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# Effect of Contact Insecticides Against the Invasive Goldspotted Oak Borer (Coleoptera: Buprestidae) in California

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## Abstract

The goldspotted oak borer, *Agrilus auroguttatus* Schaeffer (Coleoptera: Buprestidae), was linked in 2008 to ongoing tree mortality in oak woodlands of southern California. Mortality of coast live oak, *Quercus agrifolia* Née, and California black oak, *Q. kelloggii* Newb., continues as this exotic phloem borer spreads in southern California. Management options are needed to preserve high-value oaks and maintain management objectives. From 2009 to 2012, we tested four contact insecticide formulations in four experiments against *A. auroguttatus* in California. The impact of contact insecticides was evaluated ∼<1, 8, and 12 mo postapplication against *A. auroguttatus* adults in no-choice leaf-feeding or walking bioassays. At <1 mo postapplication, bifenthrin, carbaryl, lambda-cyhalothrin, and permethrin all reduced adult survival and feeding in leaf-feeding and walking bioassays. At 8 mo postapplication, only bifenthrin reduced adult feeding, but had no effect on survivorship. At 12 mo postapplication, adult *A. auroguttatus* survived fewer days and fed less in leaf-feeding bioassays with bifenthrin, carbaryl, and permerthin. These results support the annual application of contact insecticides prior to *A. auroguttatus*' flight period to reduce adult leaf maturation feeding and activity on the bark surface (e.g., oviposition), but additional studies are needed to show these contact treatments can prevent tree mortality from this invasive species.

**Key words:** bifenthrin, carbaryl, exotic, oak mortality, *Quercus* spp

The release and establishment of exotic forest insects occurs frequently in the United States. To date, the greatest accumulation of established alien species has occurred in the northeastern part of the country, but an increase in invasions has also been persistent along the western coast (Liebhold et al. 2013). Furthermore, the frequency of exotic phloem- and wood-boring beetle establishments has increased in recent decades, causing notable damage to North American forests (Aukema et al. 2010). In California, numerous exotic phloem- and wood-boring beetles, including the banded elm bark beetle, *Scotlyus schevyrewi* Semenov (Scolytinae), redhaired pine bark beetle, *Hylurgus ligniperda* (F.) (Scolytinae), Mediterranean pine engraver, *Orthotomicus erosus* (Wollaston) (Scolytinae), and Eucalyptus longhorned beetle, *Phoracantha semipunctata* F. (Cerambycidae), have been detected in urban landscapes and native forest stands in the state (Lee et al. 2007, Paine et al. 2009).

The goldspotted oak borer, *Agrilus auroguttatus* Schaeffer (Buprestidae), represents another recent exotic phloem-borer introduction to California. In 2008, Coleman and Seybold (2008) linked *A. auroguttatus* to tree injury and mortality in San Diego County, CA. Oak mortality has been observed in San Diego Co. (USDA FHM 2015) since 2002, but the beetle has likely been in the area for more than two decades (Coleman et al. 2012a, b). Aerial detection surveys have identified >53,000 dead oaks in eastern San Diego Co. that are believed to have been killed by *A. auroguttatus* (USDA FHM 2015). Since its initial detection in San Diego Co., *A. auroguttatus* has established populations in at least three additional counties (Los Angeles, Orange, and Riverside Cos.) in southern California (Jones et al. 2013, Coleman 2015). Human-assisted movement of *A. auroguttatus*, especially in infested firewood, was likely responsible for much of the range expansion in southern California, and this dispersion pathway continues to present a significant pest management challenge throughout North America (Haack et al. 2010, see http://www.dontmovefirewood.org/).

In California, *A. auroguttatus* prefers to attack coast live oak, *Quercus agrifolia* Née, and California black oak, *Q. kelloggii* Newb. (both red oaks, section Lobatae), but it can complete development in numerous oak species (Coleman and Seybold 2008, Haavik et al. 2014). Tree injury and mortality were not associated with *A. auroguttatus* prior to 2008 in its native region of southeastern Arizona (Coleman and Seybold 2011), and only recently have low levels of injury and mortality been linked to this species there (Coleman et al. 2012b). In its native and introduced regions, tree injury and mortality from *A. auroguttatus* is most common on large-diameter red oaks (>49 cm DBH; Coleman et al. 2012b).

*Agrilus auroguttatus* adults primarily emerge from host trees during mid-May to early September in southern California. Adult females must conduct maturation feeding on oak foliage before ovipositing, with sexual maturity being reached ~2 wk after emergence (Lopez and Hoddle 2014). Peak flight activity occurs from late June to early July in southern California (Haavik et al. 2013, Coleman et al. 2014). Females lay eggs primarily on the lower bole on the outer bark surface or in bark cracks, making eggs difficult to see on host trees. Upon eclosion, larvae bore through the phloem to the xylem surface where most larval feeding occurs from June to December (Haavik et al. 2013). Larvae likely progress through four instars, and when mature, move to the outer phloem to construct pupal cells. In southern California, pupae are present from April to August and are found just under the outer bark (Haavik et al. 2013). Systematic sampling of host trees for *A. auroguttatus* life stages, and the continuous monitoring for adults to discern their flight period, suggests *A. auroguttatus* completes one generation per year in southern California (Haavik et al. 2013, Coleman et al. 2014).

Tree injury from *A. auroguttatus* larvae is uncommon in upper branches of the crown unlike injury associated with other *Agrilus* Curtis wood borers, including twolined chestnut borer, *A. bilineatus* Weber, and Gambel oak borer, *A. quercicola* (Fisher) (Haack and Acciavatti 1992, Sever et al. 2012). Instead, *A. auroguttatus* larval feeding occurs primarily along lower portions of the main stem and larger diameter branches (>20.3 cm; Coleman et al. 2011, Hishinuma et al. 2011, Haavik et al. 2012). Larvae feed on the cambium at the interface of the xylem and phloem, lightly scoring the outer xylem and injuring the phloem. Larval galleries are dark-colored in appearance when the bark is removed from living trees and have a meandering pattern on the xylem surface (Coleman et al. 2015). Mortality of the host is believed to be caused by girdling of the xylem and phloem (Coleman et al. 2011). Signs and symptoms associated with *A. auroguttatus* host injury include D-shaped adult emergence holes on the main stem and larger branches, crown thinning and dieback, bark staining or weeping, and foraging by woodpeckers (Coleman et al. 2011, 2015). These indicators were used to develop an oak health rating system to assist land managers, pest specialists, and homeowners with proper identification of *A. auroguttatus*; to rank severity of injury; and to assist with management decisions (Coleman et al. 2011, Hishinuma et al. 2011).

Loss of large, dominant canopy trees reduces aesthetic values and increases mitigation costs (an estimated 10 million [USD] of private and public funds have been directed to the new invasive beetle [Goldspotted Oak Borer Steering Committee San Diego Co. 2014]). Effective insecticide options for managing *A. auroguttatus* have been slow to develop, primarily because tree mortality associated with *A. auroguttatus* can take several years to manifest and because of the general difficulties of working with wood borers (e.g., lack of effective attractants and cryptic life stages; but see Chen et al. 2015). We conducted four experiments to evaluate the effects of contact insecticides of *A. auroguttatus* adults during either leaf maturation feeding or while on the bark surface (e.g., during oviposition). Foliage and cut logs were collected from all four experiments for controlled laboratory no-choice leaf-feeding and walking bioassays. The same protocols were followed in each experiment unless otherwise noted.

## Materials and Methods

### 2010–2011 Bifenthrin and Carbaryl (Experiment 1, Leaf-Feeding and Walking Bioassays)

From 3 to 4 May 2010, bifenthrin (Onyx Pro [FMC Corporation, Philadelphia, PA]) and carbaryl (Sevin SL [Bayer Crop Science LP, Calgary, AB]) were applied to *Q. agrifolia* at a study site in Japatul Valley, CA (San Diego Co., N 32.79197°, W −116.68231°, elev. 807 m). Fifteen trees were sprayed with insecticide (7 bifenthrin and 8 carbaryl) and seven trees were designated as untreated controls at this site for experiment 1. For all the experiments (1–4), insecticide treatments were randomized among larger diameter trees prior to treatment due to the increased risk from *A. auroguttatus* to this diameter class and to protect private landowners trees. Smaller diameter trees were reserved for the untreated controls. All *Q. agrifolia* used in this study were uninfested or possessed minor injury caused by *A. auroguttatus*; they were categorized as described earlier (Coleman et al. 2011).

We sprayed insecticide treatments onto the main stem and larger branches (>25.4 cm in diameter) of study trees where *A. auroguttatus*-caused injury would be concentrated. Foliage on a single branch was randomly selected by direction, flagged, and sprayed with the corresponding treatment for certain identification when needed for no-choice leaf-feeding bioassays. The same procedure was followed for selecting and marking foliage on untreated trees. At the same time, three freshly cut, uninfested *Q. agrifolia* logs (46 cm long by 15 cm diameter) were randomly treated with bifenthrin or carbaryl or left untreated in preparation for walking assays. Logs originated from the Descanso Ranger District of the Cleveland National Forest (CNF). All insecticide spraying was done with a truck-mounted skid sprayer with a hydro pump (PBM Supply & MFG., Inc., Chico, CA) using the maximum label rate for wood-boring pests (bifenthrin: 200 ml 378 liter$^{-1}$, carbaryl: 31 ml liter$^{-1}$). A Hypro spray gun (product #3281-001, PBM Supply & MFG., Inc., Chico, CA) was used in all the applications to allow for a stream or cone spray pattern. Insecticides were applied at a pressure rate of ~150–175 psi until the main stem and larger branches were saturated. Depending on tree size, ~45–136 liter were applied to an individual tree in 2–6 min. Applications occurred when mean wind conditions were <16 kmph and no precipitation was forecasted within the next 24 h.

Foliage was collected on 10 May 2010 and 4 May 2011 from bifenthrin- and carbaryl-treated study trees and untreated control study trees. Foliage collections in each experiment corresponded to either ~<1 or 12 mo postapplication for bifenthrin and carbaryl treatments. Foliage used in the experiments described below occurred from 16 May to 8 June, representing 13–33 d postapplication. At each collection date, we filled a 3.8-liter plastic bag with foliage from each flagged (marked) branch on all trees from the appropriate experiment. Foliage was collected, returned to the laboratory in a cooler with ice, and stored in a refrigerator until use in bioassays.

To assess the effect of insecticide treatments on *A. auroguttatus* adult survival and feeding, no-choice leaf-feeding bioassays were conducted with foliage from all study trees. In each bioassay, a single *Q. agrifolia* leaf was provided to a single adult beetle and monitored for a maximum of 20 d in 2010 or until the beetle died. Bioassays were conducted in 59-ml circular plastic cups (Dart Container Corporation, Mason, MI) held at ambient room temperature (~24°C), ~60% RH, and a photoperiod of 13:11 (L:D) h.

*Agrilus auroguttatus* adults were reared from infested *Q. agrifolia* bark and logs that were collected from the CNF, Descanso Ranger District and William Heise County Park (Julian, CA) for all four experiments. Material was placed into large, screened rearing cages and collected daily once emergence was observed. The sex of each beetle was determined prior to the start of each bioassay (Coleman and Seybold 2010). Each newly emerged adult was starved prior to initiation of each bioassay, and most bioassays began within the first two days of emergence.

Observations were recorded daily for beetle activity (e.g., feeding, walking, standing, and immobilized), mortality, and presence of frass in each bioassay. Leaves were replaced in bioassays when leaf tissue was completely consumed, leaves began to desiccate, or after 4 d, whichever occurred first. Frass was collected at the end of each bioassay, dried for 2 d at 60 °C and then its mass determined. Adults that were immobile for two consecutive days were considered dead. Beetle survival period and the amount of frass produced per day were used to assess treatment impact. Sixty-three (63) no-choice leaf-feeding bioassays were conducted with foliage from all study trees.

Adult no-choice walking bioassays were conducted from 17 to 24 May 2010 (representing from 14 to 21 d postapplication) with *Q. agrifolia* logs. *Quercus agrifolia* logs were treated with bifenthrin, carbaryl, or untreated, and a total of 33 bioassays were conducted with the logs. Logs were placed vertically and supplied with an untreated, *Q. agrifolia* twig that was ~12 cm long and held in a floral water pick (12.1 cm and Diamond Line, Akron, OH) as a food source. A single adult *A. auroguttatus* was placed on the top of the cut log and allowed to roam. Bioassays were conducted for a maximum of 4 d in collapsible insect cages (Bug Dorm 34 by 34 by 34 cm and 57 by 40 by 38 cm [Meadowview, Taichung, Taiwan]), with observations being recorded daily on beetle activity, mortality, and feeding. Observations of beetle activity and feeding were generally conducted either in the morning or late afternoon, and each bioassay was observed for ~1 min. Feeding activity was noted by the presence of frass, feeding on the leaf margins, and active feeding.

## 2010–2011 Bifenthrin and Carbaryl (Experiment 2, Leaf-Feeding)

Bifenthrin and carbaryl were applied on 9 September 2010 at a second site in Japatul Valley (N 32.78890°, W −116.67892°, elev. 817 m) to determine the durability of treatments (>8 mo postapplication) against *A. auroguttatus* adults. Following the same protocols as experiment 1, 18 *Q. agrifolia* were treated with insecticide (9 bifenthrin and 9 carbaryl) and four trees were designated as untreated controls. All trees were uninfested and possessed minor injury from *A. auroguttatus*. Foliage was collected on 10 May 2010 and 4 May 2011 from bifenthrin- and carbaryl-treated study trees and untreated control study trees. From 16 May to 8 June 2011, 32 no-choice leaf-feeding bioassays were conducted with foliage from all study trees, representing ~8 mo postapplication.

## 2010–2011 Bifenthrin and Carbaryl (Experiment 3, Walking Bioassays)

Fifteen *Q. kelloggii* were selected on private land in Lassen Co., CA (N 40.14772°, W −120.35120°, elev. 1,421 m) for this experiment. On 23 September 2010, three trees each were sprayed on their lower stem (<2 m) with bifenthrin or carbaryl, and the same was done on 11 April 2011 with a different group of trees. An additional three trees were left untreated. The current zone of *A. auroguttatus* infestation does not include this region of California, so *Q. kelloggii* study trees were clean of *A. auroguttatus* and apparently free of other insects and diseases. On 28 April 2011, each study tree was felled and a treated portion of the main stem was cut for use in no-choice walking bioassays with *A. auroguttatus* adults. *Quercus kelloggii* logs were cut to ~46 cm long by 15 cm diameter for use in the bioassays. Thirty-six (36) adult no-choice walking bioassays were conducted from 20 May to 8 June 2011 with *Q. kelloggii* logs, representing ~1 and 8 mo postapplication. The same aforementioned protocols were followed from experiment 1 for the no-choice walking bioassays.

## 2011 Lambda-Cyhalothrin and Permethrin (Experiment 4, Leaf-Feeding and Walking Bioassays)

We applied lambda-cyhalothrin (Warrior 2 with Zeon Technology [Syngenta Crop Protection, Inc., Greensboro, NC]) and permethrin (Astro [FMC Professional Solutions]) on 5 May 2011 to a third site in Japatul Valley (N 32.76365, W −116.72538, elev. 815 m). Following the previously mentioned protocols, 30 uninfested and lightly infested *Q. agrifolia* were treated with either lambda-cyhalothrin (16 trees) or permerthin (14 trees). Six *Q. agrifolia* were designated as untreated controls at the site. On 9 May 2011, three *Q. agrifolia* logs were treated with lambda-cyhalothrin, four logs were treated with permethrin, and two logs were treated with carbaryl for walking bioassays with *A. auroguttatus* adults. Applications of lambda-cyhalothrin and permerthin were applied using the maximum label rate for wood-boring pests (lambda-cyhalothrin: 189 ml $ha^{-1}$/75 ml 0.4 $ha^{-1}$, permerthin: 4,730 ml 378 $liter^{-1}$). Logs were felled from the CNF, Descanso Ranger District. Two *Q. agrifolia* logs were designated as untreated controls and all logs were ~46 cm in length and 10–20 cm in diameter.

Foliage was collected on 26 May 2011 and 9 May 2012 from lambda-cyhalothrin- and permethrin-treated study trees and untreated control study trees. In 2011 and 2012, 99 (2011: 61 and 2012: 38) no-choice leaf-feeding bioassays were conducted with foliage from all study trees to assess the impact of each treatment on *A. auroguttatus* adult survival and feeding. Bioassays were monitored for a maximum of 14 d from 26 May to 8 June 2011 (~<1 mo postapplication, ranging from 21 to 33 d) and 5 May to 12 June 2012 (~12 mo postapplication), or until the beetle died. Twenty-eight (28) walking bioassays were conducted from 12 May to 8 June 2011 with lambda-cyhalothrin and permethrin ~<1 mo postapplication (ranging from 7 to 33 d postapplication). No-choice feeding and walking bioassays followed the same protocols as experiment 1.

## Statistical Analysis

Three individual analyses were conducted to assess adult survival and frass produced per day in the no-choice leaf-feeding bioassays because experiments 1, 2, and 4 were conducted at different times and locations and included individual untreated control trees. A treatment by date interaction was detected for adult survival in experiment 1 and adult survival and frass produced per day in experiment 4 in the adult no-choice leaf-feeding bioassays, leading us to compare treatment effects at each leaf sampling period postapplication. Multiple bioassays were conducted on individual replicates for the leaf-feeding and walking bioassays; as a result, we considered each bioassay a subsample and pooled those from a single study tree or log to make up each replicate. For the walking bioassays, three individual analyses were conducted to assess beetle survival because not all treatments were included in the experiments (experiments 1 and 3: carbaryl and bifenthrin vs. experiment 4: lambda-cyhalothrin, permethrin, and carbaryl) and different tree species were represented in some of the experiments (experiments 1 and 4: *Q. agrifolia* vs. experiment 3: *Q. kelloggii*). A treatment by date interaction was not detected for adult survival in the *Q. kelloggii* walking bioassays from experiment 3. As a result, we compared only the effect of treatments on adult survival. All analyses employed a general linear model to assess differences in each univariate response variable (tree diameter, survival, and amount of frass produced; PROC GLM, SAS Institute 2004). Due to the unequal replicates in all analyses the type III sum of squares were reported. Statistical significance was defined as $P \leq 0.05$ and SAS 9.2 was used for all statistical analyses. Assumptions of normality were checked for all data using the Shapiro–Wilk test (PROC UNIVARIATE, SAS Institute 2008), and heterogeneity of variances were checked by comparing residuals (PROC UNIVARIATE). Significant treatment differences were assessed using the REGWQ means comparison ($\alpha = 0.05$).

## Results

### 2010–2011 Bifenthrin and Carbaryl (Experiments 1, 2, and 3)

Mean (±s.e.) diameter of the bifenthrin-treated trees (100.6 [±8.00] cm DBH) and carbaryl-treated trees (99.2 [±13.7] cm DBH) were greater than untreated control trees (54.6 [±3.91]) in experiment 1 ($F_{2,\ 15} = 4.47$, $P = 0.03$). A significant treatment by date postapplication interaction was detected for adult survival in the leaf-feeding bioassays ($F_{5,\ 36} = 31.2$, $P < 0.0001$), and therefore analyzed separately. Bifenthrin and carbaryl significantly reduced the number of days adults lived (typically lived <2 d) when compared to the untreated trees (lived 18 d), representing a 94 and 86%, respectively, reduction in survival compared to controls ($P < 0.0001$; Fig. 1A). Bifenthrin was significantly more lethal to adults than carbaryl <1 mo postapplication (Fig. 1A). Twelve-months postapplication, beetles lived for ~7 d in the insecticide bioassays compared to ~13 d for the controls (Fig. 1B). In these bioassays, adult survival was reduced by 46% in the bifenthrin treatments and by 40% in the carbaryl treatments when compared to untreated controls. The overall model was not significant for the amount of frass produced per day by adults in the bioassays from experiment 1 ($F_{5,\ 36} = 2.14$, $P = 0.08$). However, adults fed more on the untreated control leaves than either on bifenthrin- or carbaryl-treated trees, respectively, <1 mo and 12 mo postapplication (Table 1).

Mean (±s.e.) diameter of the treated trees was not statistically significant in experiment 2 (bifenthrin-treated trees: 46.6 [±3.41] cm DBH, carbaryl-treated trees: 47.3 [±4.81] cm DBH, and untreated trees: 38.7 [±4.84] DBH; $F_{2,\ 22} = 0.85$, $P = 0.44$). Eight-months postapplication, adult survival was 48% less in the bifenthrin (living 6 d) treatments compared to the untreated controls (living 12 d), but this only bordered on significance ($P = 0.06$; Fig. 2). The amount of frass produced was significantly lower in bioassays with bifenthrin (92%)-treated foliage than in untreated controls at 8 mo postapplication (Table 1).

In the 2010 adult no-choice walking bioassays (experiment 1), adult *A. auroguttatus* lived ~2 d with carbaryl-treated logs, 5 d with bifenthrin-treated logs, and 7 d with untreated logs (Fig. 3A). Adults exposed to carbaryl-treated logs lived significantly fewer days than those exposed to bifenthrin-treated logs (1.8×) and untreated *Q. agrifolia* logs (2.7×). There was not a significant treatment effect for the no-choice walking bioassays in experiment 3, but beetles lived for ~2 d in the insecticide bioassays compared to ~7 d for the untreated controls (Fig. 3B).

### 2011 Lambda-Cyhalothrin and Permethrin (Experiment 4)

Mean diameter of the lambda-cyhalothrin-treated trees (42.7 [±3.68] cm DBH) and permerthin-treated trees (36.1 [±5.31] cm DBH) were significantly greater ($F_{2,33} = 3.65$, $P = 0.04$) than the untreated trees (19.7 [±4.90] cm DBH). A significant treatment by date postapplication interaction was detected for adult survival in the lambda-cyhalothrin and permethrin study ($F_{2,\ 48} = 27.3$, $P < 0.0001$) due to the increase in adult survival from <1 mo to 12 mo postapplication in the insecticide bioassays. One-month postapplication, adults lived less than an average of 2 d in the insecticide bioassays, whereas adults lived ~12 d in the untreated bioassays (Fig. 4A). Adult survival was 86% lower in both the lambda-cyhalothrin and permethrin treatments than in the untreated controls ($P < 0.0001$). Twelve-months postapplication, adults lived ~7 d in the permethrin bioassays, 10 d in the lambda-cyhalothrin bioassays, and 11 d in the untreated bioassays (Fig. 4B). Permethrin significantly decreased adult survival by 32% when compared to lambda-cyhalothrin bioassays and by 35% when compared to untreated bioassays ($P = 0.03$).

The amount of frass produced per day by adults was partially explained by a significant treatment by month interaction ($F_{2,\ 48} = 24.3$, $P < 0.0001$). No frass was produced <1 mo postapplication in bioassays with lambda-cyhalothrin and permethrin ($P < 0.0001$; Table 1). There was no significant effect of insecticides on the amount of frass produced at 12 mo postapplication (Table 1). In the 2011 no-choice walking bioassays, adult survival significantly decreased across all insecticide treatments compared to the untreated logs (Fig. 3C). Adults lived less than 3 d in the insecticide bioassays and mortality was 79%, 57%, and 70% greater in the carbaryl, lambda-cyhalothrin, and permethrin treatments, respectively, when compared to the untreated controls, which lived a mean of 7 d.

## Discussion

In *Q. agrifolia* no-choice leaf-feeding bioassays, contact applications of bifenthrin and carbaryl effectively reduced *A. auroguttatus* adult survival and frass production <1 mo postapplication. Current recommendations for applying contact treatments for *A. auroguttatus* are to treat the main stem and larger branches (>25.4 cm in diameter) without treating the foliage (Coleman et al. 2015). Our results suggest that treating foliage may increase treatment impact of adult *A. auroguttatus* during maturation feeding. Surprisingly, only bifenthrin reduced adult survival in our leaf-feeding bioassays 8 mo postapplication. Carbaryl had no impact on adult survival at 8 mo, but both treatments increased adult mortality and reduced frass production after 12 mo in our *Q. agrifolia* no-choice leaf-feeding bioassays. Lack of impact from carbaryl 8 mo postapplication may be due to the lack of coverage of the foliage during the applications or the limited number of replications tested ($n = 9$), which was due to the availability of study trees on private land. Bark application of carbaryl and bifenthrin provided long-term (two field seasons) protection

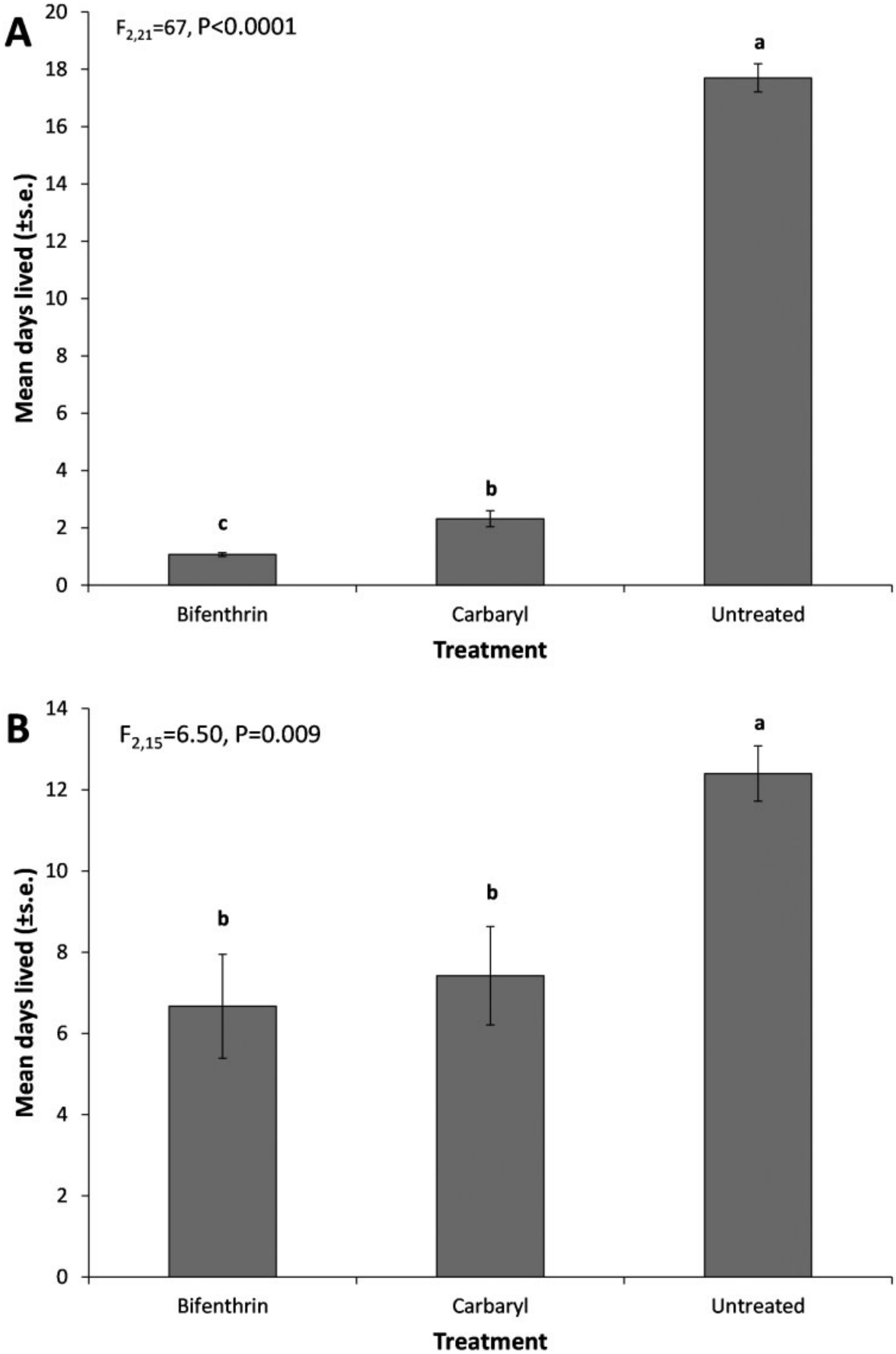


**Fig. 1.** Mean (±s.e.) days goldspotted oak borer, *A. auroguttatus*, adults lived in no-choice leaf-feeding bioassays from experiment 1 with <1 (**A**) and 12 mo (**B**) postapplication of bifenthrin and carbaryl to coast live oak, *Q. agrifolia*, foliage. Different letters above bars note statistically significant differences (REGWQ test).

of pines against the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, and western pine beetle, *D. brevicomis* LeConte (both Scolytinae), in several western states (Fettig et al. 2006a). This suggests that these active ingredients are potentially capable of controlling maturation feeding of *A. auroguttatus* adults for 12 mo on *Q. agrifolia*, but this remains to be tested.

In walking bioassays, *Q. agrifolia* logs treated with carbaryl, lambda-cyhalothrin, or permethrin effectively reduced adult survival <1 mo postapplication. This suggests that application of certain insecticides to the bole and larger branches of oaks may impact emerging adult and ovipositing female *A. auroguttatus* over this time period. A single application of permethrin reduced survival and oviposition of a cerambycid beetle, *Aeolesthes sarta* Solsky, on cut logs of field elm, *Ulmus minor* Mill. (Bijan et al. 2015). In walking bioassays with *Q. kelloggii* logs, carbaryl and bifenthrin had no effect on survivorship because replication was low ($n = 6$). *Agrilus*

**Table 1.** Mean amount (g) of frass (±s.e.) produced per day in no-choice leaf-feeding bioassays with goldspotted oak borer, *A. auroguttatus*, adults following application of four contact insecticides

| Year[a] | Experiment no. | Approximate timing of assay postapplication | Bifenthrin | Carbaryl | Untreated | $F_{df}$ | $P^b$ |
|---|---|---|---|---|---|---|---|
| 2010 | 1 | <1 mo (13–35 d) | 0.002 ± 0.002 | 0 ± 0 | 0.039 ± 0.005 | n.s. | |
| 2010 | | 12 mo | 0 ± 0 | 0.001 ± 0.001 | 0.018 ± 0.004 | n.s. | |
| 2010 | 2 | 8 mo | 0.00004 ± 0.00003b | 0.001 ± 0.0003a | 0.001 ± 0.0004a | $5.96_{2, 21}$ | 0.009 |
| | | | Lambda-cyhalothrin | Permethrin | Untreated | | |
| 2011 | 4 | <1 mo (21–35 d) | 0 ± 0b | 0 ± 0b | 0.036 ± 0.007a | $68.5_{2, 27}$ | <0.0001 |
| 2011 | | 12 mo | 0.016 ± 0.002 | 0.015 ± 0.004 | 0.017 ± 0.005 | $0.12_{2, 21}$ | 0.89 |

All assays were conducted with coast live oak, *Q. agrifolia*, foliage.
[a] Year of insecticide application.
[b] Means ± s.e. followed by the same letters within rows are not significantly different (REGWQ test).

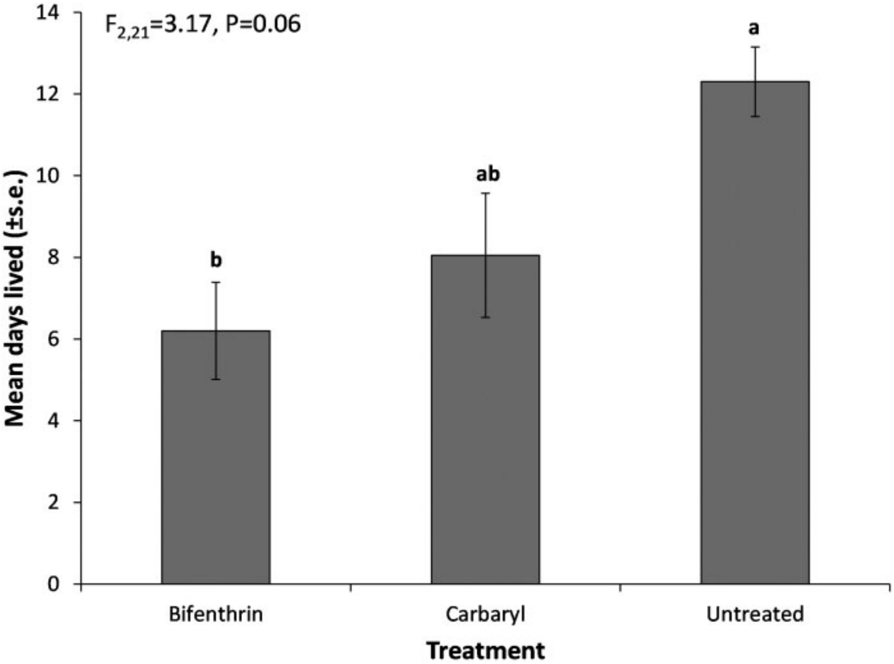


**Fig. 2.** Mean (±s.e.) days goldspotted oak borer, *A. auroguttatus*, adults lived in no-choice leaf-feeding bioassays ~8 mo postapplication of bifenthrin and carbaryl to coast live oak, *Q. agrifolia*, foliage from experiment 2. Different letters above bars note statistically significant differences (REGWQ test).

*auroguttatus* pupate directly under the bark, but it is unknown if contact applications would impact adult emergence from living trees. However, applications of bifenthrin and permethrin effectively decreased adult emergence of *A. planipennis* (90%) when applied to cut logs (Petrice and Haack 2006), so possible effects on emerging adults might be similar in our system. Application of insecticides to cut logs is generally not recommended for preventing emergence of *A. auroguttatus* adults because other options are available for controlling adult emergence from cut wood (Jones et al. 2013).

Treatment of *Q. agrifolia* foliage with lambda-cyhalothrin or permethrin reduced adult survival and frass production ~<1 mo postapplication in no-choice leaf-feeding bioassays. However, at 12 mo postapplication, only adult survival was impacted while frass production was not. Fettig et al. (2006b) report protection of lodgepole pine, *Pinus contorta* Dougl. ex Loud., from *D. ponderosae* for one field season with permethrin plus-C.

*Agrilus auroguttatus* kill trees more slowly than do some exotic insect pests, and when combined with the lack of an effective attractant, insecticide efficacy studies are difficult to successfully conduct. Oak tree mortality and growth of *A. auroguttatus* populations may take several years to manifest, and thick phloem and bark of *Q. agrifolia* and *Q. kelloggii* is not easily removed. Furthermore, small-diameter branches and trees are not attacked. Although the mean diameter of study trees differed across treatments in experiments 1 and 4, this was not a major issue since controlled laboratory bioassays were used to assess treatment effects. We did not observe tree mortality in these tests because study trees possessed no or low levels of *A. auroguttatus* injury. Combined with the lack of attractant through which to modify attack behavior, we could not directly test treatment effect for preserving live trees (efficacy) using established protocols. Future field studies should include oaks with similar diameter distributions because of the increased risk of *A. auroguttatus* to larger-diameter trees and incorporate larger sample sizes to reduce variability within treatments. Our laboratory studies support the annual application of these contact insecticides in early to mid-May to reduce survival of *A. auroguttatus* adults during maturation feeding. Future studies may incorporate surfactants to enhance the longevity of contact applications (see McCullough et al. 2011).

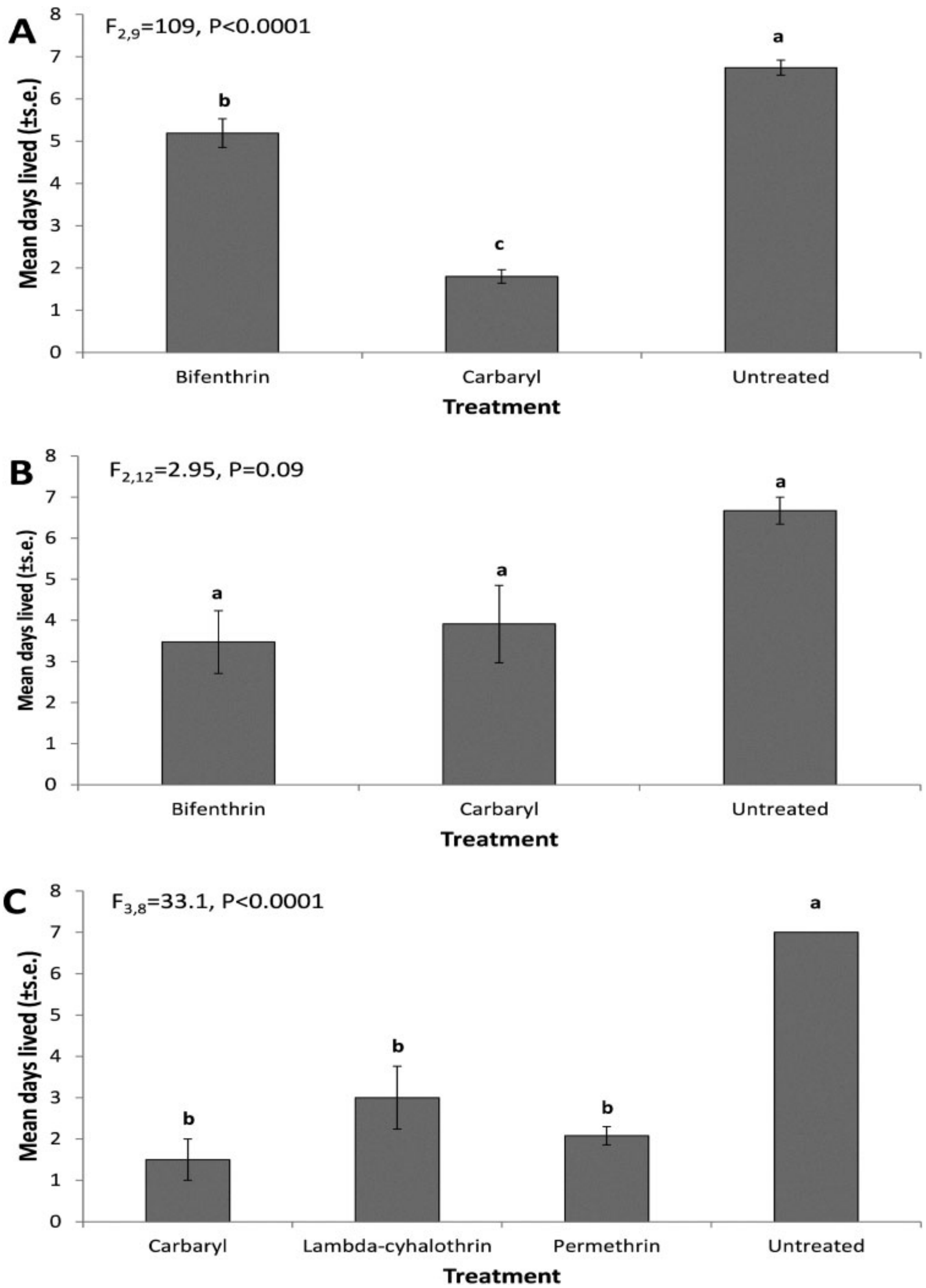


**Fig. 3.** Mean (±s.e.) days goldspotted oak borer, *A. auroguttatus*, adults lived $\sim<1$ mo following application of contact insecticides to coast live oak, *Q. agrifolia*, in 2010 (**A**, experiment 1); California black oak, *Q. kelloggii*, in 2011 (**B**, experiment 3); and *Q. agrifolia* logs in 2011 (**C**, experiment 4) and untreated logs of the same species in no-choice walking bioassays. Different letters above bars note statistically significant differences (REGWQ test).

The choice of treatment with contact or systemic insecticides depends upon management objectives. Both application methods have advantages and disadvantages, which may make them more or less desirable in particular situations (e.g., length of application time, cost of chemical, lag time for control, impact to nontarget species, risk to applicators, spray drift, equipment required for applications, durability, and previous insect injury to the tree). However, few studies have addressed the use of contact insecticides for protecting trees from exotic wood borers (but see Herms et al. 2014). Because pyrethroid insecticides (e.g., bifenthrin, lambda-cyhalothrin, and permethrin) had a similar impact as carbaryl, a carbamate, in our bioassays <1 mo postapplication, the choice of product can be made based upon other parameters, such as cost, amount of product used, environmental toxicity, and persistence in the environment. Concerns over spray drift and proximity to developed sites, different land ownerships, and environmentally sensitive areas will dictate if sprays should be applied to the main bole and larger branches or the entire tree. In forest ecosystems, insecticidal sprays have a long history of safe and effective use, especially for protecting trees from bark beetle attacks (e.g., Fettig et al. 2013).

Combining contact and systemic insecticides may be an effective treatment option for high-value oaks (Chen et al. 2015), but this

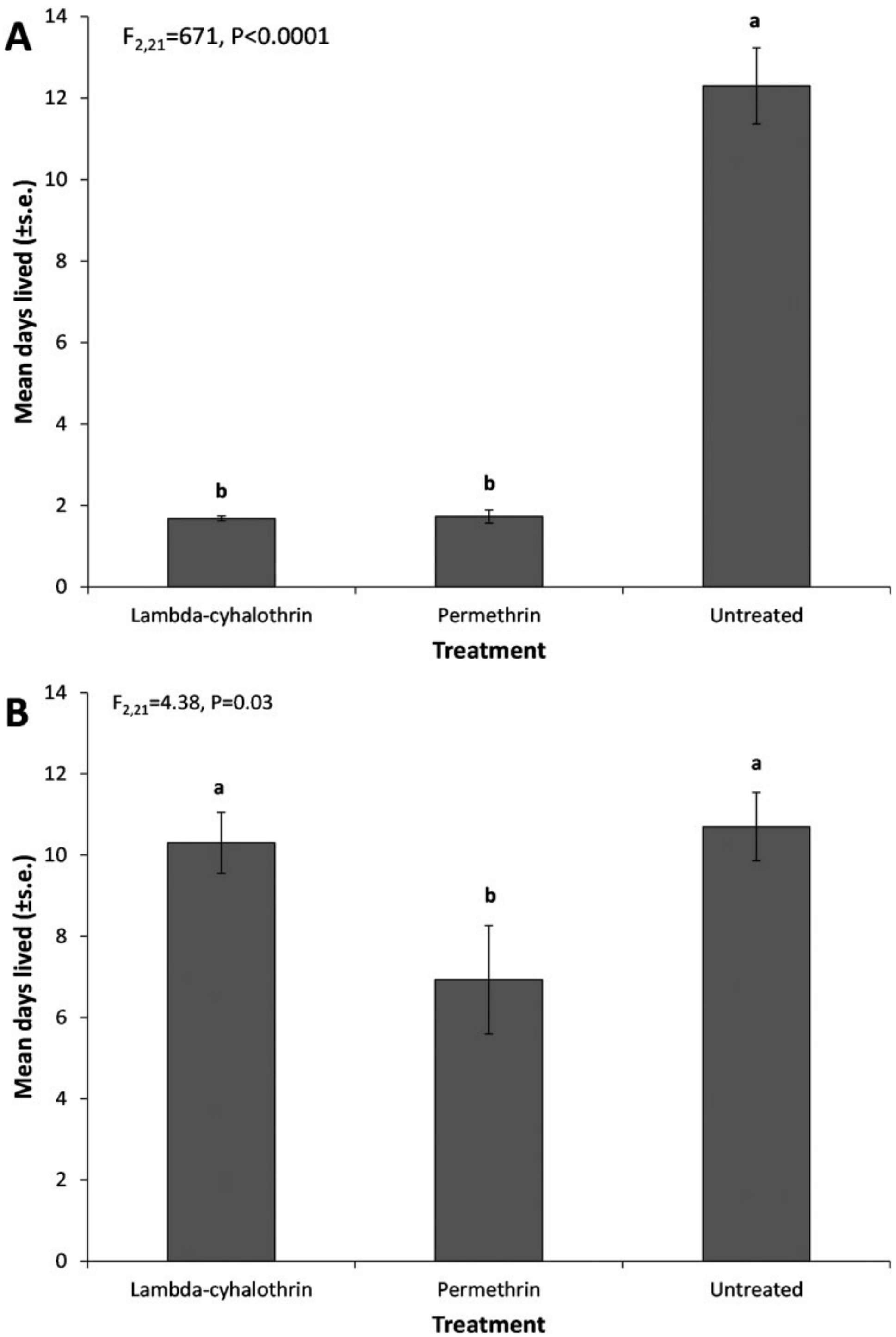


**Fig. 4.** Mean (±s.e.) days goldspotted oak borer, *A. auroguttatus*, adults lived in no-choice leaf-feeding bioassays with <1 (**A**) and 12 mo (**B**) postapplication of lambda-cyhalothrin and permerthrin to coast live oak, *Q. agrifolia*, foliage (experiment 4). Different letters above bars note statistically significant differences (REGWQ test).

approach has not been adequately assessed, only having been recently applied in response to the satellite infestation in Orange Co. where an aggressive management tactic was desired. Adopting a strategy from the SLow Ash Mortality (SLAM, McCullough and Mercader 2012) program where only a proportion of the susceptible oaks are treated during a year may be beneficial for maintaining short-term management objectives (e.g., tree canopy closure and a reduction in hazard trees) for campgrounds, parks, and communities in southern California. As the infestation and oak mortality spreads in southern California, land managers are developing longer-term management strategies for preserving high-value sites, providing the opportunity to incorporate and test components of an integrated pest management program, which may include detection trapping, tree health assessments, management of infested wood material, and contact insecticides. Results of this study show that insecticides sprayed onto oak foliage or bark can affect adult *A. auroguttatus* maturation feeding and oviposition for up to 12 mo postapplication. However, additional studies are needed to determine if annual applications of a contact insecticide can preserve living oaks from the exotic phloem borer.

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