

## Pentatomid bug pheromones in IPM: possible applications and limitations

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**Abstract:** Male-produced pheromone components have been identified from several species of agriculturally important stink bugs, including the red-shouldered stink bug *Thyanta pallidovirens*, the green stink bug *Acrosternum hilare*, the conchuela stink bug *Chlorochroa ligata*, Uhler's stink bug *C. uhleri*, and Say's stink bug *C. sayi*. The pheromone of *T. pallidovirens* consists of a thermally unstable ester, methyl (2E,4Z,6Z)-decatrienoate, in combination with one, two, or all of the sesquiterpenes zingiberene, sesquiphellandrene, and -curcumene. The pheromone attracted only females, as well as a specialist predator, the sphecid wasp *Astata occidentalis*. The pheromone of *A. hilare* consisted of two isomers, (4S)-*cis*- and (4S)-*trans*-(Z)-bisabolene epoxides, in a 19:1 ratio. Both compounds were required for attraction of females. Male *C. sayi* produced methyl geranate as a major component, with traces of two other components, methyl citronellate and methyl dihydrofarnesoate. Only methyl geranate appeared to be required for attraction. Males of *C. uhleri* and *C. ligata* produced very similar blends, with methyl dihydrofarnesoate as the major component, and methyl farnesoate and a novel compound, methyl (E)-5-2,6,10-trimethyl-5,9-undecadienoate, as minor components. Only methyl dihydrofarnesoate appeared to be required for attraction of females. Overall, relatively low numbers of bugs were caught in field trials of pheromone-baited traps, probably due in part to inefficient trap designs. In addition, phytophagous stink bugs communicate over shorter distances by means of substrate-borne vibrational signals, and these signals may be critically important in attracting bugs right up to pheromone sources. Examples of the vibrational signals for two species, *Nezara viridula* and *A. hilare*, are given.

**Key words:** Pentatomidae, stink bug, pheromone, attractant, vibrational signals

### Introduction

Phytophagous stink bugs (Heteroptera: Pentatomidae) are occasional to chronic pests in all types of crop systems, including annual crops such as grains, cotton, alfal-

fa, beans, and tomatoes, and perennial crops such as tree fruits and nuts (Schaefer and Panizzi 2000). Damage is caused by both immatures and adults, but only adults are winged and capable of long-distance movement. Injury to young seeds, fruits, or nuts produces necrotic lesions and often results in premature abortion, while attacked leaves may wilt and die. Stink bugs are also known or implicated as vectors of plant pathogens such as yeast, fungi, and bacteria, particularly in crops such as pistachio.

Many stink bug species are polyphagous and the adults are highly mobile, which complicates their monitoring and control. Bugs migrate into crops in response to natural events such as the senescence of native vegetation in the habitat, or in response to mowing or harvesting of nearby crops harboring large bug populations. Effective bug control hinges on the rapid detection of these invasions so that appropriate control measures can be implemented before serious crop damage occurs. However, sampling methods for most bug species are still relatively primitive, consisting mainly of sweep-net or beating tray sampling, or visual inspection of fruits for feeding damage or excrement. Monitoring methods based on pheromones or other attractants have not yet been developed for most of the major pest bug species.

Until recently, stink bugs often were kept under control by insecticide sprays applied to control primary pest species such as lepidoptera. However, recent changes in crop protection including the introduction of highly selective methods such as genetically modified plants that produce Bt toxins, or pheromone-based mating disruption, coupled with a corresponding decrease in the use of broad-spectrum insecticides, has resulted in a resurgence of problems with true bugs in crops such as apples, pears, and cotton. Continued high levels of damage by stink bugs and other pests may hinder the continued implementation of these new control methods. Thus, new methods of monitoring and control of stink bugs are urgently needed.

We summarize here our efforts to identify the pheromones of some of the most important stink bug pests of agriculture in California, including the red-shouldered stink bug *Thyanta pallidovirens*, the green stink bug *Acrosternum hilare*, the conchuela stink bug *Chlorochroa ligata*, Uhler's stink bug *C. uhleri*, and Say's stink bug *C. sayi*. We also describe problems encountered during the development of pheromone-based traps for these stink bug species. Finally, we describe some preliminary results relating to substrate-borne vibrational signals that stink bugs use for communication at short ranges, once males and females are on the same plant or substrate.

## Materials and methods

*Insects.* Stink bug colonies were started from bugs collected by sweep-netting of agricultural crops or native vegetation at sites in southern California. Bugs were reared on a diet of organically grown green-beans (*Phaseolus vulgaris* L.), raw

shelled peanuts (*Arachis hypogaea* L.), and raw sunflower seeds (*Helianthus annuus* L.), supplemented with bouquets of alfalfa (*Medicago sativa* L.), or seasonal weeds including mustard (*Brassica campestris* (L.)), London rocket (*Sisymbrium irio* L.), Russian thistle (*Salsola iberica* Sennen), shepherd's purse (*Capsella bursa-pastoris* L.), and cheeseweed (*Malva parviflora* L.) depending on availability. Bugs were reared in a controlled environment chamber, on a 16:8 L:D cycle, with lighting provided by banks of 8 fluorescent light tubes (Sylvania Octron, 32W, F032/T35), at  $23\pm 2^\circ\text{C}$ , and  $>50\%$  relative humidity. Eggs were collected from the colony every other day and were held in covered Petri dishes through to the second nymphal stage. After the 2<sup>nd</sup> molt, nymphs were transferred to 1.9 liter cardboard ice-cream containers with muslin lids. Nymphs were fed as described above, with food changed every other day. After the final molt, adults were collected and sexed and cohorts of virgin adults were maintained with food in clean ice-cream cartons (5-7 bugs per 0.95 liter container, 10-20 bugs per 1.9 liter container) until used for collection of volatiles or bioassays.

*Collection and analysis of insect-produced compounds.* Sexed, virgin adult bugs and a few green beans were put into glass aeration chambers lined with hardware cloth screen for the bugs to perch on. Humidified, charcoal-filtered air was drawn through the chamber, and entrained bug volatiles were collected on activated charcoal traps made from 4 mm id. glass tubes loaded with a 0.4 cm bed of 80-100 mesh activated charcoal, precleaned by heating at  $200^\circ\text{C}$  under a flow of clean  $\text{N}_2$  ( $\sim 100$  ml/min) overnight. Aerations were conducted continuously for 2-3 wk at  $\sim 25^\circ\text{C}$  with cohorts of bugs of known age, changing the food and the collectors every other day. Collectors were eluted with pentane (500  $\mu\text{l}$ ), and extracts were stored in glass vials with Teflon-lined screw caps at  $\sim -20^\circ\text{C}$  until needed. Aeration chambers were set up near the window so that bugs had natural light, and supplementary fluorescent light was provided with a light bank directly overhead to provide long day conditions (lights on from 6:00 to 22:00). Bugs that died were replaced with virgin individuals from a cohort of the same age. Dead bugs were removed as soon as discovered to minimize contamination; as muscles relaxed in dead bugs, the contents of the defensive metathoracic glands were released (Ho, pers. obs.). As a control, green beans were aerated, collecting the volatiles as described above. Extracts were analyzed by GC-MS, looking particularly for sex-specific compounds produced only by sexually mature virgin bugs.

*Laboratory bioassays.* Laboratory bioassays were carried out with a vertical glass Y-tube olfactometer (i.d., 4.5 cm, arms 14 cm long, center tube 18 cm long). Each arm of the Y terminated in a female ground glass fitting, with matching male fittings terminating in hose nipples. Teflon tubing connected the Y-tube to stimulus flasks, and vinyl tubing connected the bottom outlet to a vacuum source.

Test bugs were reared under long day conditions as described above. Lighting was provided by a light bank fitted with a daylight fluorescent lamp and a wide-spectrum "grow-light" fluorescent lamp (Sylvania Octron 32W) suspended 30 cm

above the olfactometer. The light level as the upper end of the Y-tube was ~ 600 lux, and at the lower end, ~ 300 lux. Bioassays were conducted at ambient temperature and humidity conditions in the laboratory ( $26^{\circ}\text{C} \pm 3^{\circ}\text{C}$  and  $50 \pm 15\%$  humidity). Depending on bug species, bioassays were conducted between 10:00 and 22:00.

*Field bioassays of pheromone lures.* Field bioassays generally were carried out with rubber septum lures loaded with hexane solutions of test compounds. Traps used included commercially available (Trécé Inc., Slainas CA) jug traps, consisting of a clear plastic jar with two inward-pointing screen cones, or a custom built screen trap designed especially for trapping stink bugs. We also experimented with a “trap plant” concept, in which individual plants were baited with a pheromone lure, and the number of bugs on treated and control plants were counted.

*Recording vibrational signals.* Recordings were made with virgin, sexually mature bugs in a quiet room with fluorescent lighting provided with Sylvania Optron 32W lights. Spectral and temporal characteristics of songs were determined from recordings made from bugs singing on the membrane of a 10 cm diam low-midrange loudspeaker (40-6,000 Hz frequency response, impedance 8  $\Omega$ , #WS 13 BF, Visaton, Germany). A pair of insects was placed on the speaker cone, and prevented from escaping by placing a 10 cm diam translucent Fluon®-coated plastic cylinder over the speaker. Signals were amplified with a custom-built amplifier, then digitized and recorded on the hard drive of a Pentium 4 computer equipped with a Lexicon Core2 PCI recording system for PC (Sweetwater Sound, Fort Wayne, IN), using Cool Edit-Pro™ Special Edition version 1.1 software (Syntrillium Software, Phoenix, AZ). Digitized data files were rerecorded onto CDs. Signals were followed in real time with headphones. Most insects emitted signals within a couple of minutes of being placed onto the speaker membrane, or after they had contacted each other.

Mating behaviors related to song production also were analysed from pairs of bugs placed on a potted bean plant with most of the side branches removed. Signals transmitted through the plant were recorded by placing the membrane of a dynamic microphone cartridge (impedance 600  $\Omega$ , 22 mm diameter, 40-22000 Hz frequency response ; #D 3800, AKG, Austria) in contact with the stem 3 cm above the ground. Contact between the plant and the microphone was made by a 2 x 2 mm piece of double-sided sticky tape placed between the membrane and the plant stem. The signal from the microphone was amplified, digitized, and recorded. Along with the recordings, behavioral observations were recorded in a notebook so that behaviors could be correlated with song characteristics.

Recordings from both types of substrate were analyzed using Sound Forge version 4.5 software (Sonic Foundry Inc., Madison WI). Data extracted from recordings included the dominant frequencies, durations and repetition times (the latter defined as the time interval between the start of two sequential signals) of particular pulses or pulse trains.

## Results and discussion

*Identification and bioassay of pheromones.* In all of the stink bug species studied, males began producing sex-specific compounds with the onset of sexual maturity. These compounds were entirely distinct from the defensive compounds, and with one exception, males of each species produced a unique blend. Thus, male *T. pallidovirens* produced a novel compound, methyl (2*E*,4*Z*,6*Z*)-decatrienoate **1**, in combination with three sesquiterpenes, zingiberene **2**, sesquiphellandrene **3**, and  $\alpha$ -curcumene **4** (Fig. 1) (Millar 1997, McBrien and Millar 1999). The ester **1** is thermally unstable, which complicated its identification and synthesis. In laboratory and field trials, the ester alone or the sesquiterpenes alone were not attractive. However, the ester in combination with any one, two, or all of the sesquiterpene components was attractive specifically to females, indicating that the pheromone is a sex pheromone. This degree of redundancy in an insect pheromone signal is unusual. During field trials, significant numbers of a specialist parasitoid of stink bug adults, the sphecid wasp *Astata occidentalis*, were also caught (Millar et al. 2001). Only females were caught, clearly indicating that this predator eavesdrops on the pheromone to locate its prey for provisioning its nest. The attraction of significant numbers of this specialist predator also provided indirect evidence for the correct identification of the pheromone. Further tests determined that the ester alone was attractive to the wasp.

Male *Acrosternum hilare* produced a 19:1 mixture of (4*S*)-*cis*-(*Z*)-bisabolene epoxide **5** ((4*S*)-*cis*-*Z*-BAE) and (4*S*)-*trans*-*Z*-BAE **6** (Fig. 1) (Aldrich et al. 1993; McBrien et al. 2001). These two components are also produced by the southern green stink bug *Nezara viridula*, but in a different ratio of about 1:3 (Aldrich et al. 1987; Baker et al. 1987; Brézot et al. 1993). Neither compound alone was attractive to female *A. hilare*, but a 95:5 *cis:trans* blend, mimicing the ratio naturally produced by males, was attractive to females in Y-tube bioassays. Bioassays in a field cage showed that significantly more *A. hilare* females were attracted to lures treated with a 95:5 blend of synthetic (4*S*)-*cis*-*Z*-BAE and (4*S*)-*trans*-*Z*-BAE placed inside a bouquet of alfalfa than to an alfalfa bouquet containing a pentane-treated control. In field cage studies, attraction of females was greatest during the late afternoon and evening hours, and female *A. hilare* approached the synthetic pheromone source almost exclusively by walking. Full scale field trials are continuing, but have been hampered by difficulties in locating sites with large bug populations, and by inappropriate trap design (see below).

The major component of the male-specific compounds from *Chlorochroa sayi* was identified as methyl geranate **7** (Fig. 1) (Ho et al. 2001). Two other components, methyl citronellate **8** and methyl dihydrofarnesoate **9**, were also detected in trace amounts. In laboratory and field bioassays, methyl geranate as a single component appeared to be as attractive as the three-component blend. Furthermore, significant numbers of male *C. sayi* were caught in traps baited with *C. sayi* pheromone, suggesting that the pheromone may be an aggregation pheromone rather than a sex

pheromone. However, other explanations cannot be excluded, such as the attraction of males by females once the latter are in the trap.

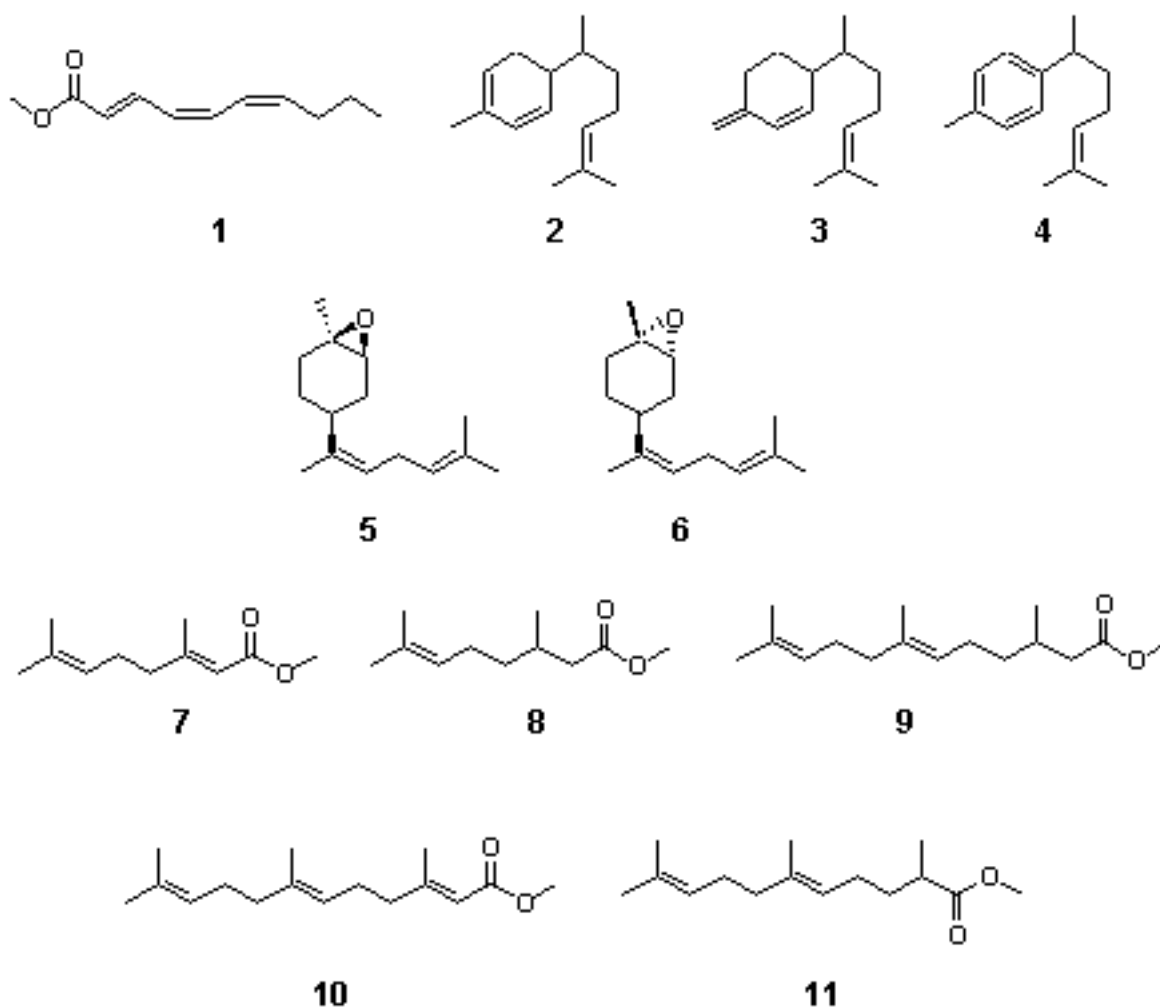


Figure 1. Structures of sex-specific compounds produced by sexually mature male stinkbugs. Compounds: **1**, methyl (2*E*,4*Z*,6*Z*)-decatrienoate; **2**, zingiberene; **3**, sesquiphellandrene; **4**, -curcumene; **5**, (4*S*)-*cis*-(*Z*)-bisabolene epoxide; **6**, (4*S*)-*trans*-(*Z*)-bisabolene epoxide; **7**, methyl geranate; **8**, methyl citronellate; **9**, methyl dihydrofarnesoate; **10**, methyl farnesoate; **11**, methyl (E)-5-2,6,10-trimethyl-5,9-undecadienoate.

Males of *C. uhleri* and *C. ligata* produced blends of male-specific compounds that were indistinguishable (Ho 2000). The major component consisted of methyl (*R*)-3-(*E*)-6-2,3-dihydrofarnesoate **9** in combination with traces of methyl farnesoate **10** and a novel compound, methyl (E)-5-2,6,10-trimethyl-5,9-undecadienoate **11** (Fig. 1). The latter compound is an analog of methyl dihydrofarnesoate that has been chain-shortened by one carbon. Laboratory and field trials indicated that the major component alone was attractive to females. In addition, as had been found with *C. sayi*, significant numbers of *C. uhleri* males were caught in pheromone-baited traps,

although it cannot be certain that they were actually attracted by the pheromone, and not by cues associated with trapped females. It is also not clear why the male-produced volatiles of these two species, which are sympatric over at least part of their ranges, are virtually identical.

*Stink bug trap development.* To date, we have demonstrated that the pheromone blends for the various stink bug species are species specific, and are attractive to one and in some cases possibly both sexes, in laboratory, field cage, and full field bioassays. However, trap catches, using pheromone lures placed in several standard types of insect traps, have been lower than expected for several possible reasons. First, the relatively long-lived adult bugs, which feed and mate multiply throughout their lives, may respond less strongly to pheromones than short-lived, non-feeding species such as some of the lepidoptera, which are under intense pressure to mate and reproduce before they exhaust their limited energy reserves and die. Second, typical insect traps that are designed to catch flying nocturnal insects may be inappropriate for catching stink bugs. Observations of stink bugs responding to pheromone baits have provided several pieces of information that proved important for designing more effective stink bug traps.

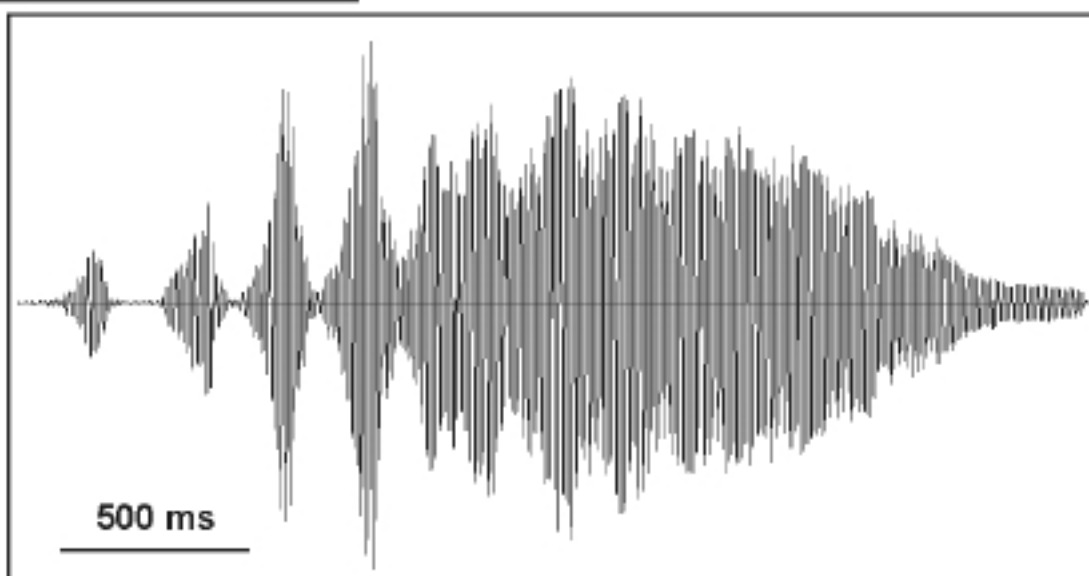
Specifically: (1) Stink bugs show a strong tendency to walk upwards on a plant, or, if on the ground, they walk towards the nearest vertical object and climb upwards. (2) Stink bugs do not like to enter dark spaces. (3) At medium range (10 cm to several meters) from a pheromone source, bugs walk towards the pheromone source rather than flying. Thus, traps must be made accessible to walking insects, so they must be in contact with the ground or better, with plant material. (4) Bugs are not easily captured in sticky traps. Bugs walk into traps, and when their feet touch the stickum, they stop, and avoid getting caught. (5) Bugs move around a lot inside traps, and frequently find their way out. Thus, traps must be easy for the bugs to enter, but difficult for them to find their way out again.

In the past year, we concentrated our efforts on designing a trap based on these design criteria, and preliminary results suggest that the new trap is much more effective, at least in row crops, with individual trap catches as high as ~40 bugs per trap over 3-7 d trapping periods (McBrien and Millar, manuscript in prep.). In the coming year, our efforts will be focused on applying the same design concepts to a trap suitable for use in tree crops.

*Substrate-borne vibrational signals.* It has been known for some time that stink bugs produce substrate-borne vibrational signals for communication at short range (Gogala 1984; Çokl 1985; Ota and Çokl 1991; Ryan et al. 1996; Çokl et al. 1999, 2000). These signals are generated with a tymbal organ that stretches across the dorsal surface under the elytra. The vibrations are transmitted into the plant stem through the insect's legs, and are propagated along the plant as bending waves (Michelsen et al. 1982). The signals are detected by vibration sensors in the legs of the receiving insect. Both males and females appear to produce several different vibrational songs. To locate each other once on the same plant, males and females pro-

duce a duet of calling songs (Figs. 2 and 3), with one or both insects following the signals to their sources. Once at close range or having contacted each other, the insects may begin producing courtship songs. There is virtually no airborne sound associated with these signals, and their primary transmission medium is clearly the plant substrate (Michelsen *et al.* 1982). Because these signals are transmitted through the plant, they may be less prone to eavesdropping by parasitoids and predators than a more widely dispersed airborne acoustic signal.

### **Acrosternum hilare**



### **Nezara viridula**

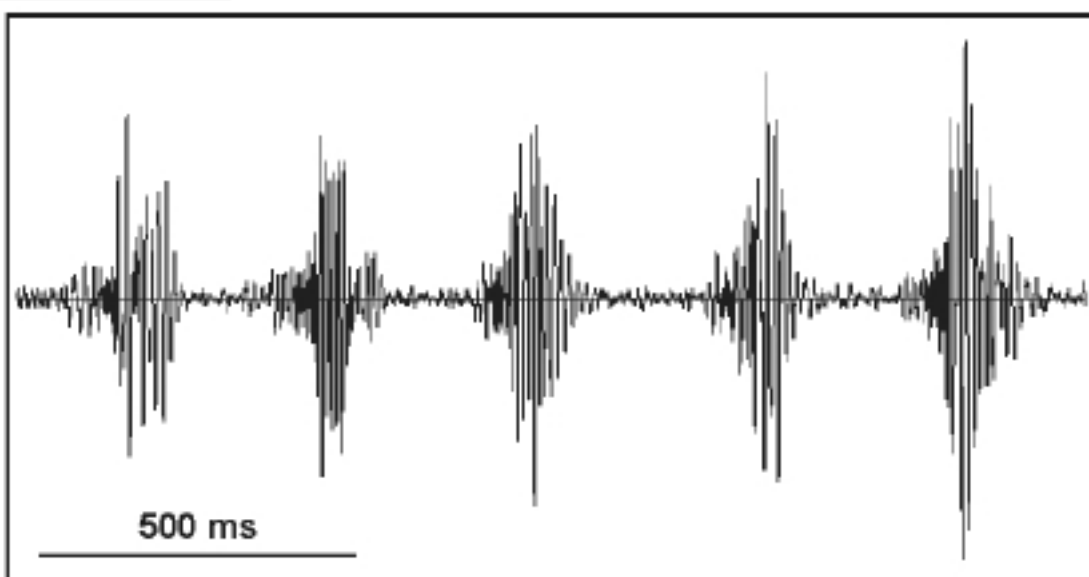
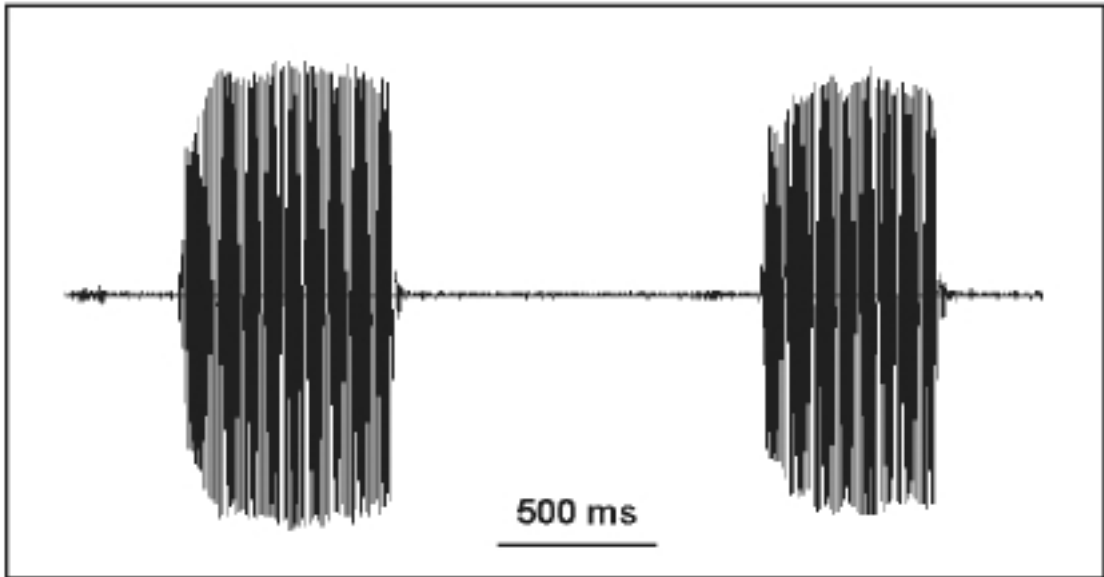


Figure 2. Oscillograms of calling songs produced by male *Acrosternum hilare* and *Nezara viridula*.

**Acrosternum hilare**



**Nezara viridula**

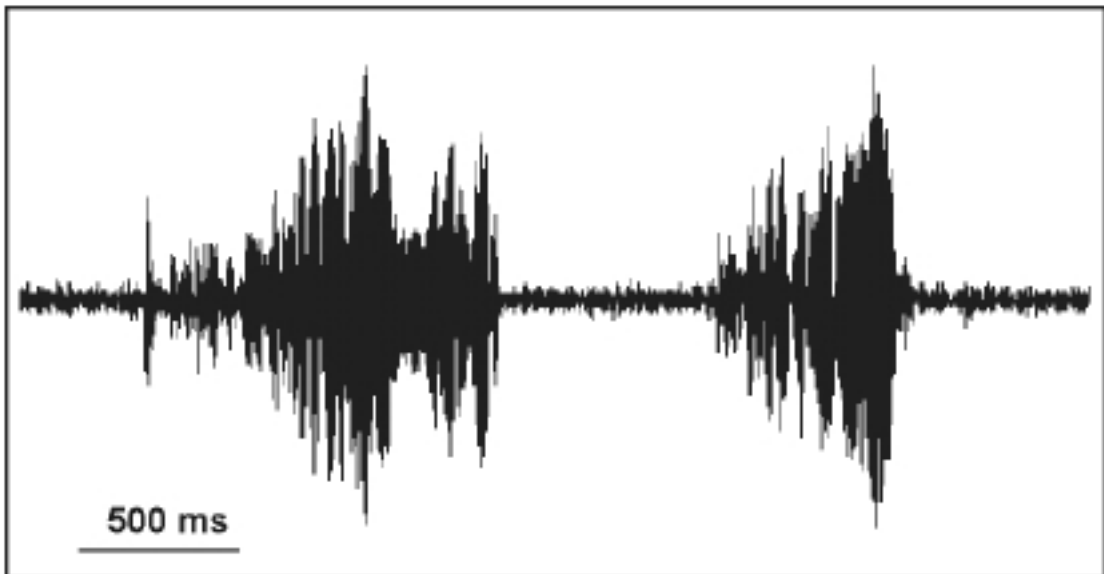


Figure 3. Oscillograms of calling songs produced by female *Acrosternum hilare* and *Nezara viridula*.

Preliminary investigations of the song repertoire of California populations of *Nezara viridula* and *Acrosternum hilare*, chosen for study because they utilize the same pheromone components, have shown distinct differences in the song repertoires of the two species (Üokl et al. 2001). Female *A. hilare* produce a calling song, and the production of this song is stimulated by male presence or calling. The temporal characteristics of this song are similar to the narrow-band *N. viridula* female calling song.

Male *A. hilare* produced two different songs, each associated with a different phase of mating behavior. In the calling phase, males produced a song composed of regularly repeated, complex pulse trains whose temporal structure resembled that of the *N. viridula* male courtship song. In the courtship phase of behavior, males of *A. hilare* emitted a courtship song which terminated female singing. This song had similar temporal characteristics to those of the narrow-band *N. viridula* male calling song. Immediately after initiating copulation, *A. hilare* pairs emitted another song which had no counterpart in the repertoire of *N. viridula*. In contrast, males of *A. hilare* did not appear to produce a song equivalent to the *N. viridula* male rival song, and neither sex of *A. hilare* produced songs equivalent to the broad-band pulses and pulse trains found within male and female *N. viridula* calling songs. Orientation of males towards females was mediated by the female calling song, which had similar spectral and temporal characteristics in both species. Overall, male songs of the two species, although they shared some spectral characteristics, differed in temporal structure and in the contexts in which they were emitted.

Because these vibrational songs bring males and females together once they are on the same plant, they may be important in sampling stink bugs with pheromone traps. Insects may be attracted to the vicinity of a trap by the pheromone, but if the shorter-range vibrational signals are not present, the insects may not move into the trap towards the pheromone source. This may explain observations by several researchers of bugs clustered in the vicinity of pheromone traps, but with few bugs actually in the traps (Aldrich *et al.* 1991; James *et al.* 1996). The interplay between the pheromonal and vibrational signals is the subject of ongoing research.

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