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Use of acoustics to deter bark beetles from entering tree material†

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Abstract

BACKGROUND: Acoustic technology is a potential tool to protect wood materials and eventually live trees from colonization by bark beetles. Bark beetles such as the southern pine beetle *Dendroctonus frontalis*, western pine beetle *D. brevicomis* and pine engraver *Ips pini* (Coleoptera: Curculionidae) use chemical and acoustic cues to communicate and to locate potential mates and host trees. In this study, the efficacy of sound treatments on *D. frontalis*, *D. brevicomis* and *I. pini* entry into tree materials was tested.

RESULTS: Acoustic treatments significantly influenced whether beetles entered pine logs in the laboratory. Playback of artificial sounds reduced *D. brevicomis* entry into logs, and playback of stress call sounds reduced *D. frontalis* entry into logs. Sound treatments had no effect on *I. pini* entry into logs.

CONCLUSION: The reduction in bark beetle entry into logs using particular acoustic treatments indicates that sound could be used as a viable management tool.
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Keywords: management; southern pine beetle; western pine beetle; *Dendroctonus*; *Ips*; acoustic

1 INTRODUCTION

Of the approximately 3500 species of bark beetles (Coleoptera: Curculionidae), less than 2% attack living, healthy trees.[1,2] In the last 30 years, billions of coniferous trees in western North America have been killed by a few native bark beetle species. Although gaps exist in current understanding of the processes leading to large-scale outbreaks, increased frequency of natural disturbances promoted by drought, fire, high forest densities and above-average low winter temperatures have resulted in greater bark beetle success. Recent outbreaks are among the largest and most severe in recorded history.[3]

Options to mitigate bark beetle outbreaks are limited.[4–6] One approach to mitigate outbreaks is to use tactics that disrupt beetle communication. Bark beetles use three primary forms of communication: chemical, visual and acoustic.[7] Visual discrimination of hosts is largely limited to taxis towards objects that are cylindrical and similar to the color of the host tree bole.[8] Olfactory stimuli such as pheromones and deterrents have been widely studied and are sometimes effective even at landscape scales.[9] Although acoustic communication is known in bark beetles,[10–13] management methods targeting acoustic communication in bark beetles are non-existent.[14] In the 1960s and 1970s, Rudinsky and collaborators found that bark beetles exhibit a wide array of acoustic abilities, ranging from aggression calls to courting calls, and these calls influence pheromone communication.[12,15–20] Thus, acoustic techniques could theoretically be used to interrupt beetle communication and interfere with mate selection and tree colonization (e.g. Polajnar and Čokl[21]).

An acoustic device to disrupt and interfere with insect reproduction and communication within wood materials has been developed by Hofstetter *et al.*[22] Acoustic signals played into tree tissues can negatively affect bark beetle reproductive output, reduce tunneling distance and adult survival and induce stress which diminishes the capacity of bark beetles to function.[14] However, the best method for tree protection against bark beetles is to reduce entry into trees, thus reducing potential tree death from girdling and microbial infection during beetle colonization. The application of sound into plants has previously been limited to the use of vibrations in disrupting Hemiptera associated with crops[21,23] or termites and ants in wood materials.[24]

Using a tactile transducer device, which allows for efficient input of sound into wood, the authors tested whether acoustic signals, both natural and unnatural, discourage bark beetle entry or disrupt beetle host selection. Tests were performed with three bark beetle species commonly found in Arizona ponderosa pine forests: the southern pine beetle *Dendroctonus frontalis* Zimmerman, the western pine beetle *D. brevicomis* LeConte and the pine engraver *Ips pini* Say. The objectives were to test the efficacy of insect-derived acoustic signals for bark beetle management and control. This acoustic technology would expand the arsenal of tools that land managers use to control bark beetles and provide

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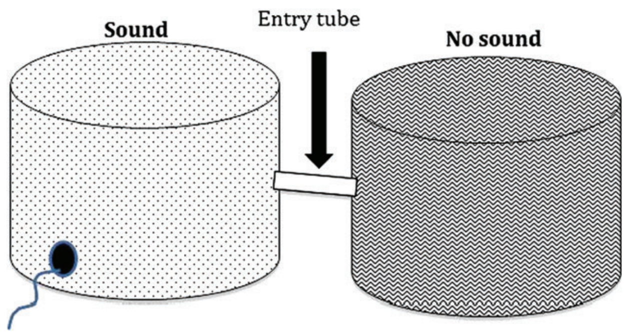

Figure 1. Illustration of choice test assay. Beetles were placed in the center tube and given the choice to enter a log with an acoustic treatment or a bolt with no sound. Sound was introduced using a tactile transducer (Excitor; HiWave Technologies PLC).

a non-chemical and environmentally friendly method of insect control.

2 EXPERIMENTAL METHODS

2.1 Assay design

To test the effects of acoustic signals on bark beetle entry into tree material, individual female beetles were presented with the choice of entering freshly cut logs with or without sound introduced into the log (Fig. 1). Beetle entry was tested using two 35 cm long ponderosa pine logs placed side by side, 5 cm apart. A set of logs was cut from the same tree to prevent potential host tree effects on beetle selection and entry.[25] Multiple trees were used for the study. Ends of logs were waxed to prevent desiccation and preserve natural moisture levels. A 3/4 inch Forsner drill bit was used to drill one hole in each log through the outer bark, with care taken not to penetrate through the phloem layer. Clear vinyl tubing (1/2 inch inside diameter, 3/4 inch outer diameter; HomeDepot) cut 6 cm long was placed between each log pair into the freshly drilled holes. A small entry hole (5 mm) was drilled through the top of the vinyl tube where beetles were initially deposited. A strip of paper was placed inside the tube to provide a substrate and facilitate movement within the tube. One log in each pair had a tactile transducer (25 mm Excitor SFH model: DAEXSFH; Dayton Audio) attached to the xylem, transmitting an acoustic treatment; the other log was left untreated (no-sound control). In order to confirm uniformity of amplitude across acoustic treatments, a digital sound level meter was used (Radio Shack SKU: 33–2055). Decibel measurements are relative, and as the Excitors used are tactile transducers, a 9.5 cm petri dish was affixed to the Excitor with the decibel meter held at a distance of 5 cm. Measuring decibels by this technique, rather than measuring the amplitude with the Excitor affixed to the bolt, avoided varying degrees of attenuation in the log owing to varying density, moisture content, bolt size and wood cell structure. All acoustic treatments were held between 65 and 70 dB, a level that was shown to have an effect on bark beetle behavior and reproduction in phloem sandwiches.[14]

Four acoustic treatments were tested: (1) attraction calls (also referred to as interrupted calls[37]) by *D. brevicomis*, *D. frontalis* or *I. pini*; (2) stress calls (also referred to as disturbance calls[26]) by *D. brevicomis, D. frontalis* or *I. pini*; (3) an artificial sound (described below); (4) wood borer stridulations created by an adult *Monochamus titillator* (F.). Example waveforms, spectrograms and power spectra can be seen in Fig. 2 for the *M. titillator* and *D. frontalis* stress call treatments. In addition, a control set with no acoustic treatment installed on either log was tested. This provided values for the expected probability of entry into either log (= H_{01}) for each bark beetle species tested. The attraction call is the stridulatory sound produced by a beetle when it enters the tunnel of a potential mate.[12,26] The stress call is a stridulatory sound produced by a bark beetle when disturbed or handled.[12,26] Stridulation by the wood borer is also considered to be a stress call (see Section 2.2). The artificial acoustic treatment comprised of a computer-generated tone using Adobe Audition 3.0 that was 10 s long and oscillated in the 0–24 kHz frequency range. The intention of the oscillating range was an attempt to mask the frequency spectrum that beetles utilize with an abiotic tone.

Once a beetle was dropped into the vinyl tube, it was given 24 h to make a choice. At the end of each 24 h cycle, the tube was removed. If the beetle was found in the tube, it was noted whether it was alive or dead. Live beetles in the tube were recorded as a 'no choice'. If a beetle was not found in the tube, the side of the tube with frass was an indicator of the beetle's choice. If the beetle entered a log, a chisel was used to extract the beetle from the log. Up to ten beetles were tested sequentially with each set of logs; new entry-tube holes were drilled for each beetle. A total of 104 *D. brevicomis*, 98 *D. frontalis* and 68 *I. pini* were tested.

2.2 Acoustic treatments

With the exception of the artificial sound, all acoustic treatments were recorded with a Tascam HD-P2 stereo recorder at 96 kHz and a 24 bit sampling rate. Audio information was delivered to the recorder using a Knowles Acoustics FG-3329 electret condenser microphone.[27] *Dendroctonus brevicomis* and *D. frontalis* stress calls were recorded at a distance of 5 mm from the specimen, which was gently held between the thumb and forefinger. *Ips pini* stress calls were recorded as a predator (*Temnochila chlorodia* Mannerheim) pursued the beetle in a 5 cm diameter plastic petri dish with the microphone at a distance of 5 mm from the bark beetle. The wood borer treatment was recorded from a live adult *Monochamus titillator* held with forceps at a distance of 5 mm from the microphone. The attraction calls for *D. brevicomis*, *D. frontalis* and *I. pini* were recorded within phloem sandwiches by Yturralde[26] using the same recording equipment. For these recordings, the host-colonizing beetle, female for *Dendroctonus* and male for *Ips*, was allowed 24–48 h to initiate tunneling before a mate was introduced. The microphone was held 1–2 mm away from the entry hole to capture attraction calls. All attraction calls were recorded within 30 min of the mates' introduction.[26]

For all treatments, recording length, number of phrases per minute and mean phrase length are presented in Table 1. Recording length represents the length of the recording; each recording was looped to provide continuous playback. Number of phrases per minute and mean phrase length were determined in Raven Pro Interactive Sound Analysis Software (v.1.4, Cornell Lab of Ornithology[28]). A phrase was a relatively continuous series of stridulation, clearly broken by silent periods.

Recording length, number of phrases per minute, mean phrase length, center-frequency and high-frequency measurements are described in Table 1 using spectrograms and waveforms produced in Raven Pro Interactive Sound Analysis Software (v.1.4).[28] Spectrograms were produced (Fig. 2) using the following parameters:[29] a Hann window with a 698 sample size, 140 hop size and 80% overlap. Recording length represents the length of the recording; each recording was looped to provide continuous playback. Number of calls per minute and mean call length were

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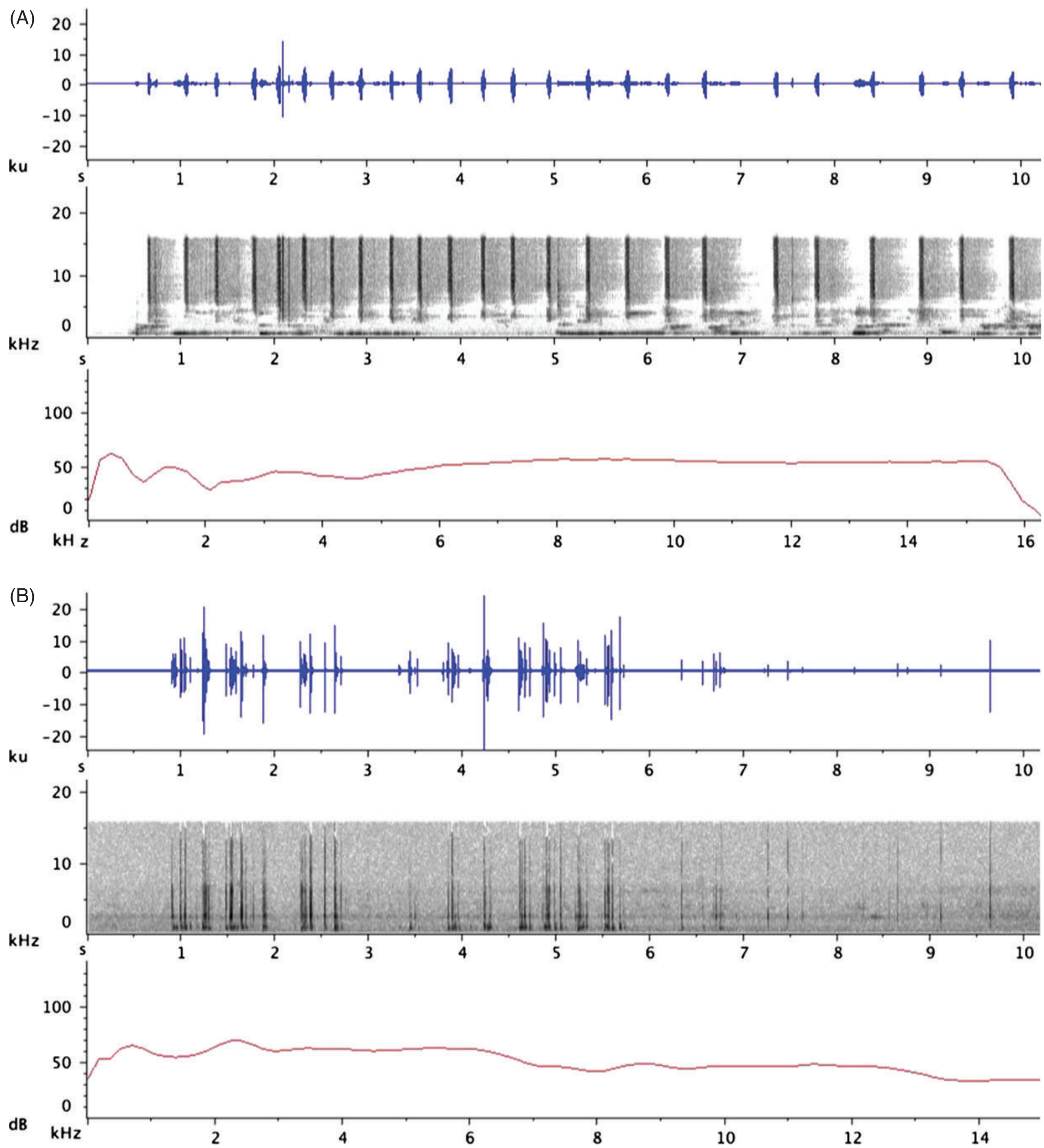

Figure 2. Example waveform, spectrogram and power spectra for the *Dendroctonus frontalis* stress (A) and *Monochamus titilator* treatment sounds (B). Figures generated in Raven Pro Interactive Sound Analysis Software v.1.4 (Cornell Lab of Ornithology[28]).

determined in Raven Pro. A call was a relatively continuous series of stridulation, clearly broken by silent periods.

2.3 Beetle collection

All beetles were collected using Lindgren funnel traps[30] baited with either the western pine beetle or pine engraver aggregation pheromones adapted for Arizona populations (Synergy Semiochemical Corp). Traps were placed in ponderosa pine forest stands near Flagstaff, Arizona (Centennial Forest; 35° 10′ N, 111° 45′ E; elevation ∼2100 m) and visited every day to ensure that beetles were vigorous and healthy. If necessary, beetles were temporarily stored in a refrigerator (15 °C), and unused beetles were discarded after 48 h. Only female *D. brevicomis* and *D. frontalis* and male *I. pini* were used in the assays because female *Dendroctonus* and male *Ips* are the initial colonizers of trees.[31]

2.4 Log collection

All ponderosa pine logs were harvested at the Centennial Forest. Trees were cut into 35 cm length logs, waxed on each end and labeled with the tree number. Log diameters ranged between 20 and 40 cm.

2.5 Statistical analysis

The effect of acoustic treatments on beetle entry into logs (regardless of which log) was tested using a two-tailed 2 × 2 Fisher

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Table 1. Description of acoustic treatments used in the study. Stress = recording of the stress (also called disturbance) call from a held beetle (*I. pini* stress call recorded as predator-pursued specimen); attraction = recording of the attraction call from a male *Dendroctonus* or female *Ips* in the presence of a mate; wood borer = recording from an adult *Monochamus titillator* held with forceps; artificial = computer-generated tone using Adobe Audition 3.0

Treatment	Recording length (s)	Number of phrases per min	Mean phrase length (ms)	Center frequency (Hz)	High frequency (Hz)
D. brevicomis stress	0:24	75	93	1500.0[a]	24000.0
D. frontalis stress	1:15	58	42	8250.0	24000.0
I. pini stress	10:14	66	129	750.0[a]	24000.0
D. brevicomis attraction	0:21	106	229	6937.5	24000.0
D. frontalis attraction	1:06	56	89	8613.3	22050.0
I. pini attraction	0:13	57	259	10 875.0	24000.0
Wood borer	4:16	39	136	7235.2	22050.0
Artificial	1:33	5	10 000	7312.5	24000.0

*The low center frequency (Hz) for these recordings is probably due to the significant background noises at low frequencies during the recording process.

exact test for each treatment. Null hypothesis 1 (H_{01}) is stated as 'beetles enter logs when no sound (control) is played in either log'. Alternative hypothesis 1 (H_{a1}) is that 'the acoustic treatment significantly attracts or deters beetle entry into logs, regardless of which log'. The effect of acoustic treatment on beetle entry into the sound log or no-sound log was tested using a two-tailed 2 × 2 Fisher exact test for each treatment. Null hypothesis 2 (H_{02}) is that 'equal numbers of beetles enter either log ($P = 0.5$)'. Alternative hypothesis 2 (H_{a2}) is that 'a significantly different proportion of beetles enter the sound log ($P << 0.5$) or the no-sound log ($P >> 0.5$)'.

3 RESULTS

3.1 Bark beetle entry into logs

Acoustic treatments did not influence which log beetles chose to enter (two-tailed 2 × 2 Fisher exact test; $P > 0.9$ for all species and treatments; reject H_{a2}) (Figs 3 to 5). However, acoustic treatments did significantly influence whether beetles entered logs at all (reject H_{01}, Figs 3 to 5) (also, see Section 4).

3.1.1 *Dendroctonus brevicomis*

In the no-sound treatment (control), beetle entry into logs was 55%. Of the four acoustic treatments, the artificial sounds negatively affected beetle entry into either log ($P = 0.035$) (Fig. 3). The artificial acoustic treatment reduced log entry by *D. brevicomis* beetles to 23%, compared with 55% when no sound was played. The wood borer treatment and stress call treatment reduced beetle entry to 22 and 25% respectively, but were not statistically different from the no-sound treatment owing to the smaller sample size (wood borer treatment $P = 0.052$; stress call treatment $P = 0.11$) (Fig. 3).

3.1.2 *Dendroctonus frontalis*

When no sound was played (control), the beetle entry rate was 50%. Of the four acoustic treatments, the stress call treatment yielded the strongest response ($P = 0.019$), reducing log entry to 14% (Fig. 4). No other acoustic treatment affected *D. frontalis* entry into logs (Fig. 4). However, the wood borer treatment reduced entry into logs to 21%, but was not significantly different to the no-sound treatment ($P = 0.096$).

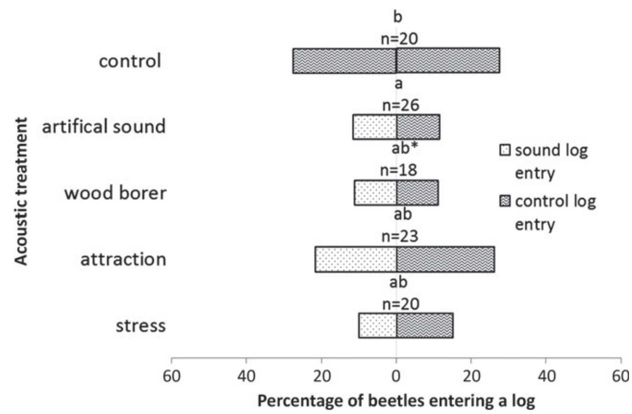

Figure 3. *Dendroctonus brevicomis* total entry percentages and choice of acoustic treatment log or no-sound log. The control treatment did not have a sound treatment. Stress and attraction treatments contain stridulations from male *D. brevicomis*. Wood borer treatment contains stridulations from an adult *Monochamus titillator*. Artificial sound treatment contains computer-generated tones, 10 s long, oscillating in the 0–24 kHz frequency range. The wood borer and artificial acoustic treatment overall entry was significantly reduced when compared with the control. Different letters indicate significance at $P < 0.05$. An * indicates statistical difference from the control at the $P < 0.1$ level.

3.1.3 *Ips pini*

When no sound was played (control), the beetle entry rate was 77%. No significant difference ($P > 0.47$) in log entry was observed between acoustic treatments and the control (Fig. 5).

4 DISCUSSION

4.1 Effects of sound on beetle entry

As bark-beetle-derived signals have been shown to have a negative effect on beetle performance and reproduction,[14] the present objectives were to test whether similar acoustic treatments would reduce bark beetle entry into tree materials. Surprisingly, in sets of logs that had acoustic treatments, no preference was given to the acoustic treatment log or no-sound log. However, although *D. brevicomis* and *D. frontalis* beetles entered control and treatment logs at the same rate, their entry into both logs was significantly reduced when particular sounds (artificial sounds for *D. brevicomis*; stress calls for *D. frontalis*) were played.

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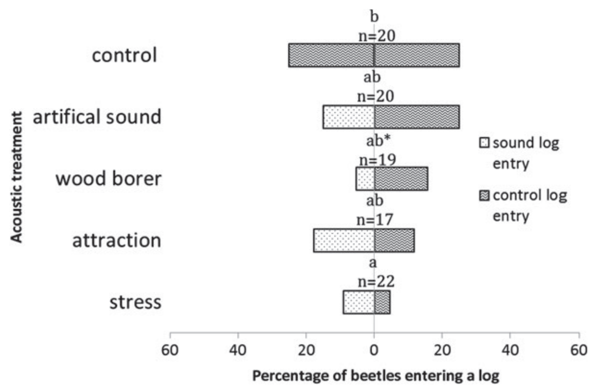

Figure 4. *Dendroctonus frontalis* total entry percentages and choice of acoustic treatment log or no-sound log. The control treatment did not have a sound treatment. Stress and attraction treatments contain stridulations from male *D. frontalis*. Wood borer treatment contains stridulations from an adult *Monochamus titillator*. Artificial sound treatment contains computer-generated tones, 10 s long, oscillating in the 0–24 kHz frequency range. Note that the stress and wood borer treatment overall entry was significantly reduced when compared with the control. Different letters indicate significance at $P < 0.05$. An * indicates significant difference from the control at $P < 0.10$.

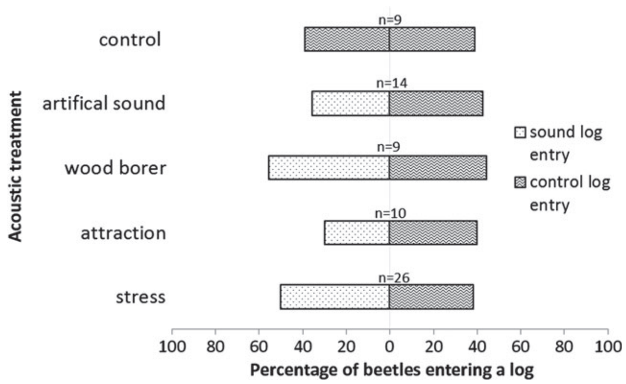

Figure 5. *Ips pini* total entry percentages and choice of acoustic treatment log or no-sound log. The control treatment did not have a sound treatment. Stress and attraction treatments contain stridulations from female *I. pini*. Wood borer treatment contains stridulations from an adult *Monochamus titillator*. Artificial sound treatment contains computer-generated tones, 10 s long, oscillating in the 0–24 kHz frequency range. No significant difference between treatments (all $P > 0.47$).

The fact that sound did not reduce entry into the treatment log may be attributed to the experimental set-up: vibrational signals probably traveled across the entry tube, which could have interfered with taxis towards or away from the sound source or could have altered beetle entry behavior. Future tests should be improved to eliminate this effect. Also, attenuation of acoustic treatments as a result of log moisture and density may have affected beetle response. In any event, artificial sound reduced entry rates of female *D. brevicomis* by 58%, and the stress call reduced entry rates of female *D. frontalis* by 72%. Although both *D. brevicomis* and *D. frontalis* entry into logs was affected by a sound treatment, why there was no congruent response to the same acoustic treatment is unclear. Further tests are needed to determine whether the *D. frontalis* stress call would affect *D. brevicomis* entry rates, and vice versa.

Ips pini entry into logs was not influenced by acoustic treatments. As *I. pini* are secondary beetles entering dead and dying hosts,[32] *I. pini* may be accustomed to an abundance of vibrations or airborne sounds from several species such as wood borers, predators and other bark beetles. This is juxtaposed to *D. brevicomis* and *D. frontalis*, which colonize living trees that are initially absent of biotic sounds from other wood-infesting species. Also, the lack of response by *I. pini* may be attributed to life history traits that differ from those of *Dendroctonus* beetles, such as the sex that initiates colonization, which is the female for *Dendroctonus* and the male for *Ips*, or differences in their ability to perceive vibrations. The frequencies or amplitude administered by the tactile transducer might not be perceived by *Ips* beetles. Studies of *Ips* by Wilkinson *et al.*[33] showed variable effects of beetle stridulation on reproduction or gallery construction. Alternatively, acoustic communication or acoustic cues may not be an important component for entry into host materials by *Ips pini*.

Bark beetles are known to employ 'stress' calls when captured by a predator.[34] Stress calls produced by bark beetles increase the probability of escaping and reduce the handling time by the predator.[34] The presence of the stress call treatment might have caused *D. frontalis* to remain still in the tube between logs, stimulating an avoidance strategy or self-mimesis.[35] Self-mimesis is a common and effective predator avoidance strategy in many insects, as most predators only capture live prey.[35,36] Why *D. brevicomis* responded to the artificial acoustic treatment and *D. frontalis* and *I. pini* did not is also unclear. The two *Dendroctonus* species studied co-occur in *P. ponderosa* in northern Arizona and have similar life histories[25] and thus experience similar acoustic environments during their life stages. *Ips pini* also occurs in *P. ponderosa* in northern Arizona, but typically colonizes the upper bole of the tree or slash material. Differences in responses of each of these species could be attributed to species-level differences in morphology, behavior or physiology.

4.2 Use of sounds for management

The use of acoustics as a management option for land managers is currently limited and consists of techniques for either detecting insects or interrupting their behavior. Detection has had greatest success in locating insects within particular habitats (e.g. in termites,[37] root weevils,[38] wood borers[39] and Caribbean fruit flies[40]). Inciting a behavioral response has proved to be more difficult than detection.[41] For example, various studies have tested the effectiveness of using sound to attract crickets (Gryllotalpidae, Gryllidae and Tachinidae) to traps.[42,43] As stated in these studies, effectiveness of acoustic traps is probably limited to species that utilize phonotaxis over large distances, like most crickets.[42] Recently, Eriksson *et al.*[44] used vibrational signals to disrupt mating in a pest leafhopper, *Scaphoideus titanus*, illustrating the potential for acoustic management of species that do not use long-range phonotaxis. Rather than transmitting airborne sounds, Eriksson *et al.*[44] transmitted a substrate-borne acoustic treatment through grapevine plants. This method of using the host as a medium is similar to the goals of the present study (i.e. transmitting sound through ponderosa pine logs).

The reduction in primary bark beetle entry into logs with particular acoustic signals provides promise that acoustic treatments can become a viable option for resource managers in the future. However, greater reduction rates are needed to prevent tree death and beetle colonization, especially if beetle populations are high and tree vigor is poor.[45] Also, further studies are needed to test the effects of acoustic treatments on standing, living trees. Once field efficacy is determined, the localized delivery of acoustic treatments used here would help to provide protection against *Dendroctonus* attack on select trees within forests or in

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high-value trees on private or public lands. Sound input from the same tactile transducer as that used in this study was detected 12 m up the bole of a 60 cm diameter (at breast height) ponderosa pine tree, illustrating the potential for complete tree protection after successful field trials have been completed.[22] Delivery of power to the transducers currently limits the use of this method in protection of large areas with large numbers of trees.

In *Dendroctonus*, females release antiaggregate pheromones when exposed to male attractant calls.[46] The potential for future management tactics, such as utilizing acoustics to reduce beetle entry into trees via antiaggregate pheromone production, appears to be likely. Thus, acoustic technology could substantially lessen bark beetle reproduction and colonization success, deterring or disrupting communication between conspecific or heterospecific species.

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