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Short Communication

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Acetophenone and Green Leaf Volatiles Do Not Enhance the Efficacy of Verbenone for Inhibiting Attraction of *Ips pini* (Coleoptera: Curculionidae) to Pheromone-baited Traps in Northern Arizona

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Abstract

We assessed attraction of pine engraver, *Ips pini* (Say) (Coleoptera: Curculionidae; Scolytinae), to pheromone-baited funnel traps treated with repellent semiochemicals in ponderosa pine, *Pinus ponderosa var. scopulorum* Engelm., forests in northern Arizona. Treatments included: 1) baited control (B, ipsdienol + lanierone), 2) 70 g of SPLAT Verb (a flowable, biodegradable formulation containing 10% verbenone, ISCA Technologies Inc., Riverside, CA, USA) + B, 3) 70 g of SPLAT Verb + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone + B, 4) 7.84-g verbenone pouch (Product #3413, Synergy Semiochemicals Corp., Delta, British Columbia, Canada) + B, and 5) 7.84-g verbenone pouch + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone + B. In total, 472 *I. pini* were collected. Trap catches were highest in baited traps and declined significantly with the addition of both formulations of verbenone. Traps treated with SPLAT Verb caught significantly fewer *I. pini* and male *I. pini* than those treated with verbenone pouches. The addition of (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone to SPLAT Verb and the verbenone pouch had no effect on trap catch. Verbenone has potential as an effective tool for protecting *P. ponderosa* trees and slash from *I. pini* in northern Arizona, but the addition of (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone to verbenone is unwarranted.

Key words: acetophenone, green leaf volatiles, pine engraver, tree protection

Pine engraver, *Ips pini* (Say) (Coleoptera: Curculionidae; Scolytinae), is a primary driver of ponderosa pine, *Pinus ponderosa var. scopulorum* Engelm. (Pinales: Pinaceae), mortality in northern Arizona (Negrón et al. 2009; USDA Forest Service 2019, 2020, 2021). Recent outbreaks of *I. pini* and of other engraver beetles (e.g., Arizona fivespined ips, *I. lecontei* Swaine) in Arizona have been positively correlated with drought (Negrón et al. 2009; USDA Forest Service 2019, 2020, 2021). With climate change models projecting that extreme weather events will occur more often in the western United States, as well as decreases in precipitation and increases in temperature (Williams et al. 2013, Easterling et al. 2017, Vose et al. 2017), we anticipate *Ips* spp. will continue to drive widespread pine mortality in northern Arizona (McDowell et al. 2008, Bentz et al. 2010, Kolb et al. 2016).

Many bark beetle species use pheromone communication systems to facilitate mass attacks that result in mortality of the host tree. As the host tree begins to reach colonization capacity, anti-aggregation pheromones are produced, repelling additional beetles from attacking the same tree, and regulating inter- and intra-specific competition within the phloem. Managers use these and other semiochemicals for monitoring of, and protecting trees from, several important bark beetle species in the western United States (Seybold et al. 2018). However, the efficacy of semiochemical treatments varies widely. Repellents are especially desirable for protecting trees from bark beetles as, compared to insecticides they tend to be less expensive, can be used near water sources, and pose fewer environmental risks including fewer nontarget effects (Fettig et al. 2013, Gillette and Fettig 2021). Verbenone (4,6,6-trimethylbicyclo[3.1.1]hept-3-en-2-one), derived from degradation of α-pinene, a terpene found in almost all conifers and one of the most abundant terpenes in *P. ponderosa* (Seybold et al. 2006, Blomquist et al. 2010, Kolb et al. 2019), is often considered a general bark beetle repellent (Seybold et al. 2018). The effects of verbenone are well studied in *Dendroctonus* spp., but poorly understood in *Ips* spp. despite several studies (e.g., Paine and Hanlon 1991, Miller et al. 1995, Lindgren and Miller 2002), including a recent study on *I. pini* in northern Arizona (Gaylord et al. 2020). These studies on *Ips* spp. have demonstrated that verbenone inhibits the response of *Ips* spp. to baited traps. DeGomez et al. (2008b) reported verbenone had no effect on colonization of *P. ponderosa* slash by *Ips* spp.

Since bark beetles are known to use host terpenes to locate host tree species, nonhost volatiles have been investigated as bark beetle repellents (e.g., Zhang and Schlyter 2004, Fettig et al. 2005, Huber et al. 2021). The first work of this kind in the United States was by Dickens et al. (1992) who demonstrated that two green leaf volatiles (GLVs) acted individually or in combination to reduce catches of southern pine beetle, *D. frontalis* Zimmermann, small southern pine engraver, *I. avulsus* (Eichhoff), and eastern fivespined ips, *I. grandicollis* (Eichhoff), in baited traps. Subsequent studies on several bark beetle species in North America, Europe, and Asia have generally shown that nonhost signals are generic, redundant, and that behavioral effects are increased by increasing amounts of nonhost volatiles. Over the last two decades, several studies have shown that tree protection may be enhanced by combining nonhost volatiles with anti-aggregation pheromones such as verbenone (reviewed in Huber et al. 2021). Our choice of (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol in this study was guided by previous work that indicated these GLVs inhibited attraction in *Dendroctonus* spp. when combined with verbenone (Poland et al. 1998; Fettig et al. 2005, 2009, 2012a).

Acetophenone was identified in volatiles emitted from several *Dendroctonus* spp. as well as *I. pini* (Pureswaran et al. 2000, 2004; Sullivan 2005). One study examining the potential for its use as a repellent found acetophenone inhibited the response of western pine beetle, *D. brevicomis* LeConte, to baited traps more than verbenone alone (Erbilgin et al. 2008), the latter being the primary anti-aggregation pheromone component of *D. brevicomis*. Acetophenone has also been demonstrated to inhibit *D. frontalis* (Sullivan 2005) and Douglas-fir beetle, *D. pseudotsugae* Hopkins, (Pureswaran and Borden 2004) in trapping assays. A recent study demonstrated that combining acetophenone with GLVs and the anti-aggregation pheromone MCH (3-methyl-2-cyclohexen-1-one) significantly reduced colonization and mortality of Engelmann spruce, *Picea engelmannii* Parry ex. Engelm. (Pinales: Pinaceae), by spruce beetle, *D. rufipennis* Kirby, in Wyoming (Audley et al. 2022).

A semiochemical-based tree protection strategy for *I. pini* in southwestern *P. ponderosa* forests would be invaluable to forest managers and property owners (DeGomez et al. 2008a). As described by Gaylord et al. (2020), preventative thinning treatments are currently the best option for increasing forest resilience to disturbance; for decreasing levels of tree water stress; and for preventing *I. pini* attacks (Fettig et al. 2007, Kolb et al. 2016, Sankey and Tatum 2022). Once an *I. pini* infestation occurs, options for tree protection are limited to the use of insecticides (Fettig et al. 2013) and supplemental watering (Kegley et al. 1997). However, these options are often not feasible due to logistical constraints and environmental concerns. The primary objective of this study was to determine the effects of two formulations of verbenone, with and without acetophenone and GLVs, on the response of *I. pini* to pheromone-baited traps in northern Arizona. This research builds on previous work by Gaylord et al. (2020) who demonstrated that verbenone is effective for reducing aggregation of *I. pini* and may hold promise for tree protection.

Materials and Methods

Release Rate Assay

Release rates for each of the four semiochemical repellents were determined gravimetrically under laboratory conditions. Each repellent was evaluated independently of other components. Ten release devices (either pouches or a single dollop of SPLAT Verb placed on ~23 cm^2-pieces of cardboard) of each repellent (*N* = 40) were hung from twine in a fume hood. Two HOBO Pro v2 External Temperature data loggers (Onset Computer Corporation Bourne, MA) were placed in the study arena and temperature was recorded every 15 min. A Vaneometer swing vane anemometer (Dwyer Instruments Michigan City, IN) was used to record airflow (i.e., the fume hood was left partially open during the experiment). Following 24 h exposure of release devices in the fume hood (i.e., which presumably allowed for some stabilization of release), devices were weighed every 1–4 d from 10 September–18 December 2020. During this period, average temperature in the fume hood was 21.2°C (range, 18.5–23.9°C) and air flow was ~53 m/min. Changes in the weights of release devices were modeled using a linear function (lm). Data after 50 d of exposure were excluded from analyses. A 95% confidence interval was generated for the average daily change in weight. Analyses were conducted using the Stats package in R Statistical Software (R Core Team 2020). Results are included below in the treatment description for the trapping assay.

Trapping Assay

A trapping assay was conducted on the Kaibab National Forest (~40 km west of Flagstaff, Arizona; 35° 17′ 50″, 111° 59′ 60″; ~2135 m above sea level) during 24 June–5 August 2020 in a *P. ponderosa*-dominated forest with active tree thinning operations nearby. Ground surveys prior to the assay found *I. pini* activity in multiple locations around the study site. *I. pini* were abundant in recently cut material but caused little tree mortality. The Flagstaff area experiences annual average precipitation of 58.8 cm, approximately half as mid- to late-summer rains and half as winter precipitation (US Climate Data 2020). In 2020, temperatures were close to average in June (26°C) with only trace precipitation recorded. June is typically the driest month in northern Arizona (rssWeather.com). July and August 2020 were abnormally warm (1.3°C and 4.1°C above normal for July and August, respectively) and dry (2.9 cm and 7.1 cm below normal for July and August, respectively).

We installed 50, five-unit funnel traps in two lines of 25 traps. Adjacent traps were spaced ≥25 m and all traps were ≥2 m horizontally from the outer edge of the crown of any *P. ponderosa*. The stand was relatively flat, untreated, homogenous *P. ponderosa* with no dominant terrain features that might affect trap catches. Treatments were completely randomized and ten replicates of five treatments were evaluated: 1) baited control (B), 97% (—) ipsdienol (~75 µg/d at 20°C; 40% purity), and lanierone (~10 ug/d at 20°C; 99% purity) (release rates obtained from Synergy Semiochemicals Corp., Delta, British Columbia, Canada), 2) 70 g of SPLAT Verb (29.3 mg/d at 21°C; 99% purity; 10% verbenone) + B, 3) 70 g of SPLAT Verb + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol (20.0 mg/d at 21°C; 98% purity) + acetophenone (103.5 mg/d at 21°C; 98% purity) + B, 4) 7.84-g verbenone pouch (Product #3413) (17.3 mg/d at 21°C; 98% purity) + B, and 5) 7.84-g verbenone pouch + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone + B. Traps, baits, and verbenone pouches were obtained from Synergy Semiochemicals Corp. SPLAT Verb, (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol pouches, and acetophenone pouches were obtained from ISCA Technologies Inc. (Riverside, CA). Baits and pouches were affixed to the middle funnel on the funnel trap. SPLAT Verb was deployed using four ~17.5-g dollops (Fettig et al. 2015) with each dollop applied to a piece of cardboard. The pieces of cardboard were hung on the three trap connector straps at the same height as the other release devices. One strap held two pieces of cardboard. One small piece of Hot Shot No-Pest Strip2 (18.6% 2,2-dichlorovinyl dimethyl phosphate; Spectrum Group, St. Louis, MO) was placed in each trap collection cup.

Trap catches were collected every 7 d, and stored in a freezer until collections were identified, counted, and sorted by species and sex using available keys (Wood 1982) and voucher specimens. The number of *I. pini* caught per week was analyzed using generalized linear models (glm). Responses for all *I. pini* and for males and females were compared and modeled using treatment (five treatments), week (six weeks), and trap (50 traps). Interactions of model terms were also considered. Each model was first fit using a Poisson distribution, however, the dispersion parameters were significantly greater than 1 for each of the three models (dispersion test function in the AER package) indicating overdispersion. To address this, each model was fitted using a negative binomial distribution with a log link. Model selections were made based on Akaike Information Criterion (AIC) values and likelihood ratio tests (Zuur et al. 2009). Pairwise, post hoc, multiple means comparisons were made using a least squares means (lsmeans function in the emmeans package) test with a Bonferroni correction ($\alpha = 0.05$). Analyses were conducted using R Statistical Software (version 3.4.4) via RStudio (version 1.2.1335) (R Core Team 2020).

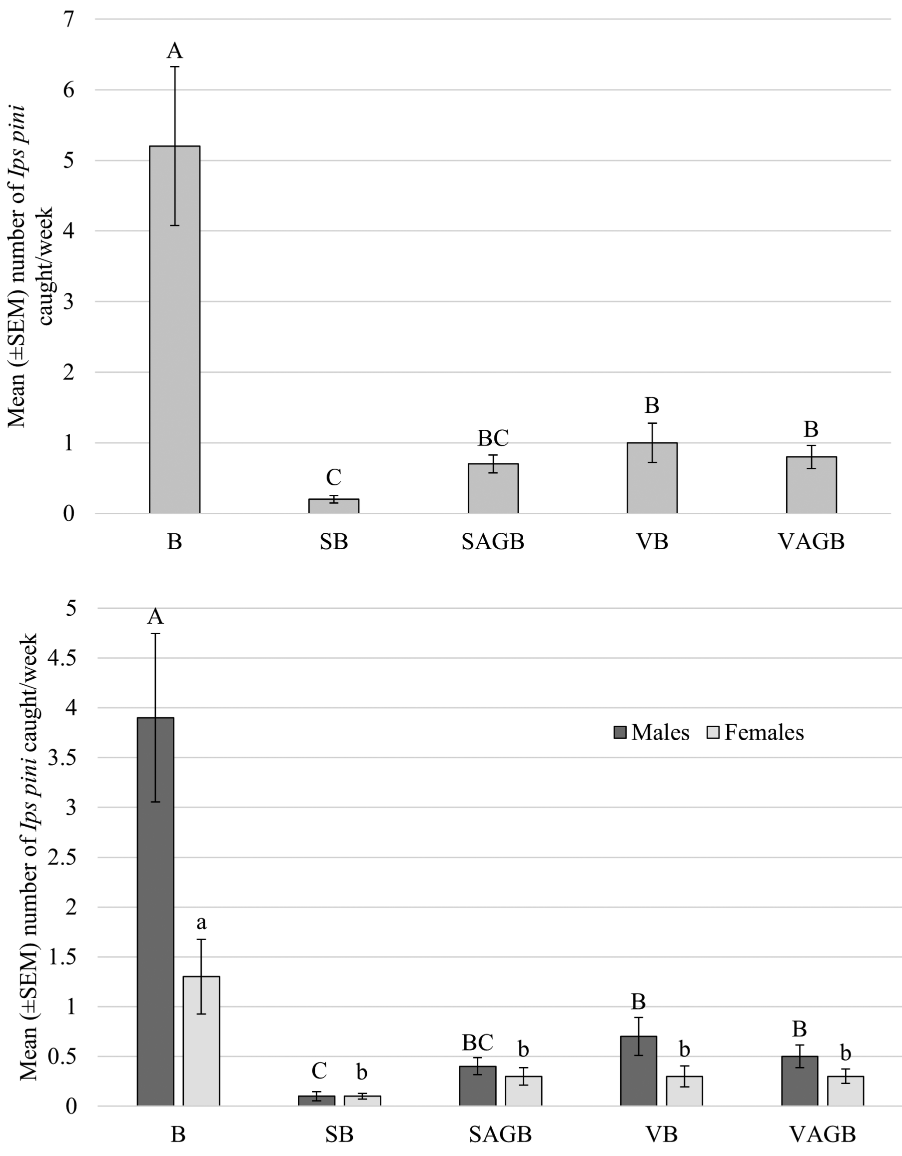

Fig. 1. Mean captures (±SEM) of pine engraver, *Ips pini* (Say), in five-unit funnel traps baited with *I. pini* attractant alone (B), or in combination with SPLAT Verb (SB), SPLAT Verb + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone (SAGB), the verbenone pouch (VB), and verbenone pouch + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone(VAGB). Traps were deployed 24 June–5 August 2020 on the Kaibab National Forest, Arizona. Bars associated with the same letter within assay are not significantly different ($n = 10$; Tukey's HSD; $P > 0.05$).

Results

We collected a total of 472 *I. pini*, 337 males and 135 females. All treatment variables were significant in the final model for total *I. pini* catches (all $P < 0.001$), male *I. pini* catches (all $P < 0.001$), and female *I. pini* catches (all $P < 0.001$). Post hoc Kruskal–Wallis tests revealed significant differences among mean trap catches across treatments for all *I. pini* ($\chi^2 = 67.9$, df = 4, $P < 0.001$), for males ($\chi^2 = 72.5$, df = 4, $P < 0.001$), and for females ($\chi^2 = 31.9$, df = 4, $P < 0.001$). Baited traps (B) caught significantly more *I. pini* than any other treatment (Fig. 1). Traps treated with SPLAT Verb caught significantly fewer *I. pini* and male *I. pini* than those treated with verbenone pouches (Fig. 1). The addition of (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone to verbenone, regardless of formulation, did not affect trap catch (Fig. 1).

Discussion

Similar to Gaylord et al. (2020), this study demonstrates that SPLAT Verb and the verbenone pouch inhibit attraction of *I. pini* to pheromone-baited traps. Trap catches were significantly lower when verbenone was present for both males and females and when data were pooled by sex. Overall, SPLAT Verb exhibited higher levels of inhibition than the verbenone pouch (Fig. 1), which disagrees with Gaylord et al. (2020) who reported no differences between these treatments for *I. pini*. However, this may be explained by the substantially (~69%) higher release rates observed for the SPLAT Verb compared to the verbenone pouch in the release rate assay. Interestingly, the release rate of the verbenone pouches determined independently in this study (17.3 mg/d at 21°C) was lower (~75%) than the reported release rate (~70 mg/d at 20°C) of verbenone pouches in Gaylord et al. (2020) and lower than the current reported release rate from Synergy (50 mg/d at 25°C). The source of this discrepancy in release rates is unexplained but may help explain the difference observed in performance of the verbenone pouch between the two studies. The method of deployment and positioning of SPLAT Verb on traps also differed between the two studies. Studies in whitebark pine, *P. albicaulis* Engelm., in California and Montana found SPLAT Verb was more effective for reducing mountain pine beetle, *D. ponderosae* Hopkins, attacks than the verbenone pouch (Progar et al. 2021); whereas in lodgepole pine, *P. contorta* Dougl. ex Loud., in Idaho no differences were observed between SPLAT Verb and the verbenone pouch (Fettig et al. 2015).

The addition of acetophenone and GLVs to SPLAT Verb and the verbenone pouch had no effect on inhibition (Fig. 1). Fettig and Munson (2020) compared the efficacy of SPLAT Verb and SPLAT Verb + (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone for protecting *P. contorta* from mortality attributed to *D. ponderosae* in Utah. Both SPLAT Verb and SPLATVerb+ (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol + acetophenone were effective, but no differences were observed between treatments. These repellents were originally identified for *D. brevicomis* ('Verbenone Plus', Fettig et al. 2012b) and represent the only repellents demonstrated to consistently protect *P. ponderosa* from mortality attributed to *D. brevicomis* (Huber et al. 2021).

Given the results of this study and that of Gaylord et al. (2020), it appears verbenone has potential as an effective tool for protecting *P. ponderosa* trees and slash from *I. pini*. The addition of acetophenone and (*E*)-2-hexen-1-ol+(*Z*)-2-hexen-1-ol to verbenone is unwarranted as no significant reductions in trap catch were observed due to these repellents. Further studies using verbenone on baited *P. ponderosa* trees and slash are necessary prior to recommending the use of either formulation of verbenone for protecting *P. ponderosa* from *I. pini* in northern Arizona. Our research was conducted under endemic population levels of *I. pini*. Outbreak populations may respond differently. Furthermore, to our knowledge no robust phenology model has been developed for *I. pini*, which would be useful for optimizing timing of semiochemical treatments for *I. pini*.

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