However, adoption of NOW MD is driven by decisions of individual growers based on the effect of pest management practices on overall return such as was measured in the current study. Using MD to reduce insecticide input is desirable at an industry and societal level. It can be economically favorable as demonstrated by the case of the 2018 Wasco participant who demonstrated growers with historically low NOW damage levels can replace two insecticide sprays with a similarly-priced MD system and achieve net gains averaging \$83.5 ha^{-1}. In general, NOW MD in almonds can currently be viewed as an insurance policy against high losses from NOW. Full achievement of the potential of MD to reduce insecticide input will require further improvements in the ability to use in-season monitoring data to anticipate damage.

In summary, the current study found that four of the most used products for MD for NOW provide similar crop protection in almond. The economic benefit is dependent on NOW abundance. Other caveats are that these results do not necessarily extend to other products, such as microencapsulated formulations, which may have different optimum use patterns. The relationship between benefit from MD and damage is likely also different in other crops, such as pistachios and walnuts.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

Acknowledgments

We thank Chris Cucuk, Brian Dugo, Candice Harris, Gary Osteen, Misty Rex, Doug Raymond, Gary Suthers, and Matt Thompson for coordinating field operations with cooperating almond growers and Daniel Rivers for data collection and technical support. Funding was provided by the Almond Board of California and California Department of Pesticide Regulation Pest Management Alliance Grant Program. In-kind contributions of mating disruption dispensers and monitoring supplies were provided by Trécé Inc, SemiosBio Technologies Inc., Pacific Biocontrol, and Suterra LLC.

References Cited

Abd El-Ghany, N. M. 2019. Semiochemicals for controlling insect pests. J. Plant Prot. Res. 59: 1–11.

Adams, C. G., P. S. McGhee, J. H. Schenker, L. J. Gut, and J. R. Miller. 2017. Line-trapping of codling moth (Lepidoptera: Tortricidae): a novel approach to improving the precision of capture numbers in traps monitoring pest density. J. Econ. Entomol. 110: 1508–1511.

[ABC] **Almond Board of California. 2019a**. Almond Almanac 2019. Almond Board of California document #2019IR0308, Modesto, CA. http://www.almonds.com/processors/resources/almond-almanac.

[ABC] **Almond Board of California, 2019b**. Almond orchard 2025 goals. California Almond Sustainability Program, Almond Board of California document #2019CN0208, Modesto, CA. http://www.almonds.com/growing-good/2025-goals.

Benelli, G., A. Lucchi, D. Thomson, and C. Ioriatti. 2019. Sex pheromone aerosol devices for mating disruption: challenges for a brighter future. Insects 10: 308.

Blue Diamond Growers, 2018. 2018 quality adjustment schedule. Blue Diamond Growers, Modesto, CA. http://bluediamondgrowers.com/wp-content/uploads/2018/07/2018-Quality-Adjustment-Schedule-Final-7-05-18.pdf.

Burks, C. S. 2017. Combination phenyl propionate/pheromone traps for monitoring navel orangeworm (Lepidoptera: Pyralidae) in almonds in the vicinity of mating disruption. J. Econ. Entomol. 110: 438–446.

Burks, C. S., and D. R. Thomson. 2019. Optimizing efficiency of aerosol mating disruption for navel orangeworm (Lepidoptera: Pyralidae). J. Econ. Entomol. 112: 763–771.

Burks, C. S., and D. R. Thomson. 2020. Factors affecting disruption of navel orangeworm (Lepidoptera: Pyralidae) using aerosol dispensers. J. Econ. Entomol. 113: 1290–1298.

Burks, C. S., B. S. Higbee, D. G. Brandl, and B. E. Mackey. 2008. Sampling and pheromone trapping for comparison of abundance of *Amyelois transitella* in almonds and pistachios. Entomol. Exp. Appl. 129: 66–76.

Burks, C. S., L. Kuenen, and K. M. Daane. 2016. Phenyl propionate and sex pheromone for monitoring navel orangeworm in the presence of mating disruption. J. Econ. Entomol 109: 958–961.

Burks, C. S., L. P. Kuenen, and K. M. Daane. 2016. Phenyl propionate and sex pheromone for monitoring navel orangeworm (Lepidoptera: Pyralidae) in the presence of mating disruption. J. Econ. Entomol. 109: 958–961.

Burks, C. S., B. S. Higbee, and J. J. Beck. 2020. Traps and attractants for monitoring navel orangeworm (Lepidoptera: Pyralidae) in the presence of mating disruption. J. Econ. Entomol. 113: 1270–1278.

Curtis, C. E., P. J. Landolt, and J. D. Clark. 1985. Disruption of navel orangeworm (Lepidoptera: Pyralidae) mating in large-scale plots with synthetic pheromone. J. Econ. Entomol. 78: 1425–1430.

Dorhout, D. L., T. W. Sappington, and M. E. Rice. 2008. Evidence for obligate migratory flight behavior in young European corn borer (Lepidoptera: Crambidae) females. Environ. Entomol. 37: 1280–1290.

Elkins, R. B., K. M. Klonsky, and R. L. DeMoura. 2005. Cost of production for transitioning from conventional codling moth control to aerosol-released mating disruption ("puffers") in pears. Acta Hortic. 671:559–563.

Evenden, M. 2016. Mating disruption of moth pests in integrated pest management, pp. 365–393. *In* J. D. Allison and R. T. Carde (eds.), Pheromone communication in moths. Evolution, behavior, and application. University of California Press, Oakland, CA.

Gut, L. J., and J. F. Brunner. 1998. Pheromone-based management of codling moth (Lepidoptera: Tortricidae) in Washington apple orchards. J. Agric. Entomol. 15: 387–405.

Hamby, K. A., and F. G. Zalom. 2013. Relationship of almond kernel damage occurrence to navel orangeworm (Lepidoptera: Pyralidae) success. J. Econ. Entomol. 106: 1365–1372.

Haviland, D. R., W. J. Bentley, J. P. Siegel, B. A. Holtz, K. M. Daane, and B. S. Higbee. 2016. Navel orangeworm and obliquebanded leafroller. *In* L. Ferguson and D. Haviland (eds.). Pistachio production manual. Publication 3545, University of California Agriculture and Natural Resources, Oakland, CA.

Haviland, D. R., M. Yaghmour, E. J. Fichtner, B. L. Sanden, M. Culumber, M. Viveros, and D. Stewart. 2019. 2019 Sample costs to establish an orchard and produce almonds: San Joaquin Valley south. University of California Agriculture and Natural Resources Agricultural Issues Center, UC Davis Department of Agriculture and Resource Economics. https://coststudies.ucdavis.edu/en/.

Haviland, D. R., R. A. Baldwin, K. J. Hembree, T. J. Michailides, B. B. Westerdahl, R. H. Beede, M. M. Daane. 2020a. Revised continuously. UC IPM pest management guidelines: pistachio. Publication 3461, University of California Agriculture and Natural Resources, Oakland, CA. http://www2.ipm.ucanr.edu/agriculture/pistachio.

Haviland, D. R., E. J. Symmes, J. E. Adaskaveg, R. A. Duncan, J. A. Roncoroni, W. D. Gubler, B. Hansen, K. J. Hembree. 2020b. Revised continuously. UC IPM Pest management guidelines: Almond. Publication 3431, University of California Agriculture and Natural Resources, Oakland, CA. https://www2.ipm.ucanr.edu/agriculture/almond.

Higbee, B. S., and C. S. Burks. 2008. Effects of mating disruption treatments on navel orangeworm (Lepidoptera: Pyralidae) sexual communication and damage in almonds and pistachios. J. Econ. Entomol. 101: 1633–1642.

Higbee, B. S., and J. P. Siegel. 2009. New navel orangeworm sanitation standards could reduce almond damage. Calif. Agric. 63: 24–28.

Higbee, B. S., and C. S. Burks. 2011. Effect of bait formulation and number of traps on detection of navel orangeworm (Lepidoptera: Pyralidae) oviposition using egg traps. J. Econ. Entomol. 104: 211–219.

Higbee, B. S., and J. P. Siegel. 2012. Field efficacy and application timing of methoxyfenozide, a reduced-risk treatment for control of navel orangeworm (Lepidoptera: Pyralidae) in almond. J. Econ. Entomol. 105: 1702–1711.

Higbee, B. S., C. S. Burks, and T. E. Larsen. 2014. Demonstration and Characterization of a Persistent Pheromone Lure for the Navel Orangeworm, Amyelois transitella (Lepidoptera: Pyralidae). Insects. 5: 596–608.

Higbee, B.S., C. S. Burks, and R. T. Cardé. 2017. Mating disruption of the navel orangeworm (Lepidoptera: Pyralidae) using widely spaced, aerosol dispensers: Is the pheromone blend the most efficacious disruptant? J. Econ. Entomol. 110: 2056–2061.

Kanno, H., L. P. Kuenen, K. A. Klingler, J. G. Millar, and R. T. Cardé. 2010. Attractiveness of a four-component pheromone blend to male navel orangeworm moths. J. Chem. Ecol. 36: 584–591.

Kuenen, L. P. S., W. Bentley, H. C. Rowe, and B. Ribeiro. 2008. Bait formulations and longevity of navel orangeworm egg traps tested. Calif. Agric. 62: 36–39.

Landolt, P. J., C. E. Curtis, J. A. Coffelt, K. W. Vick, P. E. Sonnet, and R. E. Doolittle. 1981. Disruption of mating in the navel orangeworm with (*Z*,*Z*)-11,13-Hexadecadienal. Environ. Entomol. 10: 745–750.

Leal, W. S., A. L. Parra-Pedrazzoli, K. E. Kaissling, T. I. Morgan, F. G. Zalom, D. J. Pesak, E. A. Dundulis, C. S. Burks, and B. S. Higbee. 2005. Unusual pheromone chemistry in the navel orangeworm: novel sex attractants and a behavioral antagonist. Naturwissenschaften. 92: 139–146.

Light, D. M., J. A. Grant, R. P. Haff, and A. L. Knight. 2017. Addition of pear ester with sex pheromone enhances disruption of mating by female codling moth (Lepidoptera: Tortricidae) in walnut orchards treated with meso dispensers. Environ. Entomol. 46: 319–327.

McGhee, P. S., D. L. Epstein, and L. J. Gut. 2011. Quantifying the benefits of areawide pheromone mating disruption programs that target codling moth (Lepidoptera: Tortricidae). Am. Entomol. 57: 94–100.

McGhee, P. S., L. J. Gut, and J. R. Miller. 2014. Aerosol emitters disrupt codling moth, *Cydia pomonella*, competitively. Pest Manag. Sci. 70: 1859–1862.

Miller, J. R. and L. J. Gut. 2015. Mating disruption for the 21st century: matching technology with mechanisms. Environ. Entomol. 44: 427–453.

Miller, J. R., L. J. Gut, F. M. de Lame, and L. L. Stelinski. 2006. Differentiation of competitive vs. non-competitive mechanisms mediating disruption of moth sexual communication by point sources of sex pheromone (part I): Theory. J. Chem. Ecol. 32: 2089–2114.

Miller, J. R., C. G. Adams, P. A. Weston, and J. H. Schenker. 2015. Trapping of small organisms moving randomly: principles and applications to pest monitoring and management. Springer, New York, NY.

Naranjo, S. E., P. C. Ellsworth, and G. B. Frisvold. 2015. Economic value of biological control in integrated pest management of managed plant systems. Annu. Rev. Entomol. 60: 621–645.

Onstad, D. W., and L. M. Knolhoff. 2009. Finding the economics in economic entomology. J. Econ. Entomol. 102: 1–7.

Palumbo, J. D., N. E. Mahoney, D. M. Light, J. Siegel, R. D. Puckett, and T. J. Michailides. 2014. Spread of *Aspergillus flavus* by navel Orangeworm (*Amyelois transitella*) on almond. Plant Dis. 98: 1194–1199.

Pickel, C., J. Hasey, W. Bentley, W. Olson, and J. Grant. 2002. Pheromones control oriental fruit moth and peach twig borer in cling peaches. Calif. Agric. 56: 170–176.

Reinke, M. D., P. Y. Siegert, P. S. McGhee, L. J. Gut, and J. R. Miller. 2014. Pheromone release rate determines whether sexual communication of Oriental fruit moth is disrupted competitively vs. non-competitively. Entomol. Exp. Appl. 150: 1–6.

Rice, R. E., L. L. Sadler, M. L. Hoffman, and R. A. Jones. 1976. Egg traps for the navel orangeworm, *Paramyelois transitella* (Walker). Environ. Entomol. 5: 697–700.

Rosenheim, J. A., B. S. Higbee, J. D. Ackerman, and M. H. Meisner. 2017. Predicting nut damage at harvest using different in-season density estimates of *Amyelois transitella*: analysis of data from commercial almond production. J. Econ. Entomol. 110: 2692–2698.

Rovnyak, A. M., C. S. Burks, A. J. Gassmann, and T. W. Sappington. 2018. Interrelation of mating, flight, and fecundity in navel orangeworm (Lepidoptera: Pyralidae) females. Entomol. Exp. Appl. 166: 304–315.

Sappington, T. W., and C. S. Burks. 2014. Patterns of flight behavior and capacity of unmated navel orangeworm Lepidoptera: Pyralidae) adults related to age, gender, and wing size. Environ. Entomol. 43: 696–705.

SAS Institute, Inc. 2015. SAS/STAT 15.1 user's guide. SAS Institute Inshoreyc. Cary, NC.

Schatzki, T. F., and M. S. Ong. 2001. Dependence of aflatoxin in almonds on the type and amount of insect damage. J. Agric. Food Chem. 49: 4513–4519.

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

Soderstrom, E. L. 1977. Seal of almond shells and resistance to navel orangeworm. J. Econ. Entomol. 70: 467–468.

Trécé, Inc. 2020. Specimen label, Cidetrak® NOW Meso. Trécé Incorporated, Adair, OK.

[UC] **University of California, 2002**. Integrated Pest management for Almonds, 2nd ed. University of California, Division of Agriculture and Natural Resources, Oakland, CA.

Van Steenwyk, R. K., W. W. Barnett, W. J. Bentley, and J. H. Connell. 1986. Improved NOW egg traps. Calif. Agric. 40: 24–25.

Wade, W. H. 1961. Biology of the navel orangeworm, *Paramyelois transitella* (Walker), on almonds and walnuts in northern California. Hilgardia 31: 129–171.

Welter, S., C. Pickel, J. Millar, F. Cave, R. Van Steenwyk, and J. Dunley. 2005. Pheromone mating disruption offers selective management options for key pests. Calif. Agric. 59: 16–22.

Witzgall, P., P. Kirsch, and A. Cork. 2010. Sex pheromones and their impact on pest management. J. Chem. Ecol. 36: 80–100.

Zalom, F. G., W. W. Barnett, and C. V. Wheatley. 1984. Efficacy of winter sanitation for managing the navel orangeworm, *Paramyelois transitella* (Walker), in California almond orchards. Prot. Ecol. 7: 37–41.