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Sanitation Options for Managing Oak Wood Infested With the Invasive Goldspotted Oak Borer (Coleoptera: Buprestidae) in Southern California

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ABSTRACT Movement of invasive wood-boring insects in wood products presents a threat to forest health and a management challenge for public and private land managers. The goldspotted oak borer, *Agrilus auroguttatus* Schaeffer (Coleoptera: Buprestidae), is a new pest in San Diego and Riverside Cos., CA, believed to have been introduced on firewood. This beetle has caused elevated levels of oak mortality since 2002. From 2009–2011, we tested several sanitation methods, applicable to large and small land parcels, to reduce or prevent goldspotted oak borer emergence from infested oak wood. In most experiments, emergence of goldspotted oak borer adults from the positive controls demonstrated that the beetle could complete development in firewood-sized pieces of cut oak wood. In 2009, adult emergence from sun-exposed oak wood began and peaked 2- to 4-wks earlier at a low elevation site than at a high elevation site (late May to late June). However, there were no significant effects of elevation or host species on the emergence response of goldspotted oak borer by solarization treatment in this study. Solarization of infested wood with thick (6 mil) and thin (1 mil) plastic tarpaulins (tarps) did not significantly reduce emergence of adults despite recordings of greater mean and maximum daily temperatures in both tarped treatments and greater relative humidity in the thick-tarped treatment (all compared with nontarped controls). Grinding wood with a 3"-minus screen (≤7.6 cm) significantly reduced goldspotted oak borer emergence compared with control treatments, and this was the best method for reducing adult emergence among those tested. In a separate grinding study, no adults emerged when wood was ground to 9"-minus (22.9 cm), 2"-minus (5.1 cm), or 1"-minus (2.5 cm) screen sizes, but a low level of adult emergence from the positive controls limited any inferences from this experiment. Debarking cut wood pieces eliminated goldspotted oak borer emergence from the wood fraction, but adults emerged from the shaved bark and phloem.

KEY WORDS debarking, firewood, grinding, oak mortality, solarization

Invasive species represent a significant threat to forests in North America and the introduction of exotic forest pests has increased with the growth of international commerce (Haack 2006, Moser et al. 2009). Two recent invaders in the northeastern and midwestern United States, the Asian longhorn beetle, *Anoplophora glabripennis* Motschulsky (Coleoptera: Cerambycidae), and the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), demonstrate the potential ecological and economic damage posed by wood-boring species (Poland and McCullough 2006, Dodds and Orwig 2011). Slowing the spread of exotic forest insects is imperative for sustaining long-term forest health.

Invading species are often dispersed through movement of wood products, nursery stock, and firewood (Yates et al. 1981, Galford 1984, Haack et al. 2010, Jacobi et al. 2012). In California, wood borers (Buprestidae and Cerambycidae) in cut wood account for the majority of insects detected at regulatory border stations (Bokach et al. 2011). Treatment of wood products, federal and state quarantines, and outreach/education have been suggested as management strategies for slowing and reducing the spread of populations of invasive woodborers (Haack and Acciavatti 1992, Mayfield 2007, USDA Animal and Plant Health Inspection Service [APHIS] 2010). However, regulating the movement of wood, especially the small

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quantities transported as firewood, can be difficult to enforce and monitor. Eliciting and obtaining public interest and involvement have proved to be additional hurdles.

Firewood movement was likely responsible for the introduction of the goldspotted oak borer, *Agrilus auroguttatus* Schaeffer, into San Diego Co., CA, from its native region of southeastern Arizona or northern Mexico (Coleman and Seybold 2011, Coleman et al. 2012a). First described in 1905 from specimens collected in Arizona, goldspotted oak borer was never considered a threat to forest health or an economically important pest in its native region. It was absent from a major compendium on forest insects of the western United States (Furniss and Carolin 1977), and no life history information was known for goldspotted oak borer until 2008, when it was first linked to tree mortality in California (Coleman and Seybold 2008a,b). The goldspotted oak borer was first collected in 2004 in California and is considered to be invasive to this region (Coleman and Seybold 2011, Coleman et al. 2012b).

Since its introduction, the goldspotted oak borer has killed tens of thousands of oak trees in and adjacent to the Descanso Ranger District, Cleveland National Forest (CNF), Cuyamaca Rancho State Park, and several communities in San Diego Co. (Coleman and Seybold 2008a,b; Coleman et al. 2012b). Elevated levels of oak mortality have continued since 2002, covering an estimated 213,000 ha (USDA Forest Health Monitoring [FHM] 2011). The zone of infestation and tree mortality is located primarily in eastern San Diego Co. However, two known satellite infestation were detected in 2009 in urban San Diego and 2012 in Riverside Co., CA which are hypothesized to have resulted from the movement of infested cut wood (Coleman and Seybold 2011). Several native species of oaks in California are being killed by the goldspotted oak borer, but large diameter coast live oak, *Quercus agrifolia* Née, and California black oak, *Q. kelloggii* Newberry, are the preferred hosts (Coleman et al. 2012b).

The goldspotted oak borer is believed to be univoltine with peak adult emergence occurring from late-June to early July in southern California (Coleman and Seybold 2008b), although longer development times may occur in healthier hosts as with other *Agrilus* (Poland and McCullough 2006). Several generations can develop in large trees. Adults lay eggs singly or in clusters on the outer bark in cracks and crevices (T.W.C., unpublished data). First-instar larvae hatch and tunnel from the bark surface into the phloem, likely completing four instars, similar to other *Agrilus* in North America (Haack and Acciavatti 1992, Katovich et al. 2000, Poland and McCullough 2006). Larval feeding is concentrated on the main stem and larger branches of oaks at the surface of the xylem, but the larvae also injure the cambium and phloem (Hishinuma et al. 2011). Larvae are present year round under the bark (L.J. Haavik, Canadian Forest Service, personal communication), but prepupae are found predominantly in the outer phloem during the dormant season (October to May). Pupation occurs in early May in southern California. The quiescent, mature, and relatively resistant life stages in the outer phloem make the movement of cut wood a significant threat for spreading this new pest species.

After several years of extensive and repeated bouts of larval feeding, tree health declines and trees eventually succumb (Coleman and Seybold 2008a, Coleman et al. 2011). The area of oak mortality has continued to expand from the hypothetical point of origin in eastern San Diego Co. (Coleman et al. 2012b) and is impacting a wide variety of land ownerships. The distributions of goldspotted oak borer's preferred hosts extend north from northern Baja California Norte, Mexico through California up to southern Oregon. The spread of the goldspotted oak borer into residential communities portends the potential for a significant increase in expenditures for prophylactic treatments and the management of dead trees by local governments and private landowners. For example, the Resource Conservation District of Greater San Diego Co. (2010) received three million dollars to mitigate hazard trees in communities near the heart of the goldspotted oak borer infestation. The high probability of continued range expansion through flight dispersal or human-assisted dispersal via infested cut wood represents a significant threat to forest health throughout California and southern Oregon.

Oak firewood is a valuable commodity in southern California and no quarantines currently restrict the movement of this wood from the goldspotted oak borer zone of infestation. Therefore, preventing the movement of goldspotted oak borer-infested wood can be a challenge. Additionally, the California Board of Forestry does not regulate timber management in oak woodlands. These features, coupled with the absence of a substantive timber industry in this area of the state; low economic return for biomass products; and reduced road access for removal of large-diameter oaks across the landscape limit utilization options and the economic return for trees killed by this new woodboring pest. Thus, firewood harvesting is the most profitable disposal option for goldspotted oak borer-killed oaks (L. Swan, USDA Forest Service, PNW Region, personal communication). Effective mitigation measures for cut wood are necessary to reduce the long-distance spread of the goldspotted oak borer to new areas in California and the United States.

Our objective was to test the efficacy of several sanitation methods to assist landowners in reducing and eliminating goldspotted oak borer populations in cut oak wood. We tested three types of treatment for goldspotted oak borer-infested wood including: Solarization with thin and thick tarpaulins (tarps), various mechanical grinding treatments, and manual debarking of cut wood. We hypothesized that the solarization, grinding, and debarking treatments would successfully eliminate or significantly reduce goldspotted oak borer populations in the infested wood. If arborists, foresters, land managers, and tree removal companies can be provided with efficacious and feasible management options for sanitation of goldspotted oak borer-infested wood, the risk of infested wood leaving the zone of infestation could be greatly reduced.

Materials and Methods

Solarization Experiments. Solarization treatments were conducted during 2008–2010 on the Descanso Ranger District, CNF in San Diego Co. All experiments used wood from trees showing extensive goldspotted oak borer injury, that is, D-shaped emergence holes and meandering larval feeding on the xylem surface (Coleman et al. 2011, Hishinuma et al. 2011). The wood sections for these experiments were from trees that had been felled within 6 mo of treatment.

2009 Treatments. This experiment used goldspotted oak borer-infested wood from a total of 11 *Q. agrifolia* and *Q. kelloggii* trees (all >50 cm DBH, diameter at breast height) collected from the Descanso Fire Station, Desert View Picnic Area, and Burnt Rancheria Campground (CNF); and Julian Estates Community and William Heise County Park in Julian, CA. Felled trees were cut into rounds (<0.5 m in height), large rounds were split into quarters, and then randomized within a species before a treatment was assigned. The goldspotted oak borer favors the lower part of the main stem (Coleman et al. 2011, Haavik et al. 2012), so pieces of wood from this part of the stem were preferred when sampling from felled trees. Each woodpile, or replicate, contained six to eight pieces of cut wood, which was standardized by filling a 0.54 m^3 aluminum wire screen bag. The barked surface area of each piece was ≈293 cm^2. Treatments were initiated between November 2008 and April 2009, and they were randomly assigned to replicates and then partitioned between two sites. These sites were chosen to assess the effect of treatment, species, and elevation on the emergence of goldspotted oak borer adults. Experiments were carried out at: 1) Glencliff Fire Station (CNF), 1,005 m = low elevation and 2) Camp Ole Fire Station (CNF), 1,676 m = high elevation. Number of replicates varied between the low and high elevation sites. Treatments included: 1) direct sunlight ($n = 10$, low and $n = 4$, high); 2) thick tarp (6 mil clear polyurethane plastic sheeting; Husky; Grand Prairie, TX) covering and exposed to direct sunlight ($n = 10$, low and $n = 4$, high); and 3) fully shaded controls ($n = 11$, low and $n = 8$, high). The replicates were separated by 1 m and laid out in two transects (spanning 0.1 ha), whereas the shaded controls were similarly spaced in a third transect in full-shade under adjacent conifer trees at the same site.

2010 Treatments. This experiment used goldspotted oak borer-infested wood from six *Q. agrifolia* (all >50 cm DBH) felled at William Heise County Park. Cut wood (<0.5 m in height) was partitioned into piles containing eight quarter pieces, and then randomized among one of three treatments. Studies were carried out only at low elevation at the Glencliff Fire Station (CNF) site. Treatments were initiated from 22 March to 28 April 2010, and they included: 1) thick tarp (6 mil clear polyurethane plastic sheeting) exposed to direct sunlight ($n = 8$); 2) thin tarp (1 mil clear polyurethane plastic sheeting) exposed to direct sunlight ($n = 8$); and 3) exposed to direct sunlight only (control treatment, $n = 6$). The 2010 controls were established in direct sunlight because no significant differences in adult emergence were recorded between direct sunlight and shaded control treatments in the 2009 solarization study (see Results section).

Specific Procedures for 2009 and 2010 Solarization Experiments. During both years, cut wood from all treatments was enclosed in aluminum wire screen bags (1.22 × 1.22 × 0.36 m) to facilitate collection of emerging goldspotted oak borer adults. Three sides of the screen bags were folded and sealed with metal staples, whereas one side was folded-over and sealed with metal binder clips for a sampling entry point. Clear plastic tarps, were double-layered and placed over the aluminum mesh for all tarped treatments. Tarps were held in place by burying the edges under soil.

Adult sampling began in late March and continued until late August during both years. In the 2009 study, treatments were sampled weekly for the first month after the initial emergence of goldspotted oak borer adults and then every 2 wk. Tarped treatments were sampled sporadically throughout the year in 2010 to limit disturbance of the treatments. Adults were collected by using aspirators and forceps, and then returned to the lab for identification. Treatments were dismantled in late August during both years and any goldspotted oak borer adults that were previously undetected were collected from the bottom of the enclosures.

Temperature (°C) and relative humidity (%) were monitored every 2 h in a 24-h period with three data loggers (HOBO, Onset, MA). At least one data logger was placed in a replicate for each treatment from April to September 2009 (a total of 172 d) with all data loggers located at the low elevation site. In 2009, one replicate from each treatment was monitored; in 2010, six data loggers were used and they recorded only temperature every 2 h from 1) two thin-tarped replicates and 2) one replicate each of the control and thick-tarped treatments. More data loggers were used in the thin-tarped replicates because temperature data were recorded on the wood surface (air) and the outer phloem of the logs. In 2010, temperature data were recorded from April to August (a total of 109 d).

Grinding Experiments. From 2009–2011, three grinding studies were conducted at Glencliff Fire Station and Cuyamaca Rancho State Park (both low elevation sites). Wood used for these experiments was procured and handled as it was for the solarization experiments. Wood pieces from mature *Q. agrifolia* that had been severely injured or recently killed by goldspotted oak borer were collected from Pine Creek Trailhead, CNF in 2009 and Green Valley Campground, Cuyamaca Rancho State Park in 2011.

Experiment 1. Wood from the main bole of a single felled *Q. agrifolia* (69.1 cm DBH) was cut, partitioned into piles containing approximately eight pieces of cut wood (<0.5 m in height), and then randomized into

Fig. 1. Adults and adult clay models of the goldspotted oak borer, *Agrilus auroguttatus*, used to determine the percentage of injury after a 3″-minus screen grinding treatment in 2010. (Online figure in color.)

two treatments: 3“-minus grinding screen (≤7.6 cm) and control (no mechanical treatment). All grinding was carried out on 23 November 2009 by using a 3 m tub grinder (Imperial Valley Resource Recovery, Brawley, CA). The ground wood was collected and partitioned into individual replicates (n = 8 for 3“-minus screen; n = 6 for controls) at the Glencliff Fire Station on 2 December 2009. Both the cut wood (controls) and ground wood were enclosed in aluminum-screened bags as described for the solarization studies. Control logs were left as rounds or quarters to mimic the size and shape of regular firewood pieces and stacked to prevent obstruction of the exterior bark. Temperature (°C) was monitored with four data loggers at 2-h intervals in a 24-h period from April to August 2010 (a total of 112 d). Temperature data were recorded from two grind replicates at the surface of the grind piles (air) and at a depth of ≈25.0 cm in each pile. Emerging adults were sampled by hand every 2 wk from May to August 2010. The grind was sifted at the termination of the study in late August by hand and any additional adults were collected.

To estimate the percentage of damaged goldspotted oak borer life stages during the 3“- minus grinding treatment, clay (Sculpey, Polyform Products, Elk Grove Village, IL) replicas of goldspotted oak borer adults were inserted into four coast live oak logs (≈60 cm long × 30 cm diameter) and ground with the infested wood. One hundred models were stamped from a mold of a goldspotted oak borer adult, baked at 157°C to maintain shape, and painted day-glow orange to ease detection in the grind (Fig. 1). Twenty-five holes (0.3 cm in diameter) were drilled randomly into each log to a depth of ≈2.5 cm in the outer phloem. Adult models were inserted into the logs and sealed with bark shavings and wood glue. Models and fragments of models were collected at three intervals: After the grinding treatments; during the partitioning of grind into replicates; and upon termination of the study.

Experiments 2 and 3. Two separate studies were established in 2011 at Cuyumaca Rancho State Park with wood from 23 *Q. agrifolia.* Both studies used a 3 m tub grinder (Viramontes Express, Corona, CA) at Puerta La Cruz Conservation Camp, CA Department of Forestry and Fire (San Diego Co., CA). The first study (established 7 January 2011), included three treatments and a control: 1) 9“-minus screen (22.9 cm); 2) 2“-minus screen (5.1 cm); 3) 1“-minus screen (2.5 cm); and 4) an untreated control. 9“-minus, 2“-minus, or 1“-minus ground material from each individual treatment was partitioned into 10 replicates (≈2.5 m^3/replicate). The second 2011 grind study (established 28 March 2011) re-tested goldspotted oak borer adult emergence between a 3“-minus screen grinding treatment and an untreated control, as in experiment 1. Grind from the second 2011 study was partitioned into seven replicates (2.0 m^3/ replicate). Separate control groups were established for the two experiments (10 replicates for experiment 2 and seven replicates for experiment 3). Control logs were left as rounds or quarters and stacked to prevent obstruction of the exterior bark. Control replicates contained approximately 10 pieces of cut wood in each grinding study. Temperature (°C) was monitored in the 9“-, 2“-, and 1“-minus treatments with six data loggers (two data loggers/treatment). Data loggers recorded temperature on the surface of the pile and at a depth of ≈25.0 cm in each pile. Two data loggers recorded temperature on the surface (air) and within the bark of the control logs. All data loggers recorded at 2-h intervals in a 24-h period from 28 February to 22 August 2011 (a total of 207 d).

In 2011, grinding and control treatments were enclosed in no-see-um insect netting cages (399 × 399 cm, Mombasa, Arlington, TX) beginning on 2 February for the first study with multiple grinding treatments and on 8 April for the second study with only the 3"-minus treatment. Netting for the cages was supported by a 1.5 m length of 2 cm diameter aluminum conduit held in place by a 1 m long × 0.13 m diameter piece of rebar driven into the soil. The edges of the netting were covered with soil and the cage opening rolled-up and affixed with several metal clamps to prevent escape of emerging adults. Treatments were sampled every week from 28 April to 29 June and every 2 wk thereafter until 29 August 2011. The study was terminated and dismantled in late August and any previously undetected goldspotted oak borer adults were collected from the bottom of the enclosures or from the grind.

Debarking Experiment. Ten goldspotted oak borer-infested *Q. agrifolia* (all >50 cm DBH) were cut from the Descanso Ranger District, CNF from 14 to 31 March 2011. The lower boles were collected from the felled trees and randomized among three treatments: 1) shaved bark and phloem; 2) debarked wood; and 3) untreated control logs. All wood was split by hand into firewood-sized pieces (each piece was ≈30.5 long × 12.5 cm diameter). Approximately eight pieces of cut wood were equally partitioned into each replicate. The volume of wood in each replicate was standardized visually. Wood for the debarking treatments had >95% of the bark and phloem removed, and no phloem >1 cm in thickness remained on the xylem surface. We removed the bark and phloem by hand with an axe, and attempted to minimize the removal of xylem. Due to the moist, freshly cut wood, all of the phloem was not easily removed from the xylem. Debarked wood and untreated controls were enclosed in insect netting cages following the same protocols as the 2011 grinding studies. For the third treatment (shaved bark and phloem removed from debarked wood) the material was placed into separate aluminum screen bags following the same methods as the solarization studies. Treatments were established 12 April 2011 at Cuyumaca Rancho State Park and monitored during the same intervals as the 2011 grinding studies. No temperature data were recorded from treatments in this study.

Statistical Analyses. Most statistical procedures were conducted with a critical level of $\alpha = 0.05$ with SAS 9.2 (SAS Institute 2008). Exceptions are noted below. A generalized linear model was used to compare differences in goldspotted oak borer adult emergence among the solarization and 3"-minus grinding treatments to untreated controls within the same year of the study (PROC GLM). Homogeneity of variances was checked by comparison of residuals and assumptions of normality were checked for all data by using the Shapiro–Wilk test (PROC UNIVARIATE). Overall tests of significance were determined and means were compared by using the REGWQ procedure (Day and Quinn 1989). In the 2009 solarization study, species, elevation, treatment, and the corresponding interaction effects were analyzed by using the previously mentioned procedures. No significant interactions were detected among the effects, so data were pooled across species and elevation. Adult emergence data were not normally distributed for 3"-minus grinding studies (experiments 1 and 3), so $[\text{Log}_{10}(x + 1)]$ transformations were used to meet assumptions of normality and means were compared with the transformed data. The high proportion of zero responses in the data sets for the 9"-, 2"-, and 1"-minus grinding study (experiment 2) and the debarking study created circumstances where neither the assumptions of normality nor homogeneity of variance could be met. As a consequence, these data sets were analyzed by using a Kruskal–Wallis nonparametric analysis of variance (ANOVA) followed by a Tukey-Type multiple comparison by using the Nemenyi Test (Zar 2010, Elliot and Hynan 2011). Temperature and relative humidity data were analyzed with a repeated measures mixed model ANOVA with an autoregressive covariance structure (PROC MIXED). Mean and maximum daily temperatures were compared among all treatments within a year.

Results

Solarization Experiments. In total, 285 beetles were collected during the 2009 solarization experiment. Mean goldspotted oak borer emergence was highest in the untarped, direct sunlight treatment and lowest in the shaded control, but these differences were not significant (Table 1A). None of the treatments prevented or even reduced beetle emergence. Adult emergence began 2 wk earlier in the solarization treatments at the low elevation site (22 May 2009) and 4 wk earlier at the high elevation site (4 June 2009) when compared with the shaded control replicates at both sites (data not shown). Adult emergence spanned from 22 May to 24 August 2009 across all treatments with peak emergence occurring from 20 to 27 May for the solarization treatments at low elevation and from 18 to 25 June for the solarization treatments at the high-elevation site. Adult emergence peaked from 12 to 19 June 2009 in the shaded controls at the low elevation site. The experiment demonstrated that goldspotted oak borer could complete its development and emerge from firewood-sized pieces of oak.

In 2009, there were significant treatment effects on mean and maximum daily temperature and on relative humidity (Table 2A). Mean and maximum daily temperature and relative humidity in the thick-tarped treatments were significantly higher when compared with the other treatments (Table 2A). The highest temperature recorded was 69.1°C from the thick-tarped treatments (29 August, between 1145 and 1345

Table 1. Mean (±SE) emergence of adult goldspotted oak borers, *Agrilus auroguttatus*, following solarization or 3″-minus grinding techniques with infested oak wood in southern California

	Study	Year	Treatment				ANOVA[a]	
							$F_{d,f}$	P
A.	Solarization							
			Control (shade)	Direct sunlight	Thick-tarped	—		
		2009	5.75 (±0.8)	7.5 (±2.15)	6.14 (±0.97)	—	$0.25_{2,41}$	0.776
			Control (sun)	—	Thick-tarped	Thin-tarped		
		2010	21.5 (±1.78)	—	22.6 (±7.05)	10.6 (± 3.30)	$1.86_{2,19}$	0.184
B.	Grinding							
			Control	3″-minus				
	(exp. 1)	2010	3.7 (±2.08)a	0.0 (±0)b			$22.2_{1,12}$	<0.001
	(exp. 3)	2011	12.6 (±2.57)a	0.0 (±0)b			$103_{1,12}$	<0.001

[a] Threshold for significance is $\alpha = 0.05$; when the ANOVA was significant, entries with different lower-case letters within a row denote means that are significantly different (REGWQ procedure; Day and Quinn 1989).

hours). Maximum daily temperature in the direct sunlight treatment was also significantly higher than in the shaded control treatment (Table 2A).

In total, 395 beetles were collected during the 2010 solarization experiment. As was the case in 2009, there was no effect of treatment on goldspotted oak borer emergence (Table 1A). Adult emergence was recorded from all treatments with the greatest total emergence observed from the thick-tarped treatment. However, adult emergence was lowest in the thin-tarped treatment in relation to the control (this time only in the direct sun) and thick-tarped treatment. Adult emergence for the control treatment began on 28 June and continued until 19 August 2010 with peak emergence occurring from 6 to 13 July 2010. Adult emergence trend data were not available for the tarped treatments because we sampled more sporadically during this study.

There was a significant effect of treatment on all mean and maximum daily temperatures in 2010 (Table 2B). Mean and maximum daily temperature was significantly higher in the outer phloem of thin-tarped treatment than all other treatments (Table 2B). Mean daily air temperatures for the thin- and thick-tarped treatments were significantly greater than for the control treatments. Maximum daily air temperatures was significantly different among all solarization treatments and greater in the thin-tarped treatment than in the thick-tarped treatment (Table 2B). The highest maximum temperature recorded was in the phloem of wood pieces in the thin-tarped treatment (73.7°C) (17 June, between 1223 and 1423 hours).

Both layers of the thin tarp began to deteriorate by mid-July because of environmental factors, and this exposed the cut wood. The outer layer of the thick-tarped treatments began to crack by August, but the underlying tarp layer still maintained its integrity until the end of the study.

Grinding Experiments. In 2010, a total of 22 adults were collected from the control replicates between 19 May and 6 July 2010 with peak emergence occurring from 31 May to 7 June 2010 at this low elevation site. No adults emerged from the grind treatment replicates. In the experiment, there was a significant treatment effect of grinding to a 3“-minus size (Table 1B), and emergence of goldspotted oak borer adults was significantly greater from wood in the control group than from the grind in the 3“-minus grinding treatment (Table 1B). There was also a significant effect of treatment on mean and maximum daily temperatures (Table 2B). Mean daily temperatures recorded from the surface (air) and in the pile of the 3“-minus grind treatment were significantly higher than the control replicates. Maximum daily air temperature was also significantly greater from the 3“-minus grind than from the control replicates. In total, 12 clay models or pieces (whole, 2; pieces, 10) were recovered from the 3“-minus grinding treatment, representing a 12.0% recovery rate and 83% that were damaged. The treatment shredded the wood into narrow strips typically no more than 7.6 cm long, 2.5 cm wide, and 1.3 cm thick.

In 2011, there was also a significant effect of the 3“-minus grinding treatment on emergence of goldspotted oak borer adults (Table 1B). Emergence from wood in the control replicates was significantly greater relative to ground wood (Table 1B). In total, 88 adults were collected from the control replicates between 16 May and 12 July 2011 with peak emergence occurring from 16 to 31 May. No adults emerged from the ground wood.

In the other grinding study (7 January, experiment 2), a total of six adults emerged from 15 May to 29 June 2011. There was a significant effect of treatment, but there were no significant differences among the treatment means (Table 3A). This statistical result was likely a consequence of low population densities of goldspotted oak borer in the infested logs and the conservative nature of the multiple comparison technique that we used. No adults were recovered from the grinding treatments (9“-, 2“-, and 1“- minus), and the emergence was low from the control replicates (Table 3A).

In 2011, there was a significant effect of treatment on mean and maximum daily temperatures (Table 2C). Mean daily temperature was highest within the pile of the 9“-minus treatment and lowest within the pile of the 2“-minus treatment (Table 2C). With the exception of the 2“-minus treatment and the unground control, mean daily temperatures were higher

Table 2. Temperature (mean ± SE, °C) and relative humidity (mean ± SE, %) recorded from various sanitation techniques for oak wood infested with the goldspotted oak borer, *Agrilus auroguttatus*, in southern California

Year	Parameter		Treatments[a]								ANOVA[b] $F_{d.f}$	ANOVA[b] P
A.			Control (shade)	Direct sunlight	Thick-tarped							
2009	Temp. (n = 3)	Mean	19.5 (±0.40)b	20.2 (±0.42)b	27.7 (±0.44)a						$434_{2,\,360}$	<0.001
		Max.	26.8 (±0.46)c	34.6 (±0.56)b	52.8 (±0.67)a				$1{,}314_{2{,}358}$	<0.001		
	Relative humidity (n = 3)	Mean	41.9 (±1.04)b	41.5 (±0.77)b	70.5 (±0.66)a				$490_{2,\,355}$	<0.001		
		Max.	58.6 (±1.31)b	61.1 (±1.21)b	93.1 (±0.52)a						$380_{2,\,378}$	<0.001
B.			Control (direct sunlight)	Thin-tarped air	Thin-tarped phloem		Thick-tarped air		3″-minus air	3″-minus pile		
2010	Temp. (n = 10)	Mean	17.7 (±0.85)d	28.6 (±0.36)b	32.4 (±0.54)a		27.5 (±0.44)b		21.5 (±0.51)c	22.9 (±0.49)c	$520_{5,\,520}$	<0.001
		Max.	25.1 (±0.55)e	51.9 (±0.68)b	59.1 (±0.89)a		48.7 (±0.68)c		39.9 (±0.66)d	26.9 (±0.57)e	$556_{5,\,512}$	<0.001
C.			Control air	Control wood	9″-minus air	9″-minus pile	2″-minus air	2″-minus pile	1″-minus air	1″-minus pile		
2011	Temp. (n = 16)	Mean	18.5 (±0.44)abc	18.1 (±0.41)bc	20.4 (±0.47)ab	21.2 (±0.37)a	17.7 (±0.46)c	14.9 (±1.05)d	17.5 (±0.46)c	19.6 (±0.41)ab	$21.5_{7,\,1345}$	<0.001
		Max.	33.3 (±0.55)b	27.3 (±0.49)c	37.4 (±0.74)a	22.1 (±0.39)d	36.1 (±0.69)ab	16.1 (±1.06)e	36.5 (±0.75)ab	20.8 (±0.41)d	$283_{7,\,1328}$	<0.001

[a] Mean and max daily measurements are presented for individual treatments.

[b] Threshold for significance is α = 0.05; when the ANOVA was significant, entries with different lower-case letters within a row denote means that are significantly different (REGWQ procedure; Day and Quinn 1989).

Table 3. Mean (±SE) emergence of goldspotted oak borer, *Agrilus auroguttatus*, after 2011 grinding and debarking treatments in southern California

	Study	Year	Treatment				
A.	Grinding[a] (exp. 2)	2011	Control 0.6 ± 0.34a	9″-minus 0.0 ± 0.0a	2″-minus 0.0 ± 0.0a	1″-minus 0.0 ± 0.0a	Kruskal–Wallis ANOVA[c] $H = 9.47$, $P = 0.0237$
B.	Debarking[b]	2011	Control 0.75 ± 0.25	Shaved bark 1.25 ± 0.75	Debarked wood 0.0 ± 0.0		Kruskal–Wallis ANOVA $H = 3.65$, $P = 0.16$

[a] $n = 10$ for each treatment or control group.
[b] $n = 4$ for each treatment or control group.
[c] Threshold for significance is $\alpha = 0.05$; when the nonparametric ANOVA was significant, entries with different lower-case letters within a row denote means that are significantly different (Tukey-Type multiple comparison using the Nemenyi Test; Zar 2010, Elliot and Hynan 2011).

within the pile than in the air surrounding the pile or wood pieces (Table 2C). Maximum daily air temperatures were also significantly higher than maximum daily temperatures in the pile or log of the corresponding treatment (Table 2C).

Debarking Experiment. Only eight goldspotted oak borer adults emerged from 22 June to 12 July 2011 in this experiment with peak emergence occurring from 22 to 27 June 2011. There was no significant effect of debarking treatment on goldspotted oak borer emergence (Table 3B). No goldspotted oak borer adults emerged from the debarked wood treatment; the eight adults emerged from the shaved bark and phloem treatment and the control replicates.

Discussion

Our research demonstrates the relative efficacy of several practices to eliminate or reduce emergence of goldspotted oak borer from cut infested wood, thereby preventing spread of this invasive wood borer. The sanitation options tested in these studies were chosen to evaluate the most promising treatments for large and small quantities of infested wood. The most effective methods were grinding wood to a 3“-minus screen/particle size or completely removing bark and phloem. Our experiments also demonstrated that goldspotted oak borer adults do emerge from cut oak wood, even if it is exposed to full sunlight and extreme temperatures.

Solarization treatments were not effective for eliminating or even significantly reducing goldspotted oak borer emergence from cut wood. Solarization has been shown to be effective for killing some bark beetle species in coniferous wood (Buffam and Lucht 1968, Sanborn 1996, DeGomez et al. 2008) or reducing the attractiveness of hardwoods (Švihra 1987) and has been suggested for control of other wood borers. Working with a congener, *A. planipennis*, Petrice and Haack (2010) found that dark-colored tarping did not decrease emergence when compared with wood left in direct sunlight; however, they hypothesized that using clear tarp might be more effective by increasing temperatures and effectively reducing emergence.

Our solarization treatments were effective at increasing mean and maximum daily temperatures in both thick- and thin-tarped treatments when compared with control treatments (Table 2). In 2009, the seasonal maximum under the thick tarp was 69.1°C (29 August between 1145 and 1345 hours), whereas in 2010 the seasonal maximum under the thin tarp was 73.7°C (17 June between 1223 and 1423 hours). However, these maxima were preceded by 2-h measurements that were lower by 3.3 and 6.9°C, respectively. They were succeeded by 2-h measurements that were lower by 13.8 and 10.8°C, respectively. Thus, the high temperatures [International Standards for Phytosanitary Measures Guidelines for Regulating Wood Packaging Material in International Trade (ISPM-15) of 71.1°C for 75 min] recommended and necessary for killing related wood-boring insects in the woody substrate (Goebel 2010, USDA APHIS 2010) were likely not sustained in our solarization treatments, and as a consequence goldspotted oak borer populations were still able to survive and emerge under these conditions. Further, in 2009, the extremely high temperatures were achieved late in August after most of the adults had already emerged. The brief periods when we opened the tarped treatments to sample for adults (5 min, once per week) likely had little effect on achieving or sustaining the maximum temperatures under the tarp. In 2009 and 2010, we folded the clear tarp (6 mil) over on itself, creating a double and darker, more opaque layer. This may have insulated the wood and helped maintain a stable temperature similar to a dark-colored tarp. Mean and maximum daily relative humidity were greater in the thick-tarped treatment than in the other two 2009 nontarped treatments, but the thick bark found on *Q. agrifolia* and *Q. kelloggii* likely provided a buffer for goldspotted oak borers against these potentially negative effects. Air temperatures recorded under the thin tarps were 62% greater than those recorded above the control logs. Adult goldspotted oak borer emergence was reduced in the thin-tarped treatments relative to all the other solarization treatments, but these differences were not statistically significant. Similar results were found with clear and black polyethylene tarping for spruce firewood infested with the spruce beetle, *Dendroctonus rufipennis* Kirby (Coleoptera: Curculionidae, Scolytinae) (Holsten and Werner 1993).

Although they did not eliminate or significantly reduce goldspotted oak borer emergence, thin-tarped (1 mil) treatments may be a suitable management option for reducing localized populations at high-value sites with low infestations where grinding or debarking is not feasible. Properly securing the cut wood under clear tarp can limit dispersal of emerging insects (Appel et al. 2008) and can effectively reduce brood for some bark beetle species (Buffam and Lucht 1968, Negrón et al. 2001). Tarping treatments should incorporate ultra violet-resistant plastic to limit cracking and exposure of cut wood as observed in our study. Although our tarps eventually cracked, the tarps were still intact by the end of peak adult emergence (mid-July) for both thicknesses of tarping, so weathering of the tarp likely had little effect on overall adult emergence in our assessment.

Grinding infested wood to a 3"-minus screen particle size was an effective management strategy for sanitation of goldspotted oak borer-infested wood. No adult beetles emerged from the 3"-minus grind (<7.6 cm) in either 2010 or 2011, suggesting that goldspotted oak borer prepupae were destroyed by the grinding process or from piling the grind (0.5–2.5 m in height). McCullough et al. (2007) showed that no *A. planipennis* prepupae survived grinding to a 2.5 cm particle size and <1% prepupae survived grinding to a 10 cm size. Unlike *A. planipennis*, goldspotted oak borer prepupae have not been observed in the outer sapwood (Poland and McCullough 2006), but are restricted to the outer phloem. After the grind treatments, the phloem and bark were completely macerated and difficult to distinguish in the grind. Survival of goldspotted oak borer life stages in this material is very unlikely and may explain the slight differences observed between the two *Agrilus* species.

Eighty-three percent of the adult goldspotted oak borer clay models recovered from the 3"-minus grind were damaged, and the recovery rate was very low (12%), both indicating very high probability of goldspotted oak borer mortality. Wang et al. (2000) tested the effectiveness of chipping by using a similar method of surrogate models for *An. glabripennis* and found that no models were collected without damage, but these models were much larger than our goldspotted oak borer replicates. Although goldspotted oak borer prepupae rather than adults are generally found in the tree, adult models were used (conservatively) in this study to provide a more accurate mimic. The length of the adults is comparable to that of prepupae found in the outer bark (Hishinuma et al. 2011).

The 3"-minus grind treatment represents the best method for eliminating goldspotted oak borer populations in cut wood and is an appropriate treatment where large quantities of infested wood must be treated. Grinding equipment is expensive and wood must generally be brought to a centralized location for treatment, so it is not necessarily an option for an individual homeowner who seeks to treat wood from a single tree.

Low numbers of adults recovered from the control replicates in experiment 2 (9"-, 2"-, and 1"- minus grinding and untreated control) prevent us from commenting conclusively on the efficacy of these treatments for eliminating goldspotted oak borer populations in cut wood. The trees used in this study likely had low-levels of infestation, limiting our capacity to make inferences from the experiment. In addition, we used a relatively conservative multiple comparison technique in the statistical analysis of the data. Nonetheless, no goldspotted oak borer adults emerged from these grind treatments. The 9"-, 2"-, and 1"- minus treatments will likely be reassessed in future experiments where we can obtain wood with high density populations.

Maximum daily air temperature was generally higher in the 2011 grind treatments than temperature measurements recorded in the pile. However, the grind would likely insulate the core of the piles from temperature extremes, so that survival of any goldspotted oak borer life stages escaping mechanical injury would not be affected by the increased heat on the surface. Mean daily temperatures varied across all the treatments in the 2011 grind studies with no pattern across the treatments. This could be attributed to the partial canopy cover at the Cuyamaca Rancho State Park that left some treatment replicates fully or partially exposed to direct sunlight.

Removing >95% of the infested bark with no bark or phloem thicker than 1 cm remaining on the wood (debarking) completely prevented goldspotted oak borer emergence from the wood fraction of the treatment. Goldspotted oak borer larvae do not frequently feed in the xylem, but occasionally larval galleries have been observed in the outer xylem, which may be a behavioral strategy by *Agrilus* for escaping vigorous callus tissue (Balch and Prebble 1940). Debarking did not eliminate or significantly reduce goldspotted oak borer populations in the shaved bark fraction when compared with control logs. Shaved bark should be managed properly (such as sealing it with tarp or preventing its movement from an infested area) if this treatment option is used. Debarking with an axe is labor intensive and is likely to be only feasible for small quantities of cut wood, but may be useful for landowners with a few ornamental oak trees or a small parcel of forested property. As cut logs age over several years, bark removal becomes easier, but beetles should have emerged after two growing seasons (May to November) in southern California (Coleman and Seybold 2008b). Splitting cut wood into firewood-sized pieces did not eliminate goldspotted oak borer emergence in the debarking study, so splitting is not an effective management option for managing infested wood. Adult emergence of *An. glabripennis* and *A. planipennis* were also not limited by cutting wood into firewood-sized pieces (Wang et al. 2000, Petrice and Haack 2006).

Emergence of adult goldspotted oak borer during our studies generally occurred from mid-May to late-August with peak emergence from late May to early July, depending on the year of the study and the elevation of the study site (Table 4). The initial and peak emergence times appear to slightly precede the corresponding times of peak adult flight (late June to early July) (Coleman and Seybold 2008b, Seybold et al. 2010), which may have been because of the greater sun exposure and heat available to the cut wood in our research plots than would be available on the stems and branches of living trees. We assume that these standing trees have provided the sources of beetles in

Table 4. Initial and peak seasonal emergence of adult goldspotted oak borers, *Agrilus auroguttatus*, during various oak wood sanitation experiments in southern California

Experiment	Elevation	Initial emergence	Peak emergence	Seasonal range of emergence	Total emerged
2009 solarization	Low	22 May	20–27 May (sun-exposed treatments) 12–19 June (shaded controls)	22 May to 24 Aug.	240
2009 solarization	High	4 June	18–25 June	4 June to 27 July	45
2010 solarization (data from sun-exposed controls only)	Low	28 June	6–13 July	28 June to 19 Aug.	395
2010 grinding (exp. 1)	Low	19 May	31 May to 7 June	19 May to 6 July	22
2011 grinding (exp. 2)	Low	15 May	Not applicable, catch too low	15 May to 29 June	6
2011 debarking	Low	22 June	22–27 June	22 June to 12 July	8

our previous flight assessments with purple flight-intercept traps (Coleman and Seybold 2008b, Seybold et al. 2010). It is also possible that there is a lag between the time of emergence and the time of adult flight response in our trapping studies. Bentz (2006) noted a lack of correspondence between peak emergence of mountain pine beetle, *Dendroctonus ponderosae* Hopkins, from infested trees and the majority of the catch in pheromone-baited flight traps. Surprisingly in this instance, the flight trap catches tended to precede the emergence trap catches. Nonetheless, in our case, we recommend that treatments implemented to manage goldspotted oak borer-infested wood occur before May, that is, before adult emergence. Given the seasonal range of emergence that we have established (Table 4), solarization techniques to trap populations of emerging adults should continue at least until early September to be thoroughly effective.

Preventing the movement of goldspotted oak borer-infested wood should limit the impacts of this invasive species in California, and may represent the most useful management technique for limiting tree mortality on small parcels of land. An important aspect of limiting the dispersal of goldspotted oak borer in cut wood is recognizing that goldspotted oak borer prepupae can persist in dead trees or cut wood for longer than one calendar year. In this study, emergence was recorded from May to August 2009 from a tree felled in October 2008. Goldspotted oak borer emergence was also recorded from *Q. agrifolia* logs in a laboratory cage from June to October 2008 and then again in May 2009 (the logs were from trees that were felled and sectioned on 25 June 2008; Coleman and Seybold 2008b, T.W.C., unpublished data). Thus, trees felled during the goldspotted oak borer flight and ovipositional period (May to November) can harbor populations until the next emergence period of the following year. Felling dead or dying trees in November after goldspotted oak borer's flight period ensures that last year's population has emerged, but the logs from these trees harbor larvae or prepupae that will develop and emerge in the spring and summer of the following year. Trees cut and sectioned before adult emergence (May) should be free of goldspotted oak borer populations after November of the same year. Thus, to be absolutely certain, small landowners should season oak wood cut from newly killed tress on site for the duration of two growing seasons to limit the spread of the goldspotted oak borer.

The transportation of cut wood and its association with the dissemination of invasive species has gained national recognition (see www.dontmovefirewood.org; The Nature Conservancy [TNC] 2011). Educating landowners and recreational visitors can bring awareness to this issue, but additional measures are needed to ameliorate the effects of movement of infested material and to ensure the safe use of biomass generated from wood infested with invasive species. The management options tested in these studies and the information provided can assist with preventing the long-distance spread of goldspotted oak borer in California.

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