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Season-long comparison of trap lures for integrated management of the navel orangeworm (Lepidoptera: Pyralidae) in almond and pistachio

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Abstract

Monitoring navel orangeworm, *Amyelois transitella* (Lepidoptera: Pyralidae) using pheromone lures is now complicated by the use of mating disruption. Two commercially available lures that are minimally affected by mating disruption use either natural ovipositional substrates (Bait lures) or a combination of phenyl propionate (PPO), a volatile chemical that attracts both sexes and pheromone lures (Combo lures). We compared the season-long trap capture for these two lures in a sterile insect technique (SIT) demonstration project in Fresno County, California, 2020–2023. A total of 194,233 males (96.52%) were caught using Combo lures and 7006 (3.48%) caught using Bait lures, while 95,947 females (48.83%) were caught using Combo lures and 100,532 (51.17%) caught using Bait lures. Capture of *A. transitella* was 2.3-fold higher in pistachio (278,492) than in almond (119, 316), and within a commodity, there was a moderate correlation in female capture between the two lures; correlation was stronger during the period leading up to July 21 (Julian date 202). For Bait lures, 48.7% of the trap catch in almond occurred by July 21 and 87.1% of the trap catch occurred in pistachio by July 21. For Combo lures, 38.9% of the trap catch in almond occurred by July 21 while 54.6% of the catch occurred in pistachio. Bait lures became less effective after July 21, likely due to diminished attractiveness as new crop nuts split in August through October. Our data indicate that Combo lures are preferable when the goal is consistent season-long capture of *A. transitella* in almond and pistachio.

Keywords *Amyelois transitella*, Phenyl propionate, Trapping, Almond, Pistachio, Population dynamics, Ovibait

Introduction

The navel orangeworm, *Amyelois transitella* Walker (Lepidoptera: Pyralidae) is the primary pest of California almond (*Prunus dulcis;* 81% of the world supply), pistachio (*Pistacia vera*; 67% of the world supply) and walnut (*Juglans regia*) (Statista 2022, Almonds 2023). Currently these crops are planted in > 900,000 ha in California and have a combined annual farm gate value exceeding US $9 billion (Siegel and Gilcrease 2022). This multivoltine moth has a mutualistic relationship with fungal species belonging to the genus *Aspergillus* that produce aflatoxins, consequently feeding causes direct damage to the nuts and can cause secondary fungal infection (Palumbo et al. 2014; Ampt et al. 2016; Picot et al. 2017; Bush et al. 2018).

Monitoring for *A. transitella* is important because damage in almonds and pistachios results from a complex interplay of crop phenology and pest population dynamics (Wilson et al. 2020). New crop Nonpareil

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almonds, the most valuable variety, become vulnerable during hull split (late June–July) when the suture widens exposing the shell and/or nut. The period of vulnerability for Nonpareil almonds typically lasts 5 to 8 weeks until the nuts are shaken from the tree at harvest; the other almond varieties mature from late August through October (Haviland et al. 2022a). New crop pistachios are vulnerable when the hull breaks down after the nut ripens, exposing the split shell for eight to ten weeks from mid-August through mid-October (Haviland et al. 2022b). The value of the damage caused by *A. transitella* in almonds (goal is damage ≤ 1% assessed at the processor for US Fancy, the highest grade) and pistachios (goal is damage ≤ 1% assessed at the processor) has increased since 2012, due to the combination of increased host availability (currently 628,000+ ha almonds and 196,000+ ha pistachios), increased number of affected nuts, and beginning in 2012, increased heat unit accumulation during the growing season allowing an extra generation to develop each year (Pathak et al. 2021). In some years there are *A. transitella* outbreaks affecting all nut crops, when average damage increases > fivefold; 2017 was a high damage year for almonds, pistachios and walnuts, with *A. transitella* damage exceeding 20% in some loads of almonds and pistachios (Siegel 2023). In 2020 almonds contributed $21.5 billion and pistachios contributed $5.2 billion to the California economy (Almonds 2023; AmericanPistachios.Org 2023).

The population dynamics of this moth are complex because it develops on both the new crop and mummies (unharvested nuts from the previous crop) and has different generation times on mummies and new crop nuts, as well as on almond and pistachio (Kuenen and Siegel 2010; Siegel and Kuenen 2011; Siegel et al. 2010). Cohorts developing on mummies and new crop overlap from mid-July through September when the generation time is the shortest due to a combination of rapid degree day accumulation and the high nutritional quality of new crop nuts. This insect was traditionally managed by sanitation, which is the timely removal and subsequent destruction of mummies, and insecticide sprays (Higbee and Siegel 2009, 2012). Mating disruption became available after 2015 (Wilson et al. 2020; Haviland et al. 2021). This moth readily moves between orchards (Andrews and Barnes 1982, Higbee and Siegel 2009, Sappington and Burks 2014, Rovnyak et al. 2018, Reger et al. 2021) and the close proximity of almonds and pistachios in the San Joaquin Valley combined with the different time of crop maturity increases its regional abundance (Wilson et al. 2020).

Monitoring programs for *A. transitella* were refined in the late 1990s and early 2000s, but subsequently have been in flux due to rapid changes in pest management technology and crop distribution. The earlier programs were based on egg traps (Rice et al. 1976; Van Steenwyk and Barnett 1985) but their use decreased when a pheromone lure became available in 2013 (Leal et al. 2005; Kanno et al. 2010; Kuenen et al. 2010; Higbee et al. 2014). Pheromone lures are still widely used, but mating disruption has become increasingly common and can suppress pheromone traps in orchards as far away as 3 km (Burks 2017). Alternative lures that have been evaluated include oviposition baits (Burks et al. 2011; Nay et al. 2012), a kairomone blend (Burks et al. 2009; Beck et al. 2014) and the non-pheromonal attractant phenyl propionate (PPO), that was identified by mass screening (Price et al. 1967). Phenyl propionate lures are commercially available and capture both sexes and offer a more robust detection in orchards under mating disruption than pheromone lures alone, because there is a synergistic relationship when these two lures are combined (Burks et al. 2016, 2020). Pouches containing ovipositional bait used to trap gravid females are also commercially available and are increasingly used in place of egg traps. These bait pouches generally capture fewer moths than pheromone or PPO (Burks et al. 2009), but a previous study found that female attractants (egg traps or female baits) were more correlated with subsequent damage to Nonpareil almonds than were pheromone traps (Rosenheim et al. 2017).

This paper utilizes data collected from 2020–2023 from a sterile insect technique (SIT) demonstration program, to examine whether the relative effectiveness of these two lures varies with crop (almond or pistachio) and crop phenology, and whether seasonal dynamics (weekly trap catch) was similar or different between the lures. Additionally, since bait traps capture females (> 95%) whereas pheromone + PPO traps capture both sexes, we examined whether the total counts in pheromone + PPO traps paralleled the female-only count. Finally, we conducted a separate experiment to determine if trap proximity affected capture for one or both trap types that were either adjacent to each other or far apart,

Materials and methods

Site description

Trap data from two Nonpareil variety almond orchards (36.327997, −120.103126; 36.313229, −120.157808) and two Kerman variety pistachio orchards (36.458726, −120.102853; 36.356, −120.048734), 259 ha each, 2–7 km apart, located in western Fresno County, California, 2020–2022, were collected as part of a larger demonstration project for *A. transitella* SIT. Traps were placed on May 11, 2020 and on January 19 in both 2021 and 2022. Trapping ceased on December 1, 2020, October 11, 2021 and December 15, 2022. In 2023 four new 259 ha pistachio sites were established in western Fresno

County and trapping began March 29. All orchards used had active *A. transitella* management programs including sanitation, trapping and insecticide application.

Traps and lures

Pherocon 1C wing traps (Trece, Adair, OK) were placed in each orchard at a density of one trap per 7.19 ha. The traps were placed on the opposite sides of a designated tree, for a total of 36 traps per lure type, 72 wing traps total per orchard. The sites were approximately 320 m apart, and the outside traps were on the corners and edges of the orchard, with a 4×4 grid of traps in the interior of the 259 ha squares. Traps were collected weekly by the California Department of Food and Agriculture (CDFA) Navel Orangeworm Program field staff. Sterile moths were differentiated from wild moths using diet-incorporated dye; moths were crushed to reveal either a pink dyed gut (sterile moth) or non-dyed gut (wild moth). This analysis only used the data for the wild moths. Weekly data were collected as the sum of all traps with the same attractant at the same site; i.e. a sum of 36 ovibait traps and of 36 PPO-pheromone traps for each of the pistachio and almond sites. The trapping data (2021–2023) are reported on a website maintained by CDFA, https://www.cdfa.ca.gov/plant/ipc/nowp/index.html.

Lure types used

The traps used either a combination of two synthetic lures, or a lure based on natural products (Burks et al. 2020). The synthetic lures consisted of a PPO lure (Pherocon NOW PPO-HR L2, Trece, Adair, OK) and a pheromone monitoring lure (Pherocon NOW L2, Trece, Adair, OK). This combination of synthetic lures is designated "Combo" in the remainder of the manuscript. The ovibait lures consisted of packets containing a mix of crushed pistachios and almonds that were collected postharvest (Peterson Trap Company LLC, Visalia, CA). This lure is designated "Bait" in the remainder of this manuscript. All lures were replaced monthly and trap liners collected weekly.

Season division

The trapping season was divided into two portions, with the first portion beginning with the first simultaneous catch for both lure types (Julian Date 140/May 19, 2020; Julian Date 53/February 22, 2021; Julian Date 45/February 14, 2022; Julian Date 79/March 20, 2023) and ending on July 21 (Julian date 202; 203 in 2020), and the second portion continuing until the traps were removed for the season. During the first portion, mummies were the predominant host source until there were substantial split Nonpareil almonds available by the beginning of the third week of July. The cutoff July 21 was chosen because moths emerge from the new crop Nonpareil almonds infested in late June from this time onwards (Siegel et al. 2010). During the second portion of the season, the remaining new crop pollinator varieties split as do pistachios, and most *A. transitella* develop on new crop nuts, although some mummies remain available.

Analysis of trap capture and assessment of the correlation between lure type and adult capture

Differences in the count data for total moths captured by lure type and by portion of the year were assessed using 2×2 contingency chi-square analysis. The data were pooled by commodity for analysis for each year. The correlation between female capture for both bait types, as well as female and male capture in traps using Combo lures was assessed using Spearman's rho, a nonparametric statistic (JMP v 16.2, SAS Institute, Cary, NC). The observational unit (pairs) for correlation analysis was the number of females or males in all traps in individual 259 ha orchards in a monitoring period (generally 1 week).

Effect of proximity on NOW captured in Bait and Combo traps

A randomized complete block experiment designed to examine the effect of trap proximity and bait type on adult capture was conducted from June 6 to August 7, 2023, in a mature pistachio orchard, variety "Kerman", located 10.6 km south of Kerman, CA (36.1091, −120.1363). Trees were planted approximately 5 m apart in orchard rows 6 m apart. This secondary study used orange wing traps (Suterra LLC, Bend OR) previously described by Kuenen et al. (2010) and Burks et al. (2020, 2022). Four treatments were examined assessing three trap placements: (1) an isolated Combo trap; (2) an isolated Bait trap; (3) a Combo trap in the same tree as a Bait trap, (4) a Bait trap in the same tree as a Combo trap (the latter two treatments switched trap position in the tree). Orchard rows served as replicate blocks, and the trap positions were 50 m apart, with replicate blocks separated by 60 m. All trap positions were at least 50 m from the edge of the orchard. Ten replicate blocks were used. Treatment differences were examined using a nonparametric Wilcoxon rank sum test, due to heterogeneity between treatment responses. The response variable was the sum of NOW captured in each trap over the two-month time period. Differences between treatments were examined using the Dunn posterior test. The analysis was conducted using R 4.1.2 (R Core Team 2022) and the FSA package (Ogle et al. 2023).

Results

There were 397,808 moths caught in this study from 2020–2022, Table 1. Slightly more males were captured than females: 201,239 compared to 196,479. Most of the males (194,233; 96.52%) were caught using Combo traps while 7006 (3.48%) were caught using Bait traps. In contrast more females (100,532; 51.17%) were caught using Bait traps than Combo traps (95,947; 48.83%). The overall ratio of male to female was 59.3:39.7 for Combo traps and 4.8:95.2 for Bait traps. More than twice as many moths were captured in pistachio (278,492) than in almond orchards (119, 316) during the period 2020–2022 (70:30). In 2023, during the period March 28-July 12, there were 49,638 moths trapped in pistachios (16,707 males and 32,931 females). Bait traps captured 62.5% of the females and Combo traps captured 86.9% of the males.

Comparison of female capture by time period and by lure 2020–2022

In the combined Almond dataset, Table 2, there were slightly more moths caught after July 21 using Bait traps and substantially more moths (61.1%) caught after July 21 using Combo traps. Pooling the data diminished the difference between Bait and Combo traps, because Bait trap capture was substantially greater before July 21 in 2021 and 2022, at 65.4% and 78.9% respectively, while Combo

Table 2 Female capture for combo lures (pheromone + phenyl propionate) and bait (almond and pistachio meal) in Almond

Year	Lure type	Before July 21	After July 21	Total females
Combined years	Bait	7476	7884	15,360
$P < 0.0001$		**48.7%**	**51.3%**	
	Combo	16,166	25,375	41,541
		38.9%	**61.1%**	
2020	Bait	2116	5751	7867
$P < 0.0001$		**26.9%**	**73.1%**	
	Combo	2161	7258	9419
		22.9%	**77.1%**	
2021	Bait	2681	1417	4098
$P < 0.0001$		**65.4%**	**34.6%**	
	Combo	7345	9181	16,526
		44.4%	**55.6%**	
2022	Bait	2679	716	3395
$P < 0.0001$		**78.9%**	**21.1%**	
	Combo	6660	8936	15,596
		42.7%	**57.3%**	

Season is split between before July 21 and after July 21. Difference assessed using 2X2 contingency chi square

Percentage recovery is in bold type

Table 1 Breakdown of total adults captured (397,808) by site, and lure type, 2020–2022

Site	Male combo	Female combo	Male bait	Female bait	Site total	Overall total
2020						
Pistachio 1	4231	1114	192	6019	11,556	
Pistachio 2	22,761	2720	255	4756	30,492	
						42,048
Almond 1	9291	4226	143	4611	18,271	
Almond 2	11,314	5193	138	3256	19,901	
						38,172
2021						
Pistachio 1	30,188	12,097	1479	13,302	57,066	
Pistachio 2	49,823	18,808	1725	15,345	85,701	
						142,767
Almond 1	5509	5312	67	1303	12,191	
Almond 2	14,379	11,214	143	2795	28,531	
						40,722
2022						
Pistachio 1	18,098	9661	871	13,434	42,064	
Pistachio 2	28,790	10,006	1297	11,520	51,613	
						93,677
Almond 1	5575	6419	136	970	13,100	
Almond 2	15,160	9177	560	2425	27,322	
						40,422

Combo traps contain pheromone + phenyl propionate lures and Bait traps contain almond and pistachio meal

Total moths recovered for each commodity by year are in bold type trap capture ranged from 42.7–44.4% during this same period. All of these differences were statistically significant. For the combined data set the chi-square value was 439.1, $P<0.0001$, while for the individual years the values were chi-square = 23.2, $P<0.0001$; chi-square = 577.6, $P<0.0001$; chi-square = 1370, $P<0.0001$, for 2020–2022 respectively. Overall, there were 2.2-fold more females captured in Combo traps than Bait traps. In the combined Pistachio dataset, Table 3, during the period before July 21, 87.1% of the females were caught using Bait traps in contrast to 54.6% of the females caught using Combo traps during this same time period, chi-square = 16,602, $P<0.0001$. These differences held for all three years and were more pronounced in 2021 and 2022, with chi-square = 289.4, $P<0.0001$; chi-square = 13,170, $P<0.0001$; chi-square = 811, $P<0.0001$, for 2020–2022 respectively. In a reversal from the Almond dataset, there were 2.0-fold more females caught using Bait traps than Combo traps in pistachio.

Correlation between lure type for female capture

There was one strong (≥0.7) season-long correlation between Bait and Combo traps for Almond in 2021, and the remaining correlations were moderate but significant at $P<0.005$, Table 4. We could not assess the season long correlations in 2023 because Bait traps were discontinued after July 12 because of cost and manpower issues. In the analysis using the first portion of the season (through July 21) the strength of the correlations increased compared to the season-long values, Table 5. There were strong correlations between the two lures for both Almond and Pistachio in 2021, for Almond in 2022, and Pistachio in 2023. The strength of the correlation between lure type also increased for pistachio in 2022 from 0.57 to 0.66, $P<0.0001$. There was no correlation between the lures in 2020 for this same time period, probably because of the smaller sample size; there were 8–13 fewer pairs in this dataset. In pistachios in 2023, the correlation between female capture for the two lures was strong, 0.83, 18 pairs, $P<0.0001$.

Table 3 Female capture for Combo lures (pheromone + phenyl propionate) and Bait (almond and pistachio meal) in Pistachio

Year	Lure type	Before July 21	After July 21	Total females
Combined Years	Bait	61,779	9145	70,874
$P<0.0001$		**87.1%**	**12.9%**	
	Combo	30,319	25,201	55,520
		54.6%	**45.4%**	
2020	Bait	11,630	5164	16,794
$P<0.0001$		**69.3%**	**30.7%**	
	Combo	2644	2304	4948
		53.4%	**46.6%**	
2021	Bait	26,139	2508	28,647
$P<0.0001$		**91.2%**	**8.8%**	
	Combo	15,034	15,871	30,905
		48.6%	**51.4%**	
2022	Bait	23,960	1473	25,433
$P<0.0001$		**94.2%**	**5.8%**	
	Combo	12,641	7026	19,667
		64.3%	**35.7%**	

Season is split between before July 21 and after July 21. Difference assessed using 2X2 contingency chi square

Percentage recovery is in bold type

Table 4 Season-long correlation (Spearman's rho) between females caught using Combo lures (pheromone + phenyl propionate) and females caught using Bait lures (almond and pistachio meal) for 2020–2022. Bold type indicates a strong correlation.

Year	Site	Rho	Significance	Pairs
2020	Pistachio	0.54	0.003	29
	Almond	0.54	0.003	28
2021	Pistachio	0.54	0.0004	39
	Almond	**0.79**	<0.0001	29
2022	Pistachio	0.57	0.0002	39
	Almond	0.56	0.0006	34

A rho value in bold indicates a strong correlation (≥0.7)

Season-long correlation between male and female capture using Combo lures 2020–2022

All correlations were significant, and four correlations were strong for Almond in 2020 and 2021 and for Pistachio in 2021 and 2022, Table 6. Male and female trap capture by commodity for each year is shown in Figs. 1, 2, 3. There were at least four peaks with more males trapped than females after July 21 in almond and pistachio

Table 5 Correlation (Spearman's rho) between female capture using combo lures (pheromone + phenyl propionate) and bait lures (almond and pistachio meal) through July 21 (Julian date 202), 2020–2023

Year	Site	Rho	Significance	Pairs
2020	Pistachio	0.21	NS	11
	Almond	0.37	NS	10
2021	Pistachio	**0.75**	<0.0001	26
	Almond	**0.83**	<0.0001	19
2022	Pistachio	0.66	<0.0001	23
	Almond	**0.75**	<0.0001	19
2023	Pistachio	**0.83**	<0.0001	18

A rho value in bold indicates a strong correlation (≥0.7)

Bold type indicates a strong correlation

Table 6 Season-long correlation (Spearman's rho) between males and females caught using combo lures (pheromone + phenyl propionate) for 2020–2022

Year	Site	Rho	Significance	Pairs
2020	Pistachio	0.48	0.008	29
	Almond	**0.76**	< 0.0001	29
2021	Pistachio	**0.78**	< 0.0001	38
	Almond	**0.82**	< 0.0001	29
2022	Pistachio	**0.78**	< 0.0001	39
	Almond	0.66	< 0.0001	35

A rho value in bold indicates a strong correlation (≥ 0.7)

Bold type indicates a strong correlation

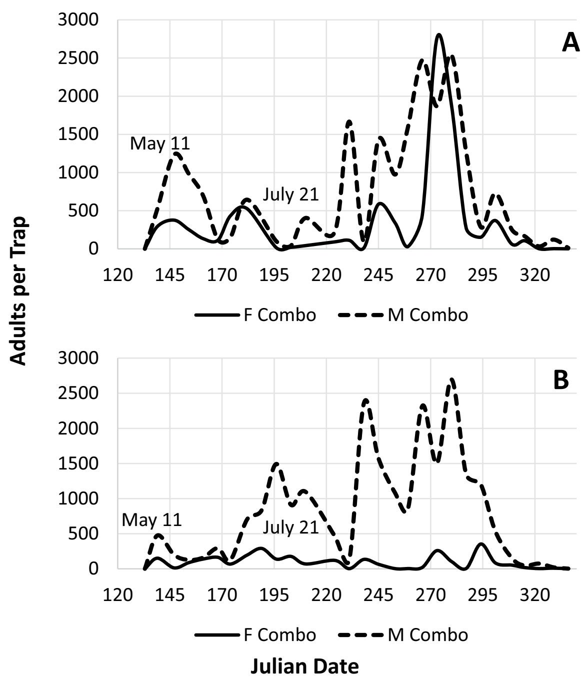

Fig. 1 Female (F) and Male (M) capture using Combo traps (pheromone + phenyl propionate) in Almond (**A**) and Pistachio (**B**) in Fresno County, 2020. Almond Nonpareil hull split occurs from Julian dates 175–222 (June 24–August 10) and Pistachio hull breakdown occurs from Julian dates 232–290 (August 20-October 17)

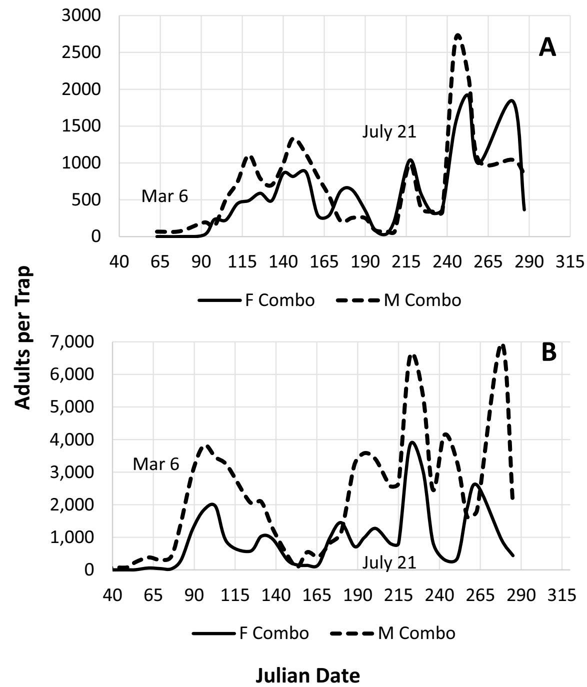

Fig. 2 Female (F) and Male (M) capture using Combo traps (pheromone + phenyl propionate) in Almond (**A**) and Pistachio (**B**) in Fresno County, 2021. Almond Nonpareil hull split occurs from Julian dates 175–222 (June 24–August 10) and Pistachio hull breakdown occurs from Julian dates 232–290 (August 20–October 17)

respectively (male: 38,805, female: 25,423; male: 76,605, female: 24,877). Throughout the season there was a male peak corresponding to every female peak.

Effect of trap proximity 2023

Significantly more *A. transitella* were captured in Combo than in Bait traps, chi-square = 25.9, df = 3, $P < 0.0001$, Table 7. However, there was no difference between the number of *A. transitella* captured in traps with the same bait when isolated or when presented together, indicating that the two trap types behaved independently when placed in the same tree.

Discussion and conclusions

The data set from the SIT demonstration project for navel orangeworm offers an unprecedented opportunity to compare monitoring systems between commodities. These 259 ha orchards were located in areas where mating disruption is frequently used, and one almond orchard employed mating disruption starting 2021. While mating disruption suppresses pheromone traps within the orchard where it is used as well as adjacent orchards (Burks et al. 2017) it does not affect Bait or Combo traps. The four orchards used in this study are typical of Fresno County, because all used insecticide sprays and had a sanitation program, but the consistency of sanitation was not independently verified. This is an area of ongoing research within the SIT pilot project. Trap capture varied by commodity and by year, with more moths caught in the combined dataset for pistachio than in almond, and in the combined dataset there were more than twice as many females captured in pistachio than in almond for both 2021 and 2022. The higher population of *A. transitella* in pistachios has been previously

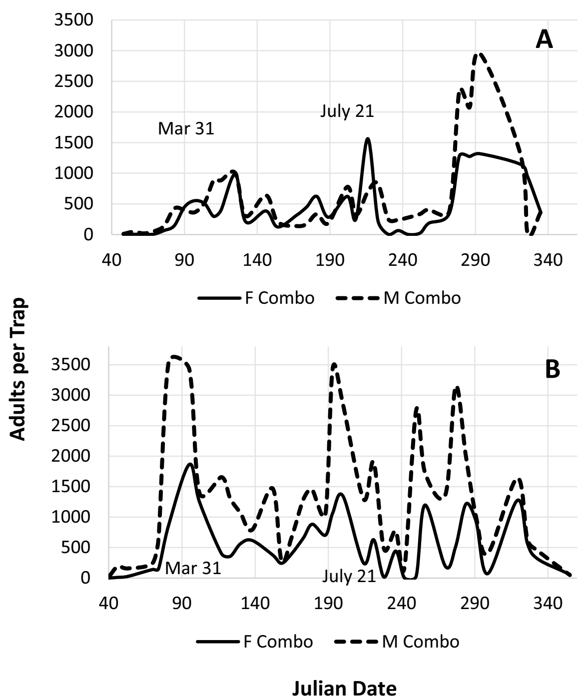

Fig. 3 Female (F) and Male (M) capture using Combo traps (pheromone + phenyl propionate) in Almond (**A**) and Pistachio (**B**) in Fresno County, 2022. Almond Nonpareil hull split occurs from Julian dates 175–222 (June 24–August 10) and Pistachio hull breakdown occurs from Julian dates 232–290 (August 20–October 17)

Table 7 Total adults per trap (Mean ± SE, n = 10) using Combo lures (pheromone + phenyl propionate) and Bait (almond and pistachio meal) in pistachio from June 5-August 7, 2023

Treatment	Moths per trap
Combo trap in isolation	99 ± 8.3a
Combo trap near Bait trap	95 ± 15.1a
Bait trap in isolation	22 ± 2.5b
Bait trap near Combo trap	25 ± 2.6b

Means in rows with different letters were significantly different at $P < 0.0001$)

described and is due to difficulties sanitizing pistachios (Kuenen and Siegel 2010). The dataset for 2020 differs from the two succeeding years and the numbers captured probably would have been larger if the traps had been set up earlier in the season; there is substantial adult emergence through April and early May that was missed in 2020 (Siegel and Gilcrease 2022). The overall differences in trap capture observed most likely reflect a higher population in pistachio orchards, because almonds are both easier to sanitize than pistachios and have an established mummy threshold for management, while pistachios do not. These differences contribute to a greater overwintering carryover and host availability in pistachio (Kuenen and Siegel 2010; Siegel and Gilcrease 2022; Haviland et al. 2022a, b).

We cannot explain the difference in almond and pistachio between the magnitude of female trap capture using Bait lures, nor can we explain the differences in the percentage of females caught by trap type before July 21. This difference in percentage catch is more pronounced when the data for 2020 for almond are excluded, but the pattern of a greater percentage of females caught using Bait than Combo traps before July 21 held every year for pistachio. When total numbers were evaluated, more females were caught with Combo traps after July 21, with the exception of pistachio in 2020. These differences in trap capture before and after July 21 were reflected by the moderate season-long correlations calculated in both commodities.

The reduced effectiveness of egg and more recently bait traps in the second half of the season has been previously described (Rice et al. 1976; Sanderson and Barnes 1990; Burks et al. 2008) and is attributed to competition with the new crop once hull split begins. To our knowledge, this study is the first to document a higher rate of capture of *A. transitella* in Bait traps in pistachio (87.1% overall) compared to almond (48.7% overall) in the first portion of the season. The population of *A. transitella* is usually higher in pistachio than in almond (Burks et al. 2008; Higbee and Siegel 2009), but the current observation is about the effectiveness of baits for trapping *A. transitella* females in pistachio (1.6-fold difference) rather than moth abundance. The observations in the current study are consistent with those in Nay et al. (2012), but in that study the attractants were different mixtures of almond and pistachio meal compared between the two commodities and they did not distinguish between differences in abundance.

If the difference in female capture between Bait and Combo traps after July 21 simply reflected competition between Bait and new crop nuts (Tables 2 and 3), the pattern should be similar between almond and pistachio, especially because new crop nuts are first available in almond. However, the reduction in capture was greater in pistachio. While there are undoubtedly different volatiles that attract gravid females for these two commodities (Beck et al. 2014) further research is necessary to determine if any of the compounds identified using electroantennogram produce the differences observed between female capture in almond and pistachio. If the difference resulted from a reduced preference for Bait lures by moths emerging from new crop nuts instead, most of these adults emerged from almond, (the first adults that developed on new crop pistachios emerge in September), yet the effect was more pronounced in pistachio. We think it is unlikely that these differences in capture were caused by competition between the two lures when both traps were hung from the same tree because we found no position effects, Table 7. An alternate explanation for the difference in female capture between almond and pistachio for Bait lures is that differences in canopy fill and canopy density between the two commodities affect female attraction to the two lures studied. In general, pistachios have a more compact canopy than almonds and pistachio clusters are distributed throughout the canopy, while in mature almonds the nuts are found higher in the canopy (above 3 m). The only thing that is clear-cut is that in pistachio, there was a dramatic drop in Bait trap capture after July 21.

In the plot of flight activity, Figs. 1, 2, 3, there were multiple peaks in both commodities, as well as considerable agreement between male and female peaks in both almonds and pistachios for 2021 and 2022. Some of the dips in trap capture for both sexes were caused by insecticide applications that had adult activity (pyrethroids, chlorantraniliprole, spinetoram). In almonds, insecticides might be sprayed on mummy nuts (unharvested nuts from previous crop year) during the period Julian dates 118–125 (April 28–May 5) and hull split sprays are usually applied to Nonpareil almonds during Julian dates 185–195 (July 4–July 14). In many almond orchards there is a follow-up application 10–14 d after the first hull split application, Julian dates 199–209 (July 18–July 28), and there may be a pollinator variety spray during Julian dates 222–236 (Haviland et al. 2022a). For pistachios, insecticide application usually occurs from Julian dates 235–245 (August 23–September 2), with subsequent applications during Julian dates 274–283 (October 1–October 10) (Haviland et al. 2022b). Additionally, in some years pyrethroid insecticides are applied to both commodities in April and May (Julian dates 90–145; April 31–May 25) to control Hemipteran pests. In this study neither the timing of insecticide applications nor insecticide choice were coordinated among the participating orchards, yet there still was considerable congruency in the peaks for almond and pistachio in 2021 and 2022, Figs. 2, 3. The almond data were consistent for all three years and pistachio data were more variable because female capture was much lower in 2020, Fig. 1; we cannot explain this discrepancy.

Rosenheim et al. (2017) reported that female-specific traps are more associated with subsequent *A. transitella* damage to Nonpareil almond than pheromone traps that capture males. In their six-year study evaluating damage to Nonpareil almonds they compared the number of males caught in traps baited with unmated females as a pheromone source, females caught in bait traps (with a different formulation and presentation than the present study), and eggs laid in egg traps. The counts of egg traps and the capture of females in bait traps were highly correlated. Rosenheim et al. (2017) concluded that female-based monitoring methods (either egg traps or bait traps) were the most highly correlated with subsequent damage. However, traps containing PPO were not included in their study, therefore the SIT dataset enabled us to compare Bait and Combo lures over a large hectarage and across several years.

With one exception, the season-long correlation for females between Combo and Bait lures was moderate, but when the focus shifted to the period leading up to July 21 for the years 2021–2023, the correlations strengthened. When we shift focus to the Combo traps, there were strong season-long correlations between male and female capture for both commodities, Table 6, Figs. 1, 2, 3. Burks et al. (2020) reported that a high percentage of gravid females are attracted to Combo traps, and we propose that the size of their peak is a surrogate for mating success during that time period. In these three figures the female peaks at Julian dates 190 (July 9), 250–270 (September 7–27) and 280–290 (October 7–17) correspond to tree nut phenology. The peak observed on July 9 coincides with Nonpareil hull split, the peak observed at September 7–27 coincides with both almond pollinator hull split and pistachio hull breakdown, as does the peak at October 7–17.

In this study, traps baited with Combo lures and traps using Bait as an ovipositional attractant had similar profiles. Bait traps were more effective earlier in the season (through July 21), and during this period female capture was strongly correlated between Bait and Combo traps. Traps containing each of these baits can be used in close proximity to the other without affecting trap counts, which increases the ease of using both at the same time, and in the spring bait traps captured *A. transitella* females more efficiently in pistachios than in almonds. These findings have implications for both commercial orchard management and researchers seeking to determine an economic threshold for *A. transitella*. From a research perspective, although Bait traps with their higher female capture appear to be the ideal tool for the elusive goal of determining an economic threshold for Nonpareil almonds (whose split begins in late June and continues through mid-July), their performance in pistachios is a concern because of the drop-off in female trapping during late August through October. This is a critical period because both pistachios and pollinator varieties of almonds split and become susceptible to infestation. From a commercial perspective (the customer for most of these traps and lures) trapping is conducted for population monitoring, the timing of pesticide applications and assessment of application efficacy. The effort taken to determine the sex of the moths captured is too time-consuming, giving Bait traps an advantage since they predominantly capture females.

Is one lure superior? Given a limited budget, Bait traps would appear to be an ideal choice because they predominantly capture females (95:5 ratio in this study), eliminating the need to determine the sex of the moths captured, but their efficacy, as measured by both the number of females trapped in almonds and pistachios, as well as the percentage of total females captured, significantly decreased after July 21. In contrast, Combo traps consistently captured females over the entire season and furthermore, female capture was strongly correlated with male capture, enabling an orchard manager to compare Combo data to trapping datasets from previous years that used pheromone lures. A pest control adviser or orchard manager could make a rough estimate of the number of females trapped by taking 30–40% of the weekly Combo trap capture (sex ratio of M:F of 60:40) instead of attempting to determine the sex of the individual moths caught. Given financial/labor constraints, it is unrealistic to expect both trap types to be used for an entire season, and if an orchard manager can only afford one trap type, Combo traps are preferable because they provide the most consistent season-long capture. The sterile insect technique (SIT) demonstration program made this decision after July 2023 because of these reasons. However, as a compromise, both lures can be used to aid in management decisions before July 21 if labor is available.

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Availability of data and materials
The 2020 data are available by contacting the corresponding author. The data for the other years are available on https://www.cdfa.ca.gov/plant/ipc/nowp/index.html.

Declarations

Competing interests
The authors declare that they have no competing interests.

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