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Effects of Food Bait and Trap Type on Captures of *Rhynchophorus palmarum* (Coleoptera: Curculionidae) and Trap Bycatch in Southern California

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Abstract

Rhynchophorus palmarum (L.) is an invasive pest responsible for killing thousands of ornamental Canary Islands date palms (*Phoenix canariensis* Chabaud) in San Diego County, CA. Two field experiments were conducted to compare the attractiveness of six different baits and two trap types. The tested baits were dates + water; dates + water + *Saccharomyces cerevisiae*; dates + water + *S. bayanus*; dates + water + *S. pastorianus*; 15% sugarcane molasses water solution mixed with 3% paraffinic oil, and a no bait control treatment. The two traps tested were white bucket traps (hanging 1.5 m above the ground and set on the ground) and black cone shaped Picusan traps (set on ground only). All traps were loaded with commercially available *R. palmarum* aggregation pheromone and the synergist ethyl acetate. Differences in weevil capture rates were observed across bait and trap types. Weevil captures were almost five times greater in Picusan traps compared to bucket traps that were hanging or placed on the ground. Adding dates and water alone or combined with *S. cerevisiae* to traps increased weevil captures compared to other baits and controls. Trap and bait types affected bycatch of nontarget arthropod species. In general, spiders, earwigs, and carabid beetles were most commonly recovered from Picusan traps, regardless of bait type. Scarab beetles, moths, and flies were found more frequently in bucket traps baited with molasses or dates mixed with *S. bayanus*. No effects of bait and trap type were associated with bycatch species richness.

Key words: bycatch, detection tools, invasive species, palm weevils, trap efficiency

Rhynchophorus palmarum (L.) is an invasive palm (Arecales: Arecaceae) pest that was first detected in San Diego County in southern California in 2011 and established there around 2014. It is likely that San Diego County was invaded by weevils that originated from Tijuana, Baja California, Mexico, where infestations and dead palms were detected in 2010 (Hoddle and Hoddle 2017). Native to parts of Mexico, Central and South America, and the Caribbean, *R. palmarum* is a significant pest of commercial [e.g., oil palms (*Elaeis guineensis* Jacq.) and coconuts (*Cocos nucifera* L.)] and ornamental palms [e.g., Canary Islands (*Phoenix canariensis* Chabaud)] (EPPO 2005, Löhr et al. 2015). Palm mortality results from larval feeding damage to the apical meristem. Although not currently detected in California, adult weevils can also vector a plant pathogenic nematode, *Bursaphelenchus cocophilus* (Cobb) (Aphelenchida: Parasitaphelenchidae), the causative agent of a lethal palm malady, red ring disease, which may hasten mortality (Giblin-Davis 2001, Milosavljević et al. 2019). It is estimated that more than 10,000 ornamental *P. canariensis* have been killed by *R. palmarum* in San Diego County (APC 2020).

Large urban infestations of *R. palmarum* in San Diego County pose a significant risk to the $100 million per year edible date (i.e., *P. dactylifera*, a known host for *R. palmarum*; EPPO 2005) industry in the Coachella Valley, CA, an area of ~4,000 ha where ~47,000 tons of fruit per year are grown (USDA-NASS 2018). The northern most urban infestation foci of *R. palmarum* in San Diego County are a linear distance of ~130 km from edible date production areas of the Coachella Valley. Adult *R. palmarum* are highly vagile, capable of flying long distances in relatively short periods of time, and may be able to disperse naturally into date production areas from infested regions (Hoddle et al. 2020).

Rhynchophorus palmarum management in California is reliant on trapping adult insects, insecticide applications that kill larvae and adults living in afflicted palms, and removal and destruction of infested palm trees (Hoddle and Hoddle 2017, Milosavljević et al.

2019). Effective weevil trapping requires the use of traps baited with commercially available aggregation pheromone (Oehlschlager 2016) and fermenting food (Oehlschlager et al. 2002). Ethyl acetate synergistically increases the combined attractiveness of pheromones and fermenting food baits (Oehlschlager 2016). Effective traps need to capture and retain weevils attracted to them (Oehlschlager et al. 1995, 2002; Vacas et al. 2013; Navarro-Llopis et al. 2018). Due to the negative impact, *R. palmarum* is having on ornamental palms in California, weevil-monitoring activities using traps by state- and county-level agencies and private enterprises have increased substantially. However, there are no data available to assess which type of trap and what type of fermenting bait are most effective when combined with aggregation pheromone and ethyl acetate for attracting, capturing, and retaining adult *R. palmarum*. This shortcoming is especially problematic for producers of edible dates as trapping programs will be critical for early detection and, possibly later, for monitoring weevil activity in and around production areas and for suppressing pest populations within date gardens should *R. palmarum* invade these areas.

Therefore, the objective of this study was to assess the efficacy of two different trap types, the bucket trap (either hanging or set on the ground) and Picusan trap (designed for ground deployment only), and six food combinations on the number of *R. palmarum* captured in traps loaded with aggregation pheromone and ethyl acetate. Additionally, captures of nontarget arthropod species were recorded, and the effect of trap and bait type on bycatch diversity was assessed. High levels of trap bycatch may cause population declines of nontarget species (Spears et al. 2016).

Materials and Methods

Field Sites

Field experiments comparing traps and baits for capturing *R. palmarum* were conducted over 12 April–8 December 2018 and 2 April–28 November 2019. Trials were conducted on three golf courses located in an area of San Diego County with *R. palmarum* activity. The study sites used were as follows: 1) Bonita Golf Club (32°40′50.10″N, 117°00′44.92″; elevation 25 m), Bonita, CA; 2) Chula Vista Golf Course (32°39′12.63″N, 117°02′59.30″W; elevation 18 m), Chula Vista, CA; and 3) National City Golf Course (32°39′55.06″N, 117°05′03.85″W; elevation 15 m), National City, CA. *Phoenix canariensis* densities were similar across sites: Chula Vista, Bonita, and National City golf courses had 29, 28, and 23 *P. canariensis*, respectively. Each study site was located approximately 2 km from the Sweetwater Reserve, in Bonita, San Diego County, CA, a riparian area with hundreds of naturalized *P. canariensis* many of which are infested with *R. palmarum* (Hoddle and Hoddle 2017). All sites have a cool semiarid subtropical climate regime with an average annual precipitation of 280 mm (https://www.weather-us.com/en/california-usa/san-diego-climate).

Material Sources for Experiments

Trap Types Tested

Two different trap types were evaluated for capture efficacy: white bucket traps and black cone shaped Picusan traps (Supp Fig. 1 [online only]). Bucket traps were constructed from white 7.5-liter paint buckets with lids (ULINE S-9941W, Pleasant Prairie, WI), with four evenly spaced 5-cm circular holes cut into the sides of the bucket (Hoddle 2020). Each trap was wrapped with burlap fabric (ULINE S-14512, Pleasant Prairie) to enable adult weevils attracted to traps to climb the sides of the bucket to reach entry holes. The aggregation pheromone lure and ethyl acetate dispenser were hung from a wire hook attached to the underside of the bucket lid. Plastic containers with perforated lids with fermenting bait were placed in bucket traps (see below for pheromone and bait details). Weevils that entered buckets were killed by drowning and preserved in 700 ml of 50% propylene glycol solution (ChemWorld Inc., Kennesaw, GA) that was added to buckets and replenished monthly when traps were serviced. Bucket traps were suspended on chain link fences that delineated golf course boundaries or placed on the ground at the base of chain link fences. Trap color does not influence *R. palmarum* capture rates (Oehlschlager et al. 1993).

Picusan traps (ISCA Technologies, Riverside, CA [ISCA Pitfall Trap PFT]) consisted of a 4-liter cylindrical collection base (22D × 10H cm), corrugated black cone cover (43D × 26H cm; 66% slope and 1 mm between grooves) with an inverted funnel entry on the upper side which prevents trapped weevils from escaping. A green top holds the receptacle for aggregation pheromone lure (Soroker et al. 2017). Picusan traps are designed for ground placement (Vacas et al. 2013). The ethyl acetate dispenser was hung from a wire hook attached to the underside of the black cone cover. The bait container and propylene glycol were placed in the collection basin enclosed by the cone cover. The basin of the Picusan traps contained the same volume and concentration of drowning solution as the bucket traps (i.e., 700 ml of 50% propylene glycol solution). Picusan traps were placed on the ground along the base of the same chain link fences that were used for bucket trap placements.

Aggregation Pheromone and Bait Details

All traps (except controls) were loaded with aggregation pheromone and ethyl acetate. Control traps, both bucket and Picusan traps, were not baited with pheromone lures, synergists, or food bait and were set out to determine rates of accidental *R. palmarum* capture. A commercially available *R. palmarum* aggregation pheromone lure (ISCALure IT192, 700 mg at 98% purity of [4S,2E-6]-methyl-2-hepten-4-ol, ISCA Technologies) was used in traps. The ethyl acetate synergist (Grainger Industrial Supply, Jackson, MS) dispensers used in traps were screw-capped 25-ml glass vials (27D × 70H mm; Thermo Fisher Scientific, Waltham, MA) loaded with 20 ml of ethyl acetate (Grainger Industrial Supply). The lid had a 1-mm-diameter hole for synergist release. During monthly trap servicing, pheromone lures were replaced, and ethyl acetate vials were refilled.

Food bait containers placed inside traps were clear 470-ml plastic containers (114D × 76H mm; Uline Inc., Pleasant Prairie, WI) with perforated lids (~ten 0.3-mm-diameter holes per lid to permit release of attractive fermentation volatiles) loaded with bait. For food baited *R. palmarum* and *R. ferrugineus* pheromone traps, sugarcane/molasses, and dates are recommended baits, respectively (Oehlschlager et al. 1993, Faleiro and Satarkar 2005, Faleiro 2006). Additionally, preliminary studies had shown that fermenting dates were attractive to *R. palmarum* (M. S. Hoddle, unpublished data), and this bait is readily available in California, whereas sugar cane, e.g., is not. In year 1, test bait consisted of 100 g of Medjool dates (Hadley Date Gardens, Thermal, CA) in 200 ml of water, dates in 200 ml of water with 7 g of dry baker's yeast, *Saccharomyces cerevisiae* Meyen *ex* E.C. Hansen (Saccharomycetales: Saccharomycetaceae) (Kroger, Cincinnati, OH), or an 18% sugarcane molasses solution with 3% paraffinic oil. The sugarcane molasses bait was made from 200 ml of 15% sugarcane molasses water solution to which paraffinic oil was added until it made 3% of the total solution (Carolina Biological, Burlington, NC) was added to reduce evaporation (Navarro-Llopis et al. 2018). In year 2, test baits consisted of 100 g of Medjool dates in 200 ml of water only, or dates, water, and 7 g of one of three different species of yeast: 1) *S. cerevisiae*, 2) dry alcohol yeast, *S. bayanus* Saccardo (Saccharomycetales: Saccharomycetaceae) (SafSpirit FD-3, Lesaffre, Fermentis, France), or 3) dry lager yeast, *S. pastorianus* Nguyen & Gaillardin ex. Beijerinck (Saccharomycetales: Saccharomycetaceae) (SafLager W-34/70, Lesaffre, Fermentis, France).

Field Experiments

Experiment 1 was conducted 12 April–8 December 2018 and compared capture efficacy and specificity of bucket traps with Picusan traps baited with four different food baits. The experiment used a multilocation randomized complete block factorial design with two trap treatments: 1) bucket or 2) Picusan traps and five bait treatments: 1) negative control (lacking pheromone lure, ethyl acetate, and fermented fruit); 2) positive control (lacking food bait, but with pheromone lure and ethyl acetate); 3) pheromone lure + ethyl acetate + 18% molasses–3% paraffinic oil solution; 4) pheromone lure + ethyl acetate + dates with water; or 5) pheromone lure + ethyl acetate + dates with water and baker's yeast (*S. cerevisiae*). Trap and bait combinations were deployed in nine blocks, with each of the three study sites receiving three blocks of treatments each comprised of three replicates of each treatment, for a total of ninety traps (i.e., 45 bucket traps and 45 Picusan traps) across three study sites.

Traps within a block were separated by at least 50 m, and blocks were separated by at least 150 m. At each site, bucket traps were hung from a chain link fence ~1.5 m above the ground. Picusan traps were placed on the ground along the same fence line. In order to maximize trap efficacy, all traps were placed in areas with partial or full shade. Full sun exposure, especially during the hottest parts of the day, rapidly diminishes trap efficacy (see Discussion section for more details; Navarro-Llopis et al. 2018). Traps were rotated clockwise by one place within each block every 30 d to eliminate position bias (Vargas et al. 2010). At monthly intervals, traps were serviced, captured weevils were counted and sexed, baits and lures replaced, and ethyl acetate and propylene glycol replenished. Nontarget species were removed from traps and photographed on site with a Nikon D90 camera with a 60-mm Nikon macro lens. From these photographs, bycatch was identified to family or genus based on morphological characteristics. When possible, captured specimens were identified to species.

Experiment 2 was conducted 2 April–28 November 2019 at the same three golf courses and experiments were designed to compare capture efficacy and specificity of bucket and Picusan traps loaded with five different baits. The experimental layout was identical to that described for experiment 1 above. For experiment 2, bucket or Picusan traps were used to test the following five bait treatments: 1) control (pheromone lure and ethyl acetate only); 2) pheromone lure + ethyl acetate + dates with water; 3) pheromone lure + ethyl acetate + dates with water and baker's yeast (*S. cerevisiae*); 4) pheromone lure + ethyl acetate + dates with water and alcohol yeast (*S. bayanus*); and 5) pheromone lure + ethyl acetate + dates with water and lager yeast (*S. pastorianus*) for a total of 90 traps across three study sites. Bucket and Picusan traps were placed on the ground in partial or full shade along the same fence lines used in experiment 1. Within each block, traps were rotated clockwise by one place every 30 d to eliminate potential position effects on capture rates (Vargas et al. 2010). The same collection and processing methods for weevils and bycatch described previously were used.

Data Analysis

All statistical analyses were conducted using SAS 9.4 (PROC GLIMMIX; SAS Institute 2013). To test main and interaction effects of trap and bait on weevil captures over time (experiments 1 and 2), a repeated-measures generalized linear mixed models (GLMMs) was used. A variance components matrix was used to model repeated measures across eight temporal trap collection events (i.e., date of trap collection) taken in April, May, June, July, August, September, October, and November of 2018 and 2019. Number of captured weevils was the dependent variable; the independent variables were trap, bait factors, collection event, and their interactions. Site and block within site were included as random effects in the model. Separate models were conducted for each of the four weevil variables: 1) total number captured (i.e., abundance), 2) number of male, 3) female weevils captured, and 4) percentage of traps that captured at least one weevil (i.e., detection rate). All models for abundance were fit with negative binomial distributions based on the distributions of the count data. Models used for detection rates were fit with binary distributions. The between–within denominator degrees of freedom adjustment

Table 1. Results of repeated-measures analysis examining the effects of trap type, bait type, and time (month) on the abundance of *R. palmarum* (total, males, and females) captured in traps and detection rates (i.e., percentage of traps that captured at least one weevil) per site in 2018 and 2019

				Detection rates		Weevil sex					
				Total weevils		Total		Male		Female	
Year	Variable	Num. df	Den. df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
2018	Trap (T)	1	16	46.66	<0.0001	212.7	<0.0001	86.04	<0.0001	170.19	<0.0001
	Bait (B)	3	16	8.8	0.001	27.99	<0.0001	79.01	<0.0001	16.54	<0.0001
	Month (M)	7	133	0.23	0.977	6.15	<0.0001	2.98	0.006	3.47	0.002
	T × B	3	16	3.33	0.046	18.74	<0.0001	12.21	0.001	12.96	0.001
	T × M	7	133	2.89	0.009	2.87	0.008	2.80	0.009	2.71	0.012
	B × M	21	133	1.92	0.014	1.97	0.011	1.91	0.013	1.85	0.019
	T × B × M	21	168	0.47	0.023	0.51	0.031	0.45	0.018	0.52	0.042
2019	Trap (T)	1	20	30.40	<0.0001	322.7	<0.0001	119.47	<0.0001	194.15	<0.0001
	Bait (B)	4	20	3.89	0.029	42.82	<0.0001	16.63	<0.0001	24.71	<0.0001
	Month (M)	7	144	1.23	0.296	10.33	<0.0001	3.61	0.005	6.65	<0.0001
	T × B	4	20	3.19	0.035	4.37	<0.0001	2.91	0.038	4.62	<0.0001
	T × M	7	144	2.81	0.008	3.62	0.001	3.78	0.001	2.52	0.016
	B × M	28	144	1.57	0.039	2.69	<0.0001	2.32	<0.0001	1.91	0.026
	T × B × M	28	184	0.57	0.046	0.36	0.001	0.57	0.038	0.59	0.049

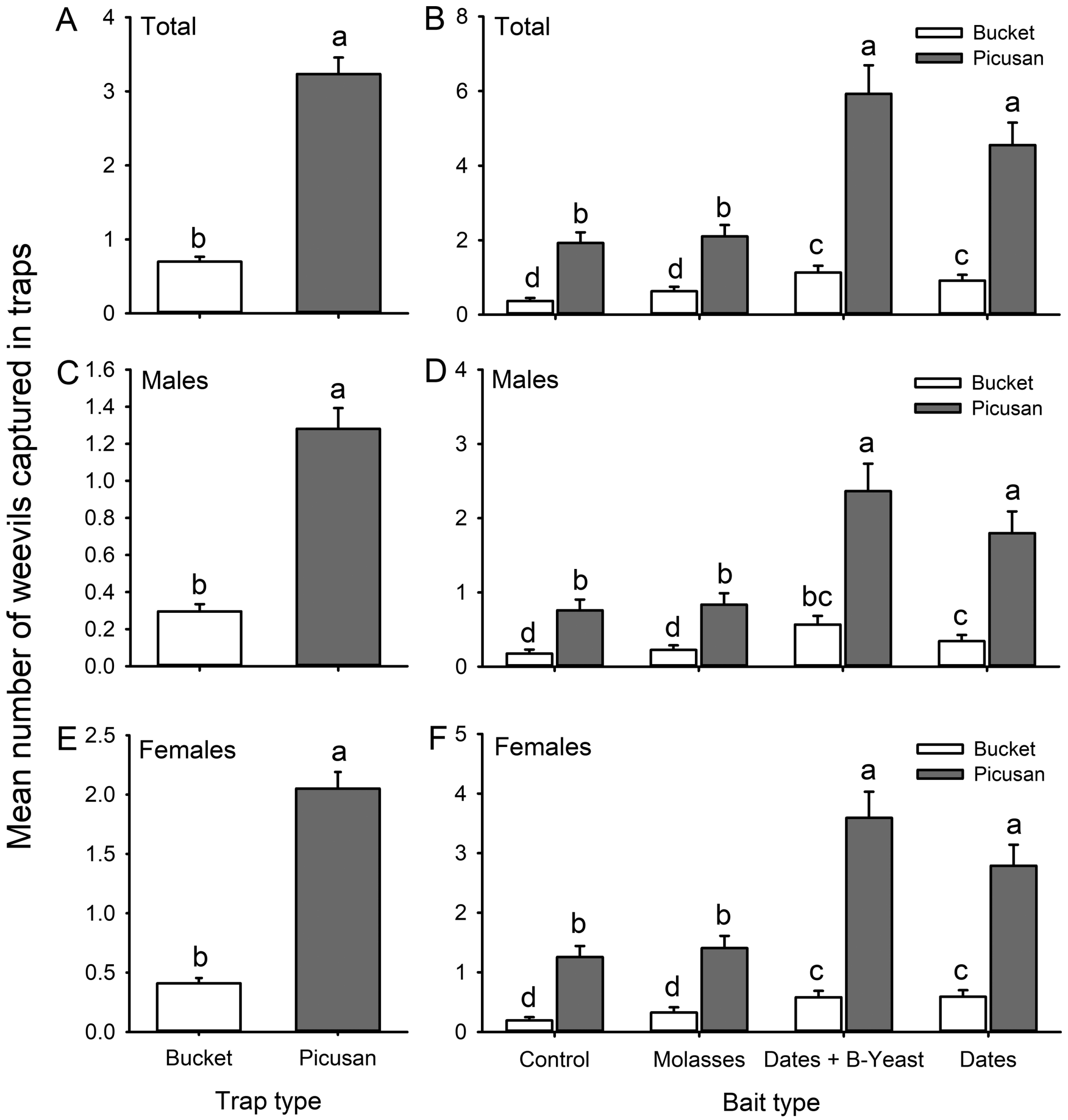

Fig. 1. Mean (±SE) number of total (A, B), male (C, D), and female (E, F) *Rhynchophorus palmarum* caught in white bucket traps suspended 1.5 m above the ground and Picusan traps placed on the ground baited with different baits (control/no lure, 18% molasses and 3% paraffinic oil solution, dates only, and dates with baker's yeast). Different lowercase letters denote differences among groups by Tukey–Kramer adjustments for main effects of trap (A, C, E) and stepdown Bonferroni adjustments for trap by bait interactions (B, D, F) at α < 0.05.

method was used as an option in all models (Li and Redden 2015). For main effects, pairwise mean comparisons were adjusted for family-wise Type I errors using the Tukey–Kramer method. Pairwise comparisons for significant interactions were examined with stepdown Bonferroni adjustments. Significance for all tests was set at $\alpha < 0.05$. Separate analyses were conducted for each year the two experiments were conducted.

The effects of trap type, bait, and their interactions over time on bycatch species richness (order and family level) and abundance (order, superfamily/family, and genus/species level) were tested using repeated-measures GLMMs and PROC GLIMMIX in SAS. Model parameters were similar as described above. The response variables were the total number of genera/species (richness) or individuals (abundance) collected per trap for each trap bait combination each month. All models for abundance were fit with negative binomial distributions based on the distributions of the count data. Models assessing species richness were fit using a normal distribution. Differences among treatments were tested with the Tukey-adjusted means comparison function at $\alpha < 0.05$ (SAS 9.4; SAS Institute 2013). GLMMs were run separately for each of the 2-yr experiments were conducted. In 2018, nontarget isopods and carabid beetles were not represented by enough individuals in bucket traps (i.e., <5) to allow for the effects of trap type to be tested by GLMMs. Therefore, the models used only included food bait, time, and their interaction as variables of interest.

Results

Effects of Trap and Bait Type Combinations on Weevil Capture and Detection Rates

In experiment 1, a total of 1,391 weevils (565 males and 826 females) were captured across all traps. No weevils were captured in negative control traps lacking aggregation pheromone and bait across sites and collection dates, and this treatment was removed from further analyses. The number of total, male, and female weevils captured in traps was affected by trap and bait type, time of year, and their interactions (Table 1). Weevil captures were approximately five times greater in Picusan traps than hanging bucket traps, regardless of bait type used (Fig. 1). Within the same trap type, captures were two times greater in traps baited with dates and water alone or combined with baker's yeast than in traps baited with 18% molasses–paraffinic oil solution and positive controls lacking fermenting food bait (Fig. 1). Adding baker's yeast to dates immersed in water increased weevil captures by ~30% compared with dates and water only, but this increase was not significant (Fig. 1). Time was a significant factor with weevil captures being most abundant from April through June. However, consistent differences in weevil captures among trap and bait types were detected over the entire trapping period under evaluation (Table 1; Fig. 2A). Weevil detection rates (i.e., capture of at least one *R. palmarum*) were affected by all trap and bait factors tested (Table 1). Picusan traps outperformed (87% of traps captured at least one *R. palmarum*) hanging bucket traps (43%), and traps baited with dates alone or combined with baker's yeast outperformed traps baited with 18% molasses–paraffinic oil solution and control traps lacking fermenting bait (Table 1; Fig. 3A). Detection rates were similar for Picusan traps baited with dates alone or combined with baker's yeast, with detection rates ranging from 89 to 97%. Additionally, consistent differences in capture rates between trap type and bait treatments (i.e., trap × time; bait × time; trap × bait × time) effects across collection dates were observed (Table 1).

In experiment 2, a total of 1,438 weevils (567 males and 871 females) were captured across all traps. Weevil captures were significantly affected by collection date, trap, and food bait type and their interactions (Table 1). Specifically, weevil captures were greater in early summer (April–June 2019), especially captures in Picusan traps, and were consistently lower in bucket traps set on the ground over the 8 mo of the experiment (Table 1; Fig. 2B). Furthermore, the combination of Picusan trap and food baits consisted of dates alone or dates combined with baker's yeast increased capture rates of weevils more than other trap type by bait treatments interactions (Fig. 4). However, weevil captures were similar for traps baited with dates alone or combined with baker's yeast. Detection rates were affected by trap and food bait types, and their interaction (Table 1). Picusan traps outperformed (89% of traps captured at least one *R. palmarum*) bucket traps (39%), and traps baited with dates alone or combined with one of the three yeast species outperformed positive control traps that lacked food baits (Table 1; Fig. 3B). The detection rates of traps baited with dates alone did not differ significantly from those of traps baited with dates combined with yeast treatments. The pattern of *R. palmarum* captures by different trap and bait treatments (i.e., trap × time; bait × time; trap × bait × time effects) was similar (Table 1).

Effects of Trap and Bait Types on Species Bycatch Richness and Abundance

Across the two experiments, 180 traps, and 16 temporal collection events, over 1,700 isopods (Isopoda) and nearly 1,200 spiders (Araneae) were captured in traps (Table 2). Isopoda richness and abundance did not differ among treatments ($P > 0.22$). Picusan traps caught as many isopods as bucket traps set on the ground. Isopod collections were dominated by Armadillididae and Porcellionidae, each of which comprised ~50% of the total capture (Table 2). The abundance of these two isopod families was not affected by any of the treatments tested ($P > 0.12$). Similarly, no treatments were associated with spider species richness ($P > 0.19$). Spider abundance, however, was affected by trap type. Mean spider capture per trap was 12 times greater in Picusan traps than in bucket traps, hanging and set on the ground (Table 2; Fig. 5). No other factors, including bait and sampling date (time), affected spider abundance ($P > 0.19$). The three most commonly collected spider species (all Araneae: Theridiidae) were *Latrodectus hesperus* Chamberlin & Ivie comprising 42% of the total spider catch, followed by *L. geometricus* Koch (34%), and *Steatoda grossa* Koch (21%). Species-level analyses showed that captures of these three spider species were significant for Picusan traps only ($P < 0.02$; Table 2; Fig. 5).

In total, 24,185 nontarget earwigs (Dermaptera) were trapped (Table 2). The two collected earwig families were Anisolabididae and Forficulidae, comprised 69 and 31% of total earwigs captured, respectively (Table 2). Earwig richness did not differ among treatments ($P > 0.22$). However, earwig abundance varied by collection date, trap type, and their interaction (Table 2). Specifically, earwig captures were greater during April–June, especially in Picusan traps (Fig. 5), yet abundances were similar across the sample dates in bucket traps, hanging, or set on the ground (trap × time effect: <0.03; Table 2). When earwig families were analyzed separately, Anisolabididae and Forficulidae were captured more frequently in Picusan traps than in hanging bucket traps or in bucket traps set on the ground ($P < 0.01$; Table 2; Fig. 5).

Over 96% of captured beetles (Coleoptera) belonged to three families: Carabidae, Elateridae, and Scarabaeidae (Table 2). In total, 3,695 carabid beetles were collected, belonging to at least three

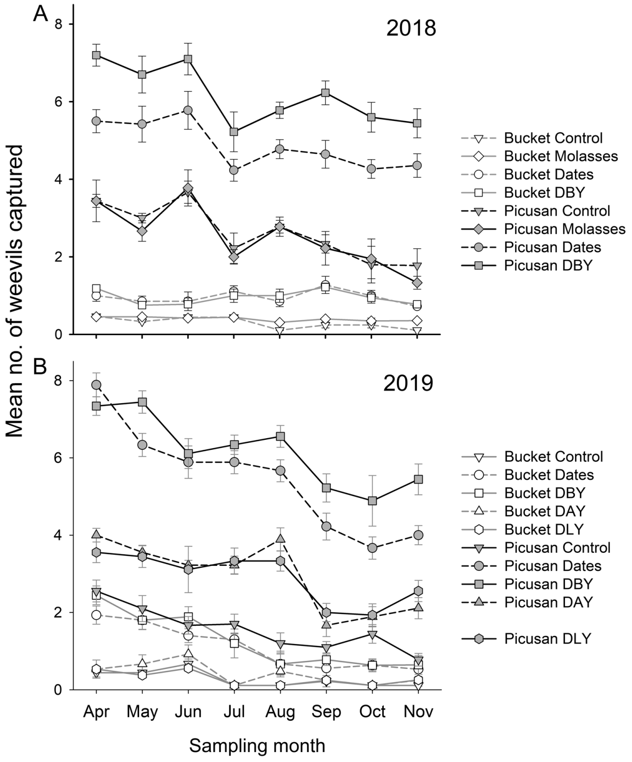

Fig. 2. Mean (±SE) number of total *Rhynchophorus palmarum* caught in white bucket traps and Picusan traps with four different bait types, control/no lure, 18% molasses–3% paraffinic oil solution, dates only, and dates with Baker's yeast (DBY) across sampling dates. (A) In 2018, buckets were suspended 1.5 m above the ground, and Picusan traps were placed on the ground. (B) In 2019, all traps were placed on the ground and five different baits were examined: control/no lure, dates only, dates with Baker's yeast (DBY), dates with alcohol yeast (DAY), and dates with lager yeast (DLY).

genera (Table 2). Across the two experiments, carabid beetle richness did not differ among treatments ($P > 0.18$). In 2019, carabid abundance was significantly affected by trap type, but not by bait and collection date (Table 2). Specifically, carabid captures were four times greater in Picusan traps than bucket traps set on the ground (Fig. 5). The most commonly captured carabid genus was *Amara* Bonelli, comprising 85% of carabids collected. *Calathus ruficollis* Dejean was the second most abundant carabid taxa comprising 11% of captures, whereas *Brachinus mexicanus* Dejean accounted for 3% of carabids collected. Species-level analyses showed that the response of carabids to Picusan traps was driven by *Amara* spp. and *C. ruficollis* ($P < 0.02$) rather than *B. mexicanus* ($P = 0.19$). In total, 5,767 elaterid beetles, belonging to two genera were captured in traps (Table 2). Trapped elaterid beetle richness and abundance were not affected by any of the variables tested ($P > 0.14$), and these results were consistent across captured genera (Table 2). The majority of collected elaterids belonged to two genera, *Ampedus* Dejean and *Heteroderes* Latreille, each comprised ~50% of the total capture (Fig. 4). Similarly, over 98% of captured scarab beetles ($n = 3,591$) belonged to two taxa, *Cotinis mutabilis* Gory & Perch. and *Serica* spp., each comprised ~50% of the total scarab capture (Table 2). No treatments were associated with scarab species richness ($P > 0.09$). However, captured scarab abundance was significantly affected by trap type, bait type, and their interaction ($P < 0.03$; Table 2). Scarab captures were greatest during early- and mid-summer in bucket traps, suspended or set on the ground (Fig. 5). However, overall abundances were similar across sample dates in Picusan traps (trap × time effect: <0.03; Table 2). Furthermore, the captures of both *C. mutabilis* and *Serica* species were greatest in bucket traps, either hanging or placed on the ground ($P < 0.02$; Table 2). Additionally, *Serica* captures were more abundant in early summer (i.e., April–June), whereas *C. mutabilis* was more abundant mid-summer (i.e., June–August).

Over 3,100 moths (Lepidoptera) and 16,700 flies and mosquitoes (Diptera) were captured by all traps (Table 2). No treatments were correlated with species richness of captured taxa (all P values > 0.16). Flies, mosquitoes, and nontarget moths responded to the main effects of trap and bait type (all P values < 0.01), and their interactions. Specifically, these taxa were more strongly attracted to bucket traps baited with molasses (suspended, 2018) and dates in combination with alcohol yeast (on the ground, 2019) than to other trap by bait treatments (Table 2; Fig. 5). The three most commonly captured moth taxa were Pyraloidea (40% of total moths captured), Tortricidae (32%), and *Helicoverpa* Hardwick (Noctuidae) (21%), which were captured more frequently in bucket traps baited with molasses or dates and alcohol yeast (i.e., S. *bayanus*; $P < 0.05$; Table 2). The vast majority of collected flies and mosquitoes belonged to three superfamilies, Sciaroidea (44% of total flies and

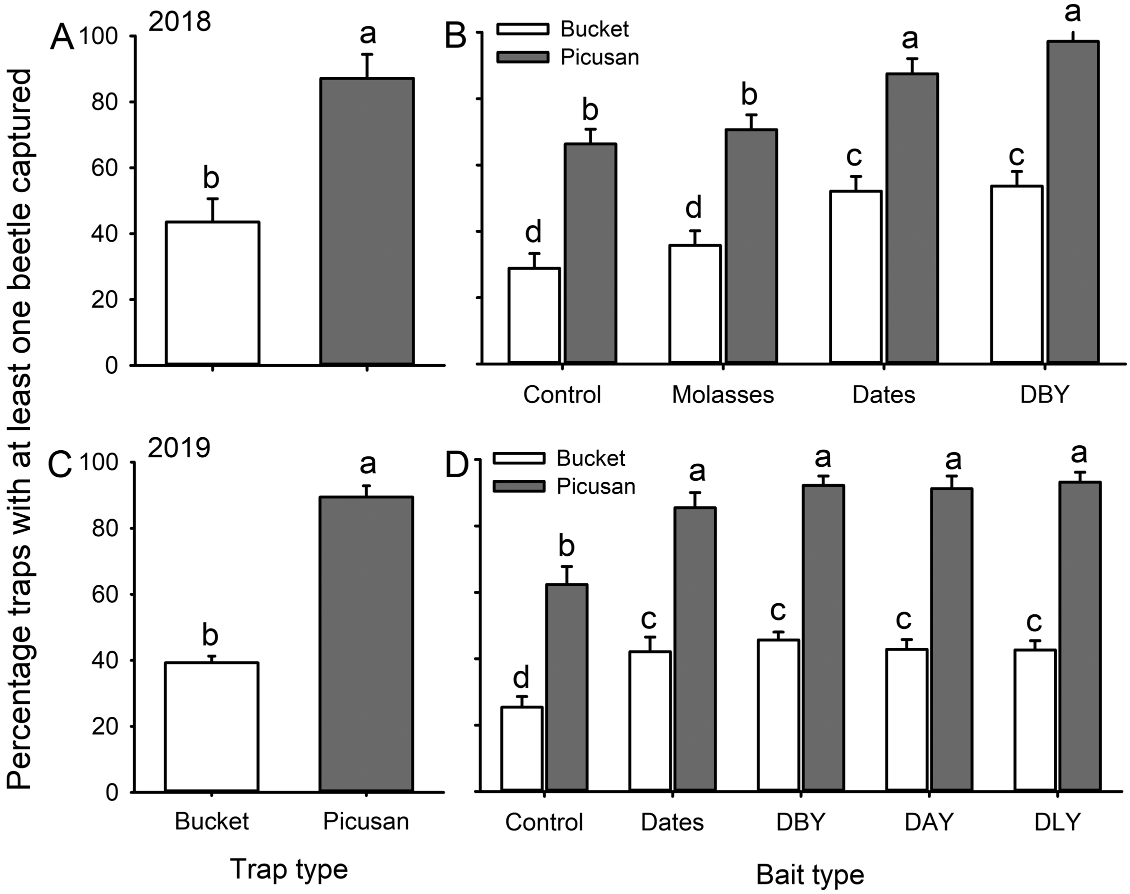

Fig. 3. Mean (±SE) probability of capturing at least one adult *Rhynchophorus palmarum* in white bucket traps and Picusan traps baited with different baits. (A, B) In 2018, buckets were suspended 1.5 m above the ground, and Picusan traps were placed on the ground. Four different baits were tested: control/no lure, 18% molasses–3% paraffinic oil solution, dates only, and dates with baker's yeast (DBY). (C, D) In 2019, all traps were placed on the ground and five different baits were teste: control/no lure, dates only, dates with baker's yeast (DBY), dates with alcohol yeast (DAY), and dates with lager yeast (DLY). Letters at the top of each bar indicate differences among groups by Tukey–Kramer adjustments for main effects of trap (A, C) and stepdown Bonferroni adjustments for trap by bait interactions (B, D) at $\alpha < 0.05$.

mosquitoes captured), Culicoidea (42%), and Muscoidea (13%). When these taxa were analyzed separately, the response of flies and mosquitoes to buckets baited with dates was mainly driven by flies (Muscoidea and Sciaroidea: $P < 0.05$) rather than mosquitoes (Culicoidea: $P > 0.18$).

Discussion

Rhynchophorus palmarum has killed thousands of *P. canariensis* palms in San Diego County (Milosavljević et al. 2019, Hoddle et al. 2020); however, no quarantine restrictions have been imposed to limit movement of live palms from infested zones into uninfested areas. The continuing spread of this pest and the economic impact it causes necessitate efficient detection and monitoring protocols, which are reliant on trapping programs. This is especially important for the edible date industry where early detection programs using traps are operating in advance of anticipated *R. palmarum* incursions into production areas of California and Arizona. Results presented here suggest that Picusan traps loaded with the *R. palmarum* aggregation pheromone, ethyl acetate synergist, and baited with dates and water only or in combination with baker's yeast are superior to similarly loaded bucket traps for detecting and capturing weevils. Other tested baits, 18% molasses–paraffinic oil solution, dates with water and alcohol yeast, and dates with water and lager yeast were inferior in their attraction for *R. palmarum*. Consequently, it is recommended that detection and monitoring programs for *R. palmarum* use Picusan traps loaded with aggregation pheromone and ethyl acetate synergist and baited with dates and water. The addition of baker's yeast to the dates and water bait combination marginally increased capture efficacy by 30%, but this was not significantly different from dates and water only ($P < 0.07$). Adding baker's yeast to dates is an additional trapping cost that may not be warranted, as statistically, it does not significantly improve captures.

Trap capture results reported here for *R. palmarum* support findings by Vacas et al. (2013), who demonstrated that Picusan traps are 45% more effective than bucket traps for capturing the red palm weevil, *R. ferrugineus* Olivier. Previous studies have indicated that bucket traps have low retention efficacy and more than 30% of captured weevils escape from these traps (Oehlschlager et al. 1993, Gonzalez et al. 2019). In comparison, cone shaped traps, like Picusan traps, retain more than 95% of captured weevils (Gonzalez et al. 2019). These observed differences in capture efficacy

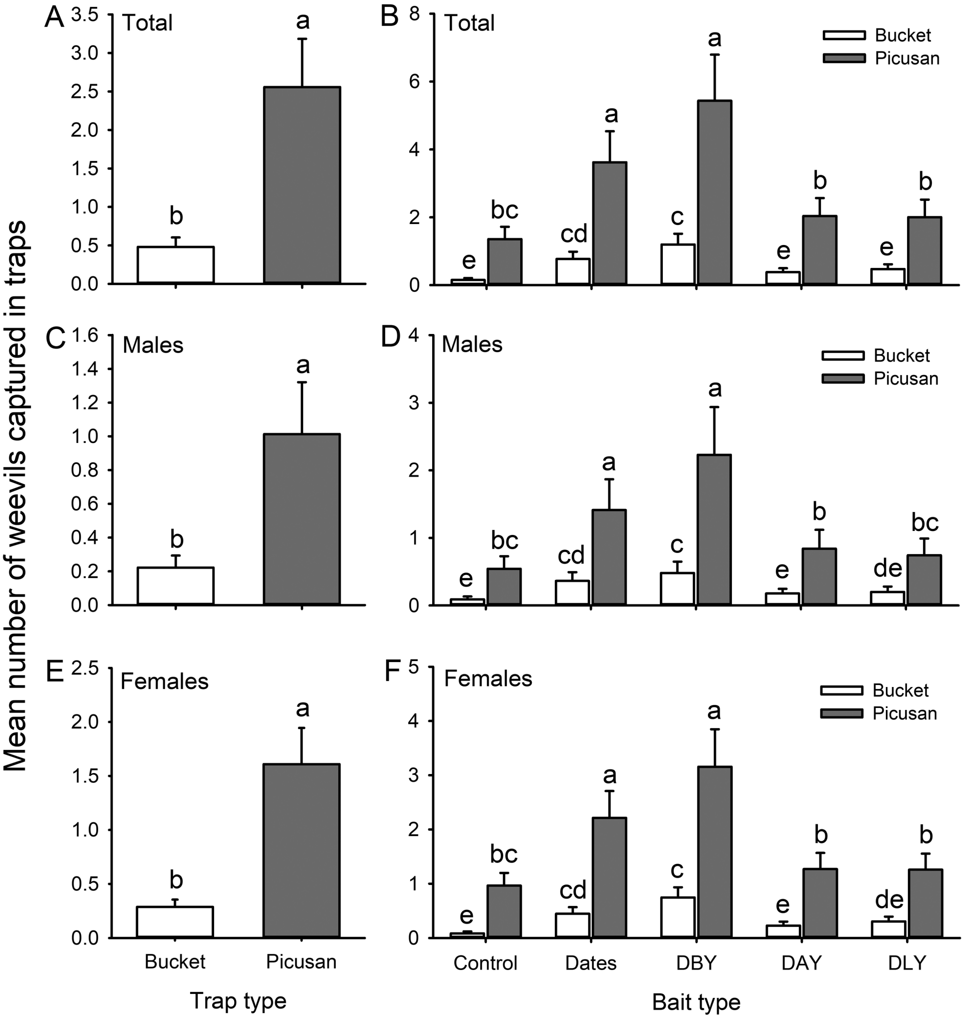

Fig. 4. Mean (±SE) number of total (A, B), male (C, D), and female (E, F) *Rhynchophorus palmarum* caught in white bucket traps set on the ground and Picusan traps placed on the ground. Traps were baited with five different baits (control/no lure, dates only, dates with baker's yeast [DBY], dates with alcohol yeast [DAY], and dates with lager yeast [DLY]). Bars with different lowercase letters represent differences among groups by Tukey–Kramer adjustments for main effects of trap (A, C, E) and stepdown Bonferroni adjustments for trap by bait interactions (B, D, F) at $\alpha < 0.05$.

of *R. palmarum* are likely due to physical differences in trap design (Hallett et al. 1999, Vacas et al. 2013). The Picusan trap has one funnel shaped entrance that allows ingress aided by gravity and the funnel design greatly reduces the likelihood of successful egress. In contrast, the bucket trap has four circular holes that easily facilitate the beetles' entry and exit. Trap color (i.e., white [bucket traps used here] vs. black [Picusan traps used here] vs. yellow) does not significantly affect *R. palmarum* capture rates (Oehlschlager et al. 1993). In comparison, *R. ferrugineus* are more attracted to black traps than to white or yellow traps (Al-Saoud et al. 2010, Abuagla and Al-Deeb 2012).

Irrespective of trap and bait treatments, the sex ratio of captured *R. palmarum* was female biased with nearly two times as many females captured. This result is consistent with previous studies on *R. palmarum* (Oehlschlager et al. 1993), *R. ferrugineus* (Hoddle and Hoddle 2011), *R. vulneratus* (Hoddle and Hoddle 2016), and *R. cruentatus* (Giblin-Davis et al. 1994) that also use male produced aggregation pheromones to attract conspecifics of both sexes to baited traps.

Several species of curculionids are attracted to fermentation volatiles generated by yeasts, including *Rhynchophorus* spp. (Guarino et al. 2011, Madden et al. 2018). The specific signals and emission rates of these volatiles to which curculionid species are attracted differ (Zada et al. 2002, El-Shafie and Faleiro 2017) and yeast species can affect fermentation chemistry and subsequent sensory properties of food baits (Madden et al. 2018). In this study, substantial variation was observed in the attraction of *R. palmarum* to traps baited with dates and three different yeast species. Specifically, baker's yeast, *S. cerevisiae*, was most attractive, and the addition of *S. bayanus* (alcohol yeast) or *S. pastorianus* (lager yeast) to dates and water resulted in significantly lower captures of adult weevils. Differential attraction across yeast species could be explained by the

Table 2. Results of repeated-measures analysis examining the main effects of trap, bait, and time (*P* value) on the abundance and species richness of bycatch captured in traps per site in 2018 and 2019

	2018					2019				
Variables	Number	Trap (T)	Bait (B)	Time (M)	Interaction	Number	Trap (T)	Bait (B)	Time (M)	Interaction
Non insect arthropods										
Isopoda species richness	2	—	0.981	0.824	—	2	0.895	0.389	0.271	—
Isopoda abundance	499	—	0.618	0.256	—	1,221	0.607	0.621	0.221	—
Armadillididae abundance	256	—	0.823	0.188	—	608	0.183	0.524	0.154	—
Porcellionidae abundance	243	—	0.455	0.212	—	613	0.925	0.167	0.121	—
Araneae species richness	4	0.689	0.193	0.445	—	4	0.615	0.675	0.482	—
Araneae abundance	426	0.009*	0.267	0.192	—	749	<0.0001*	0.449	0.654	—
Theridiidae species richness	3	0.532	0.191	0.342	—	3	0.481	0.882	0.233	—
Theridiidae abundance	416	<0.0001*	0.202	0.234	—	724	<0.0001*	0.451	0.198	—
Latrodectus geometricus Koch	181	<0.0001*	0.660	0.811	—	255	0.003*	0.616	0.237	—
Latrodectus hesperus Ch. & Ivie	146	<0.0001*	0.712	0.913	—	314	<0.0001*	0.265	0.129	—
Steatoda grossa Koch	89	0.925	0.895	0.525	—	155	0.266	0.169	0.267	—
Insects										
Dermaptera species richness	2	0.527	0.623	0.912	—	2	0.667	0.821	0.121	—
Dermaptera abundance	7,231	<0.0001*	0.382	0.003*	T × M*	16,954	<0.0001*	0.089	0.0003*	T × M*
Anisolabididae: *Euborellia* spp.	2,154	<0.0001*	0.423	0.0001*	T × M*	5,214	<0.0001*	0.255	0.049*	T × M*
Forficulidae: *Forficula* spp.	5,077	<0.0001*	0.102	<0.0001*	T × M*	11,740	0.006*	0.621	<0.0001*	T × M*
Coleoptera species richness	17	0.575	0.225	0.435	—	17	0.947	0.192	0.910	—
Coleoptera abundance	4,910	<0.0001*	0.565	0.001*	T × M*	8,143	<0.0001*	0.209	<0.0001*	T × M*
Carabidae species richness	4	—	0.187	0.659	—	4	0.265	0.481	0.127	—
Carabidae abundance	836	—	0.903	0.274	—	2,859	0.002*	0.615	0.149	—
Amara spp.	581	—	0.258	0.551	—	2,553	0.025*	0.972	0.54	—
Brachinus mexicanus Dejean	52	—	0.514	0.059	—	92	0.197	0.839	0.953	—
Calathus ruficollis Dejean	203	—	0.827	0.142	—	214	0.002*	0.892	0.098	—
Elateridae species richness	3	0.153	0.336	0.218	—	3	0.640	0.791	0.886	—
Elateridae abundance	2,181	0.190	0.821	0.141	—	3,586	0.345	0.573	0.490	—
Ampedus spp.	1,115	0.069	0.309	0.058	—	1,763	0.893	0.644	0.612	—
Heteroderes spp.	1,046	0.057	0.146	0.392	—	1,805	0.475	0.911	0.731	—
Scarabaeidae species richness	2	0.091	0.571	0.690	—	2	0.295	0.513	0.587	—
Scarabaeidae abundance	1,893	0.029*	0.234	<0.0001*	T × M*	1,698	<0.0001*	0.156	<0.0001*	T × M*
Cotinis mutabilis Gory & Perch.	1,011	<0.0001*	0.178	<0.0001*	T × M*	1,381	<0.0001*	0.298	0.007*	T × M*
Serica spp.	1,882	0.003*	0.746	0.002*	T × M*	1,317	0.001*	0.830	<0.0001*	T × M*
Lepidoptera species richness	4	0.723	0.784	0.182	—	4	0.612	0.762	0.165	—
Lepidoptera abundance	1,924	<0.0001*	0.001*	0.889	T × B*	1,226	<0.0001*	0.012*	0.155	T × B*
Noctuidae: *Helicoverpa* spp.	411	0.003*	0.001*	0.196	T × B*	281	<0.0001*	0.027*	0.093	T × B*
Pyraloidea	915	<0.0001*	0.026*	0.268	T × B*	523	<0.0001*	0.023*	0.674	T × B*
Tortricidae	598	<0.0001*	0.013*	0.573	T × B*	422	<0.0001*	0.045*	0.087	T × B*
Diptera species richness	4	0.719	0.162	0.185	—	4	0.302	0.227	0.284	—
Diptera abundance	8,941	0.005*	0.008*	0.227	T × B*	7,812	<0.0001*	0.039*	0.717	T × B*
Culicoidea	4,026	0.005*	0.331	0.587	—	3,423	0.002*	0.236	0.178	—
Muscoidea	1,671	0.001*	0.048*	0.349	T × B*	547	0.009*	0.034*	0.586	T × B*
Sciaroidea	3,245	0.033*	0.026*	0.473	T × B*	3,842	<0.0001*	0.012*	0.412	T × B*

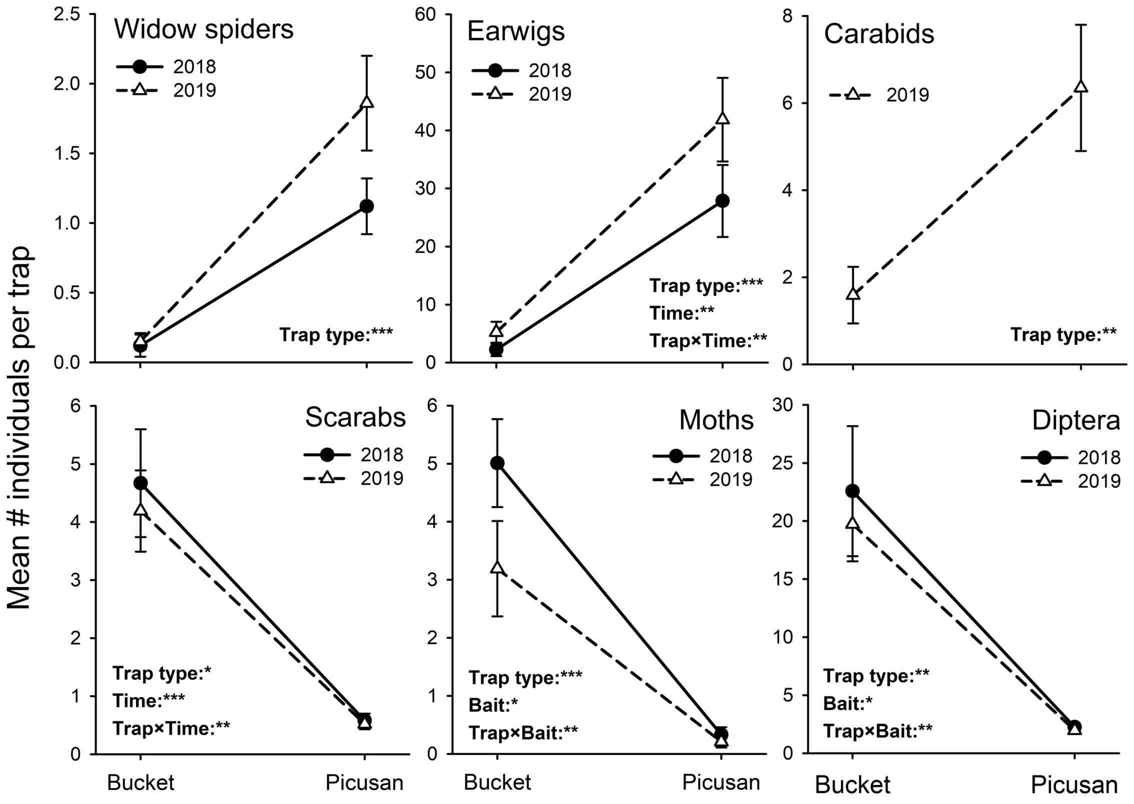

Fig. 5. Mean (±SE) number of nontarget arthropod bycatch in bucket and Picusan traps across all bait traps in 2018 (solid lines) and 2019 (dashed lines). Significant explanatory variables and/or interactions are displayed within each box (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; see Table 2). In 2018, carabid beetles were not represented by enough individuals in bucket traps (i.e., <5) to allow for the effects of trap type to be tested by generalized linear mixed models. Thus, only data from 2019 are displayed.

volatile profiles released when dates are the sugar source. Yeast species vary in their ability to utilize sugars and other compounds from colonized fruits (Madden et al. 2018). For example, aromatic esters or alcohols (Palanca et al. 2013) emanating from dates fermented by *S. cerevisiae, S. bayanus*, and *S. pastorianus* may differ and the blend of volatiles produced by *S. cerevisiae* may be more attractive to *R. palmarum*.

The evaporation and volatile emission rates of food baits were not evaluated in this study. The observed low efficacy of the molasses and paraffinic oil solution, used for monitoring *R. ferrugineus*, might be due to reduced volatile emission rates. This bait included paraffinic oil to reduce evaporation (Navarro-Llopis et al. 2018), and the addition of perforated lids to food bait dispensers may have reduced emission rates of attractive volatiles making this bait less attractive to *R. palmarum* when compared to other baits that were similarly enclosed in plastic containers with perforated lids.

Bycatch of nontarget taxa differed between the two trap designs tested but only for the number of individuals caught and not the richness of higher taxa (i.e., orders, superfamilies, and families). Capture data suggest that differences in trap design or species-specific behavioral responses of captured taxa to differences in trap type could have influenced capture results (Obrist and Duelli 1996). Captures of predominantly ground dwelling nocturnal species such as carabids and earwigs, and cavity nesting widow spiders, were caught more frequently in Picusan traps than in hanging bucket (earwigs and spiders) and bucket traps set on the ground (carabids, earwigs, and spiders). It is possible that these traps were used for shelter during the day (Thiele 2012, Trubl et al. 2012, Orpet et al. 2019). Placing traps in areas with known low populations of carabids, earwigs, or widow spiders could minimize incidental captures. In comparison to Picusan traps, nontarget captures in white bucket traps, hanging and set on the ground, were biased toward flying scarab beetles, moths, and flies/mosquitoes. Most scarabs, moths, flies, and mosquitoes rely on visual stimuli to detect their food source, which may explain why white or yellow traps are preferred to black traps (Weinzierl et al. 2005). White bucket traps baited with molasses or dates mixed with alcohol yeast were significantly more attractive to scarabs, moths, flies, and mosquitoes than other baits placed in the same trap type. However, these baits were not strongly attractive to *R. palmarum*. Bucket traps bycatch was probably biased toward flying insects because of the color but also because of the trap design. Many traps designed for fly capture have side holes and/or invaginations and the bucket trap used in this study is similar in these respects (Weinzierl et al. 2005). Interestingly, no bees or other large Hymenoptera were caught in white bucket (hanging or set on the ground) or Picusan traps, even though these taxa were observed frequently at study sites.

In conclusion, detection and monitoring programs for *R. palmarum* in California should use Picusan traps over bucket traps. Traps loaded with aggregation pheromone should be baited with dates and water. The efficacy of the synergist, ethyl acetate, on *R. palmarum* trap captures was not evaluated in this study. Inclusion of ethyl acetate in trap set up is recommended based on studies with other *Rhynchophorus* spp. (Vacas et al. 2013, 2014, 2017). However, as with the addition of baker's yeast to food baits, which increased captures by 30%, a result that was not statistically significant, the benefits of increased *R. palmarum* trap efficacy that could result from the addition of ethyl acetate may need cost-based consideration. Trapping studies from Europe on *R. ferrugineus*, indicate that it is advisable to set traps in areas that have partial or full shade to reduce adverse effects of excessive heat on trap capture efficacy that may result from prolonged exposure to direct sunlight (Navarro-Llopis et al. 2018). Trap placement with respect to palms of concern is a highly important consideration. Bucket traps, for example, may only have capture efficacy of around 30% (Navarro-Llopis et al. 2018). Therefore, if traps are placed too close to palms, weevils attracted to traps but not retained and killed in traps may attack nearby palms (Hunsberger et al. 2000). If the goal is to detect *R. palmarum* activity in the general vicinity of palms of concern, then traps could be deployed outside the immediate area of concern, perhaps ~1 km away. If weevils are captured at this distance from the palms of interest, it likely indicates that there is probably risk of weevil attack and steps should be promptly considered and implemented for protecting those palms.

Supplementary Data

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

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