Evaluation of Mass Trapping and Mating Disruption for Managing *Prionus californicus* (Coleoptera: Cerambycidae) in Hop Production Yards

ELIN C. MAKI,1 JOCELYN G. MILLAR,2,3 JOSHUA RODSTEIN,3 LAWRENCE M. HANKS,4 AND JAMES D. BARBOUR1,5

J. Econ. Entomol. 104(3): 933Ð938 (2011); DOI: 10.1603/EC10454

**ABSTRACT** Larvae of *Prionus californicus* Motschulsky (Coleoptera: Cerambycidae) feed on the roots of many types of woody perennial crops and are serious pests of hop in the northwestern United States. The adult males are strongly attracted to a volatile sex pheromone, (3R,5S)-3,5-dimethyldodecanoic acid, that is produced by females. Here, we summarize the results of field experiments that evaluated the potential for using the synthetic pheromone (in a blend of all four possible stereoisomers) to manage infestations of *P. californicus* in commercial hop yards by mass trapping or mating disruption. Our research provides evidence that mass trapping may be effective in reducing mating success of the females: positioning surrogate females (sentinel traps baited with a low dose of pheromone) within a square of eight pheromone-baited traps resulted in an 88% reduction in the number of wild males that reached the sentinel traps compared with sentinel traps that were surrounded by traps baited with blank lures. Similarly, surrogate females that were surrounded by pheromone lures (without traps) were reached by 84% fewer wild males than surrogate females surrounded by blank lures, suggesting that mating disruption also may be effective. A mark–recapture experiment indicated that male *P. californicus* were attracted to traps baited with 1 mg of pheromone from as far away as 585 m. These studies indicate that 3,5-dimethyldodecanoic acid has very good potential for managing *P. californicus* in hop yards, and perhaps in other crops where it is a pest.

**KEY WORDS** pest management; pheromone; 3,5-dimethyldodecanoic acid

The cerambycid beetle *Prionus californicus* Motschulsky (Coleoptera: Cerambycidae) is an economically important pest of many agricultural and ornamental plants and is broadly distributed throughout western North America (Linsley 1962, Solomon 1995). In the northwestern United States, it is a serious pest of hop, *Humulus lupulus* L. (Urticales: Cannabaceae; Bishop et al. 1984), a high-value specialty crop. Hops are an essential ingredient of beer, providing distinctive and proprietary characteristics during the brewing process. The United States accounts for ~39% of worldwide production of hops, ranking second only to Germany (Anonymous 2009).

Adult *P. californicus* are large (25–55 mm), crepuscular, and are active from late June through early August in the Pacific Northwest (Barbour et al. 2006). Adults do not feed and are relatively short lived (2–3 wk; Barbour et al. 2006). Females deposit 150–200 eggs in soil at the bases of living woody plants, and the larvae feed on the roots for 3–5 yr before pupating (Linsley 1962, Bishop et al. 1984). As they feed, they prune the major roots of hop, resulting in reduced plant growth due to decreased nutrient uptake and moisture stress. Heavy infestations of the larvae cause wilting, yellowing, and death of bines, or even the entire plant (Bishop et al. 1984, Solomon 1995).

*P. californicus* typically is managed by a combination of cultural and insecticidal methods. Cultural control entails completely removing the crowns and roots of hop plants from heavily infested fields, and then either fumigating the soil and replanting the following spring, or leaving yards fallow for 2–3 yr before replanting. Fumigation is prohibitively expensive (>US$700/acre; Hinman 2004). Moreover, fallowing is undesirable because the trellis system upon which the hops are grown greatly limits the opportunity to produce an alternative crop, and it is not economical to remove and later replace the trellis system (~US$2,000/acre; Hinman 2004). Finally, *P. californicus* can be managed with the organophosphate soil insecticide ethoprop (Mocap EC, Bayer Crop Science, Research Triangle Park, NC), but this chemical poses a threat to wildlife (Patterson 2003) and is a health concern.
hazard for farm workers (Ames and Stratton 1991). Thus, there is a great need for new management tactics for *P. californicus* in hop production.

Female *P. californicus* produce a volatile sex pheromone, recently identified as (3R,5S)-3,5-dimethyl-dodecanoic acid, to which males are strongly attracted (Cervantes et al. 2006, Rodstein et al. 2009). Males respond equally well to a blend of all four of the possible stereoisomers of the compound (the blend henceforth referred to as synthetic pheromone), which is more economical to produce than the pure (3R,5S) stereoisomer (Rodstein et al. 2011). Sex pheromones have been used effectively to manage insect pests by hindering mating, either by mass trapping (removing males from the population) or by mating disruption (inundating the habitat with synthetic pheromone) such that males cannot locate mates; Mil lar 2007, Witzgall et al. 2010). Here, we summarize experiments to estimate the distance over which males would respond to traps baited with the synthetic pheromone and to determine whether reproduction in field populations could be inhibited by mass trapping or mating disruption.

Materials and Methods

Traps, Lures, and Study Sites. Traps were 19-liter polypropylene buckets (38 cm in height by 30 cm in diameter) fitted with aluminum funnels (model 2815B, BioQuip, Rancho Dominguez, CA) that were buried between rows of hop plants with funnel rims flush with the soil surface. Pheromone lures were clear polyethylene sachets (low-density press-seal bags; Bagette model 14770, 5.1 by 7.6 cm, 0.05-mm wall thickness, Cousin Corp., Largo, FL) loaded with synthetic 3,5-dimethyl-dodecanoic acid (1 mg diluted in 100 μl of HPLC grade hexane; Chromasolv, Sigma-Aldrich, St. Louis, MO), synthesized as described by Rodstein et al. (2009). Lures were suspended over the trap funnels by attaching them to the wire bucket handle that had been modified to remain upright. Study sites were commercial hop yards in Canyon County, ID.

Estimating Maximum Sampling Range. We estimated the maximum sampling range over which male *P. californicus* could be attracted to pheromone traps by releasing marked beetles at a range of distances from a trap and characterizing the relationship between release distance and percentage recapture (Turchin and Odendaal 1996, Hicks and Blackshaw 2008). Males that were to be marked were captured on evenings before setting up the experiment, by using pheromone-baited traps that were deployed at least 1.5 km from the study site. This method would tend to limit the pool of males to those that already have demonstrated that they respond to the pheromone. However, nearly all males respond (see Cervantes et al. 2006, Rodstein et al. 2011) and the rare male that does not would be economically insignificant because it would not mate. We used only males that were active and undamaged. Males were randomly assigned to treatments (the distance that they were released from the pheromone trap; see below) and were marked on the metasternum with two colors of nail polish (60 Second Nail Polish, Rimmel, NY) to indicate treatment and release date.

The experiment was conducted between 30 June and 5 July (maximum air temperature, 32–35°C; average daily wind speed, 3.5–6.5 km/h; skies clear) in an 800- by 800-m hop yard (center of field: 43°41’13.13’’ N, 116°55’37.28’’ W). We set up four traps, one at each of the cardinal compass directions from the yard center, and 30 m within the yard border. Only one trap was baited on a given night: the trap that we predicted would be upwind of the yard center that evening (based on weather forecasts; National Oceanic Atmospheric Administration, http://www.noaa.gov/). The other three traps were covered with lids. We initially released marked males into the hop understory at distances of 9, 27, 82, and 247 m downwind of the pheromone trap. However, recapture rates were quite high, even at the greatest distance (see Results), so the experiment was repeated with greater release distances: 91, 183, 365, and 730 m. In both trials, we released similar numbers of beetles at each distance (*N* = 12–38, depending on availability; total *N* = 239 and 290 beetles in the first and second trial, respectively). Marked beetles were released in the mornings (0700–0900 hours), and they quickly concealed themselves in the foliage and remained sedentary throughout the day. The pheromone trap was baited with a lure in the evening of the same day, before beetles became active (2100–2200 hours). We checked the pheromone trap the following morning and recorded the number of recaptured beetles that had been released the previous morning, and their release distance. Marked and recaptured beetles were not reused for the experiment, but some unmarked and vigorous beetles that had been trapped were used in the mark–recapture experiment the next day.

We describe the relationship between the percentage of marked beetles that were recaptured and the distance that they were released from the pheromone trap by fitting the data from both trials to the negative exponential: $Pr_1 = Pr_0 \times e^{(-KD)}$ (JMP version 8.02, SAS Institute 2009), *Pr* being the percentage recapture of beetles released at a given distance and *D* being the release distance. Values of *Pr*0, the maximum percentage recapture of beetles released 0 m from the trap, and *K*, the rate constant, were estimated by iteration to yield the minimum sum of squares. We tested for a lack-of-fit to the exponential model using the replicates test (Seber and Wild 2003).

Because estimated percentage recovery using the negative binomial approaches, but never reaches zero with increasing distance, we estimated maximum trapping range by linear regression of percentage recapture (*Pr*) on release distance (*D*) from the trap, solving for *Pr* = 0 (Turchin and Odendaal 1996, Hicks and Blackshaw 2008). We used all combinations of untransformed or log$_{10}$-transformed percentage recov-
ery and release distance data to identify the regression model, of the four possible, that yielded the highest regression coefficient, then used that model to estimate maximum trapping range.

Mass Trapping and Mating Disruption. These experiments test the hypothesis that mass trapping of male *P. californicus*, or release of synthetic pheromone into the environment, will reduce the number of males that can locate and mate with females. However, a preliminary experiment revealed that caged female *P. californicus* would not reliably emit pheromone, and so could not be used to assess treatment effects on males. We therefore used sentinel traps with lures containing 0.1 mg of synthetic pheromone (pitfall traps and lures as described above) as surrogate females. These lures are as attractive to males as the 1-mg lures (described below) that surrounded the sentinel traps, which are more attractive to males than live females (Rodstein et al. 2011). Thus, the sentinel traps were at least as attractive to males as live females.

In the mass-trapping experiment, we surrounded sentinel traps with other pitfall traps that were baited with pheromone lures (hence “pheromone traps”), and our controls were sentinel traps surrounded by traps with blank lures (containing only hexane; hence “control traps”). Lures of pheromone traps contained 1.0 mg of synthetic pheromone, whereas sentinel trap lures were loaded with 0.1 mg of pheromone, as already described. We set up eight pheromone or control traps in a square configuration with the sentinel trap in the center (Fig. 1). These traps were arranged in squares of either 18 or 36 m on a side to test the effect of trap spacing on the number of males captured by sentinel traps. These trap spacings were based on the 4.5-m spacing of rows in hop yards.

The four treatment combinations (two pheromone treatments and two trap-spacing treatments) were assigned randomly to four commercial hop yards that were naturally infested with *P. californicus* (coordinates to center of plot: field 1: 43° 42' 47.20“ N, 116° 55' 21.73“ W; field 2: 43° 42' 57.03“ N, 116° 55' 40.06“ W; field 3: 43° 41' 36.23“ N, 116° 55' 16.75“ W; fields 4: 43° 41' 29.82“ N, 116° 54' 58.54“ W). The hop yards were 2–7 yr old, 10–20 ha, and the plots were separated from one another by at least 480 m. The experiment was repeated on four consecutive evenings during 10–13 July 2009 (maximum air temperature, 26–32°C; average wind speed, 2.4–4.2 km/h; no precipitation). Treatments were rotated across yards each day. We recorded the number of male beetles in sentinel traps and in pheromone traps each morning, and to avoid the possibility of trapping out local populations, we released these males (along with males caught in the pheromone and control traps) in vegetation outside the squares of traps and at least 18 m from the nearest trap, with about equal numbers released at each cardinal direction.

The mating disruption experiment used the same experimental design as the mass-trapping study (Fig. 1) and was conducted in the same four yards, but we used only lures (without pitfall traps). As described above, the sentinel traps were positioned at the centers of squares of lures (suspended ~0.67 m above the ground on wire flags) that were treated with either dilute pheromone (1 mg of synthetic pheromone in 100 µl of hexane; “pheromone lures”) or only hexane (“control lures”). The lures were arranged around the sentinel traps at the same two spacings used in the mass trapping experiment. The experiment was conducted on evenings of 14–17 July 2009 (maximum air temperature, 26–32°C; average wind speed, 2.0–2.7 km/h; no precipitation).

Data from the mass-trapping and mating disruption experiments were analyzed separately by analysis of variance (ANOVA) as imperfect Latin Squares blocked by yard and day (JMP version 8.02, SAS Institute 2009). We used orthogonal contrasts to test differences between pheromone and trap spacing treatments in the mean number of male *P. californicus* that were captured by sentinel traps. Data were transformed before analyses to normalize and stabilize variance (normality confirmed with the Shapiro–Wilk test; JMP version 8.02, SAS Institute 2009). We present untransformed means ± 1 SE throughout this article.

Results and Discussion

Estimating Maximum Sampling Range. The percentage of male *P. californicus* that were recaptured declined exponentially with the distance that they were released from the pheromone trap in the two trials, and the data were adequately described by the negative exponential model (best-fit regression: \( Pr = 43.1 (0.00995^{A}) \); \( r^2 = 0.65 \), SSE = 2.149, df = 22; replicates test \( P = 0.67 \)). On average, percentage of re-
capture fell below 10% at 200 m. Regression of percentage recovery against log<sub>10</sub>-transformed release distance (F<sub>1,6</sub> = 15.0, P < 0.0001) yielded the highest regression coefficient of the four regression analyses (Fig. 2). Solving this regression equation for Pr = 0 yielded a value of 585 m for the estimated maximum sampling range.

**Mass Trapping and Mating Disruption.** The mass-trapping experiment supported the hypothesis that the number of wild male beetles captured by sentinel traps would be reduced by surrounding the sentinel traps with pheromone-baited traps. Sentinel traps that were surrounded by pheromone traps captured a mean of 1.3 ± 0.25 males (averaged across trap spacings) compared with 10.5 ± 2.2 males captured by sentinel traps that were surrounded by control traps (Fig. 3A), an 88% reduction in the number of males (means significantly different; ANOVA: F<sub>1,6</sub> = 70.7, P = 0.0002). The spacing of traps had no significant effect on the number of males that were captured (means 5.6 ± 2.1 and 6.1 ± 2.6 for traps at 18 and 36 m, respectively; ANOVA: F<sub>1,6</sub> = 0.43, P = 0.54). During the study, the pheromone traps that surrounded the sentinel traps captured a mean of 44.0 ± 10.8 males per day, whereas control traps captured only 4.6 ± 2.5 males (means, averaged across trap spacings, significantly different; ANOVA: F<sub>1,6</sub> = 17.1 P = 0.0055), and the trap spacing effect again was not significant (ANOVA: F<sub>1,6</sub> = 0.002, P = 0.97).

The mating disruption experiment yielded results very similar to those of the mass trapping study (Fig. 3B). Sentinel traps surrounded by pheromone lures captured a mean of 2.0 ± 1.2 males whereas those surrounded by control lures captured 12.4 ± 4.5 males, an 84% reduction (means significantly different; ANOVA: F<sub>1,6</sub> = 44.1, P = 0.0006). The spacing of lures again did not significantly influence the number of males captured by sentinel traps (7.8 ± 4.70 and 6.4 ± 2.54 for traps spaced at 18 and 36 m, respectively; ANOVA: F<sub>1,6</sub> = 0.093, P = 0.77).

Our findings suggest that pheromone traps, or pheromone lures alone, may effectively decrease mating success of female *P. californicus* in hop yards by greatly restricting the number of males that reach them. The maximum sampling range estimated from our study (585 m) is well within the dimensions of most hop yards in Idaho, which usually are 400–800 m on a side (J.D.B., unpublished data). Although the spacing of pheromone traps and lures did not influence the number of males that were captured by sentinel traps, the sphere of influence of pheromone traps and lures certainly must be limited, and at some greater distance would have no effect on mating success of females. Ongoing research will focus on determining the number of traps or lures, their spatial arrangement, and dosages of pheromone required to minimize mating success of female beetles, and on assessing whether these pheromone-based tactics can significantly reduce densities of *P. californicus* larvae in hop yards, with consequent increases in hop performance and crop yield. Additional research also is needed on *P. californicus* life history traits (e.g., whether males and females mate more than once) that potentially could influence the effectiveness of pheromone management tactics.

The known life history traits of *P. californicus* would seem to render it a particularly suitable candidate for mass trapping, mating disruption, or both (see Millar 2007, Witzgall et al. 2010). Specifically, the nonfeeding adults are short lived, and consequently are under strong selection pressure to find mates before they exhaust their limited energy reserves and die. Second, adults are active for only a few weeks per year, so that the time period during which control tactics need to be deployed is short. Consequently, lures need only have an effective field lifetime of a few weeks. Furthermore, it is easy to detect the beginning of the adult flight period with pheromone-baited tracking traps, so

---

**Fig. 2.** Relationship between percentage recapture (Pr) of marked males and log<sub>10</sub>-transformed values for release distance (meters) from pheromone trap. Best-fit regression equation: Pr = 61.7 − 22.3 × log<sub>10</sub>D, r² = 0.66.

**Fig. 3.** Mean ± SE number of male *P. californicus* that were captured by sentinel traps that were surrounded, at two different spacings, by pheromone-baited or control traps (lures containing only hexane) in the mass trapping experiment (A) or pheromone lures or control lures without traps in the mating disruption experiment (B).
that mass-trapping or mating disruption can be deployed accurately to maximize their impact, while minimizing management costs. Moreover, the long generation time of this species (2–3 yr) may greatly retard recovery of local populations that have been suppressed by these tactics. Thus, repeated annual applications of mass trapping and/or mating disruption could dramatically reduce population densities to levels below the economic injury level, with populations subsequently maintained at low levels with little management effort. Pheromone-based management strategies, if effective, are likely to be adopted by hop growers because hop is a high value crop, grown on limited acreage, and current management alternatives are unsatisfactory (see Introduction). Such semiochemical-based management strategies have proven to be both highly successful and cost effective for managing other large beetle species that are important pests (Hallett et al. 1999, Oehlschlager et al. 2002, Soroker et al. 2005, Faleiro 2006; also see Koppenhöfer et al. 2005, Wenninger and Averill 2006).

If P. californicus can be managed effectively with pheromone-based tactics in hop, similar methods may be used to manage it in other crop systems, such as apple (Malus spp.) and cherry (Prunus spp.), where it can be a significant pest (Bishop et al. 1984, Solomon 1995). Furthermore, our ongoing research has demonstrated that males of several other Prionus species, including species that are important pests in other crops, are highly attracted to the pheromone of P. californicus or to one or more of its isomers (Barbour et al. 2011). This finding suggests that the structures of female-produced pheromones may be highly conserved among closely related species in the subfamily Prioninae and that other pest species in this subfamily may be suitable targets for pheromone-based management.

Acknowledgments

We thank Karen Barbour and Brenda Nelson for technical assistance and the growers of the Idaho Hop Commission for access to study sites. This project was supported by the USDA Cooperative State Research, Education, and Extension Service Western Region Integrated Pest Management grant 2007-31403-18495, the Hop Research Council, and the Idaho Cooperative State Research, Extension and Education Service.

References Cited


SAS Institute. 2009. JMP 8 user’s guide, 2nd ed. SAS Institute, Cary, NC.


tion in date palm plantations in Israel. Phytoparasitica 33: 97–106.


Received 22 December 2010; accepted 6 February 2011.