

Aggregation pheromone of the almond bark beetle *Scolytus amygdali* (Coleoptera: Scolytidae)

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Abstract: The almond bark beetle (ABB), *Scolytus amygdali* (Coleoptera: Scolytidae), is a pest of stone fruits in the Mediterranean region and southern Europe. Adults feeding on buds cause most of the damage. Applications of non-selective insecticides, burning of dead trees and pruning slash are environmentally unsafe and are often ineffective for ABB control. Preliminary experiments with ABB colonizing branches indicated the existence of an aggregation pheromone, and prompted us to identify it. Volatiles emitted by female ABB boring into plum branches were collected on Porapak Q and eluted with hexane. GC-EAD analyses of volatile extracts, using female antennae as an electroantennographic detector, revealed four EAD-active candidate pheromone components, as follows: (3*S*,4*S*)-4-methyl-3-heptanol (**SS-I**), most abundant and EAD-active component; (3*S*,4*S*)-4-methyl-3-hexanol (**SS-II**); (5*S*,7*S*)-7-methyl-1,6-dioxaspiro[4,5]decane (**III**); and 7-methyl-1,6-dioxaspiro[4,5]dec-8-ene (**IV**), the first unsaturated spiroaketal found in insects. In field experiments (1994-1998) using funnel traps baited with polyethylene pheromone dispensers, **SS-I** unlike **SS-II** was attractive by itself, while **SS-I** plus **SS-II** at a ratio of 2:1 was optimally attractive. Addition of stereoisomeric mixtures of **III** and/or **IV** did not affect trap captures. Candidate kairomones ethanol and propanol did not affect total trap catches. Methanol, in contrast, strongly inhibited attraction of beetles to pheromone-baited traps and prevented colonization of cut branches. It failed, however, to reduce damage to tree buds caused by ABB maturation feeding. Although **SS-I** plus **SS-II** was twice as attractive as the stereoisomeric mixtures of 4-methyl-3-heptanol plus 4-methyl-3-hexanol, these readily obtainable stereoisomeric mixtures can be used for both pheromone-based monitoring and control of ABB populations.

Key words: pheromone, bark beetle, Scolytidae, stone fruits, ethanol, trap

Introduction

The almond bark beetle (ABB), *Scolytus amygdali* Geurin-Meneville, is a pest of cultivated species of stone (*Prunus*) and poem (*Malus*) fruits in the Mediterranean region

and southern Europe. During the last two decades populations in Israel have again reached high densities. Most severely affected are plantations of plum, apricot and peach in Israel (Mendel *et al.* 1997), cherry in Spain (Teresa Garcia Becedas, pers. comm.), and almond in Morocco (Mahhou and Dennis 1992). Outbreaks often follow tree injury caused by flatheaded root borers, *Capnodis* spp. (Coleoptera: Buprestidae) (Ben-Yehuda *et al.* 1997). Current management of ABB by preventive applications of non-selective insecticide, burning of both dead trees and pruning slash are environmentally unsafe and often ineffective.

Only a few pheromones of *Scolytus* bark beetles have been described. Female *S. multistriatus* in Britain produce (3*S*,4*S*)-4-methyl-3-heptanol, - and - multistriatin (Pearce *et al.* 1975), the latter also being a pheromone component of *S. scolytus* in Germany (Gerken *et al.* 1978). Male *S. scolytus* in Britain produce both (3*S*,4*S*)- and (3*R*,4*S*)-4-methyl-3-heptanol (Blight *et al.* 1979a), but only the former is attractive in the field. (Blight *et al.* 1979c). Female *S. scolytus* produce (3*R*,4*S*)-4-methyl-3-heptanol and -multistriatin, the latter serving as an anti-aggregation pheromone (Blight *et al.* 1983a). 4-Methyl-3-heptanone is produced by female *S. multistriatus* and male *S. scolytus* (Blight *et al.* 1983b).

Attractants of four other *Scolytus* species were found in field screening tests. *Scolytus pygmaeus* and *S. laevis* responded to lures containing (3*S*,4*S*)-4-methyl-3-heptanol, -multistriatin plus -cubebene or (-)-limonene (Vité *et al.* 1976; Minks and van Deventer 1978; Bejer 1979). *S. mali* was attracted to volatiles produced by conspecific females (Rudinsky *et al.* 1978). On the other hand, fir engravers *S. ventralis*, select and attack trees being lured by their host primary attractants (Macías-Sámao *et al.* 1998a,b).

Most native American *Scolytus* spp. colonize gymnosperm trees and are bigamous, suggesting that pheromonal communication is controlled by males (Wood 1982). Most West Palearctic *Scolytus* spp. colonize angiosperm trees and are monogamous, with females (except male *S. scolytus*) attacking the tree (Balachowsky 1949).

In preliminary experiments we observed aggregation behavior of female and male ABB on cages containing female-infested branches, whereas few beetles alighted on cages containing uninfested branches. These observations suggested that female ABB emit an aggregation pheromone.

Our objectives were to: 1) identify the aggregation pheromone of ABB; 2) test attraction of ABBs to synthetic pheromone components; 3) examine whether candidate kairomones enhance attractiveness of the pheromone; and 4) explore the potential of synthetic semiochemicals to manipulate ABB in fruit orchards.

Materials and Methods

Insects and host material. Branches of plum (*Prunus communis*) and nectarine (*Prunus persica*) infested with ABB were collected in a stone-fruit farm at Kefar Ta-

bor in eastern Galilee. All beetles were carefully identified to ensure that only ABB, but not congeneric *S. regulosus*, were included in a mass rearing program.

Collection and extraction of volatiles. Seven to 10 branches (4-5 cm in diam.) infested with several thousand mostly unmated females were placed in a metal container (30 x 40 x 50 cm). Charcoal-filtered air was drawn through the chamber at 10 l/min, and volatiles were collected in a glass column filled with 1 gram of Porapak Q. Columns were replaced at 48 h intervals and trapped volatiles were eluted with hexane. In addition, beetle-produced frass (boring dust plus fecal matter) was extracted in hexane.

Analyses of extracts. Extracts were analyzed by coupled gas chromatographic electroantennographic detection (GC-EAD). The analyses were performed on a Hewlett Packard 5890 gas chromatograph equipped with a fused silica column (30 m x 0.25 mm ID), coated with HP-5 or FFAP. The HP-5 column was programmed at 50°C for 1 min rising at 3°C/min to 110°C and then at 20°C/min to 240°C; the FFAP column was programmed at 50°C for 5 min rising at 5°C/min to 140°C and then at 10°C/min to 220°C. EAD-active compounds were identified by coupled gas chromatography mass spectrometry (GC-MS) of insect-produced and authentic standards.

Chemicals. (3*S*,4*S*)-4-Methyl-3-heptanol (**SS-I**) and (3*S*,4*S*)-4-methyl-3-hexanol (**SS-II**), 7-methyl-1,6-dioxaspiro [4,5] decane (**III**, containing four stereoisomers) and 7-methyl-1,6-dioxaspiro [4,5] dec-8-ene (**IV**, containing four stereoisomers) were prepared at the University of Hamburg. 4-Methyl-3-heptanol (**I**) containing all four stereoisomers at a ratio of 3:3:2:2 (30% of **SS-I**) was purchased from Aldrich Chemicals. 4-Methyl-3-hexanol (**II**) containing all four stereoisomers at a ratio of 1:1:1:1 (25 % of **SS-II**) was prepared by a Grignard reaction of 2-bromopentane and propionaldehyde in dry THF at the Volcani Center.

Preparation of lures. All compounds tested in field experiments are listed in Table 1. Chemicals were dissolved in hexane and aliquots of 200 µl were applied to 1 cc polyethylene-capped vials (Just Plastic Ltd, UK). The lures were dried at room temperature. This polyethylene dispensers performed better than rubber septa (Yogev Ltd, Rishon Le'zion, Israel) as shown in preliminary tests.

Field experiments. Field experiments were conducted at Kefar Tavor in eastern Galilee in a plantation with small blocks of almond, plum, apricot and nectarine, and at Mishmar ha'Emeq (Yizre'el Valley), in a plantation of almonds of several varieties. Lures were deployed in black flat funnel traps (Röchling, Haren KG) which were suspended 1m above ground between pairs of trees at intervals of 30-50 m. Experimental treatments were arranged in randomized blocks, replicated 8-20 times.

Experiments 1-8 (Tables 2, 3) were designed to determine the most attractive pheromone blend. Experiments 9-12 (Table 4) tested whether candidate kairomones (methanol, ethanol or propanol) affected attractiveness of pheromone components. The alcohols were applied to 12 cc polyethylene-capped vials (Just Plastic Ltd, UK). Since methanol was found to inhibit the response of beetles to pheromone-baited traps, experiments 13-15 (Table 5) tested whether methanol also inhibited colonizat-

ion of branches by beetles. In these experiments, treatments were spaced > 20 m and consisted of 10-12 freshly cut branches (4-5 x 50-60 cm long) placed in the shade of trees. Numbers of beetle-produced entrance holes and attempted egg galleries were compared between untreated branches and branches treated with pheromone, candidate repellent or both. Experiment 16 (Table 6) tested whether release of methanol in orchard trees reduced the incidence of ABB bud feeding compared to control trees.

Table 1. List of field-tested attractants.

Pheromone components
1. 4-methyl-3-heptanol (containing four stereoisomers) = I
2. (3 <i>S</i> ,4 <i>S</i>)-4-methyl-3-heptanol = SS-I
3. 4-methyl-3-hexanol (containing four stereoisomers) = II
4. (3 <i>S</i> ,4 <i>S</i>)-4-methyl-3-hexanol = SS-II
5. 7-methyl-1,6-dioxaspiro [4,5] decane (containing four stereoisomers) = III
6. 7-methyl-1,6-dioxaspiro [4,5] dec-8-ene (containing four stereoisomers) = IV
Potential kairomones
1. methanol
2. ethanol
3. propanol

Analyses of results. Trapped male and female beetles were counted. Differences between means were tested by a parametric one-way ANOVA. The procedures used were PROC GLM, and PROCMEAN type III, and the sum of squares was used for computing all F values. Means were transformed into square roots + 0.5. Percentages of males were transformed into arcsin. Differences between means were tested for significance, using the Student-Neuman-Keuls test ($P=0.05$).

Results

GC-EAD analyses. In GC-EAD analyses of volatile extracts, four components consistently elicited antennal responses (Figure 1). The most EAD-active component was identified as (3*S*,4*S*)-4-methyl-3-heptanol (**SS-I**). The other components were identified as (3*S*,4*S*)-4-methyl-3-hexanol (**SS-II**), (5*S*,7*S*)-7-methyl-1,6-dioxaspiro [4,5] decane (**III**) and 7-methyl-1,6-dioxaspiro [4,5] dec-8-ene (**IV**).

Field experiments. Experiments 1-6 (Table 2). Preliminary field tests (1995) had indicated that **SS-I**, unlike **SS-II**, was attractive by itself. Increasing the amount of **SS-I** resulted in enhanced attraction of ABBs (Exp. 1). Addition of **SS-II** to **SS-I** at a ratio of 1:1 or 2:1 doubled trap captures (Exps. 2, 3). Spiroketals **III** and/or **IV** failed

to enhance attractiveness of **SS-I** plus **SS-II** (Epps. 4, 5), and did not affect the sex ratio of trapped beetles.

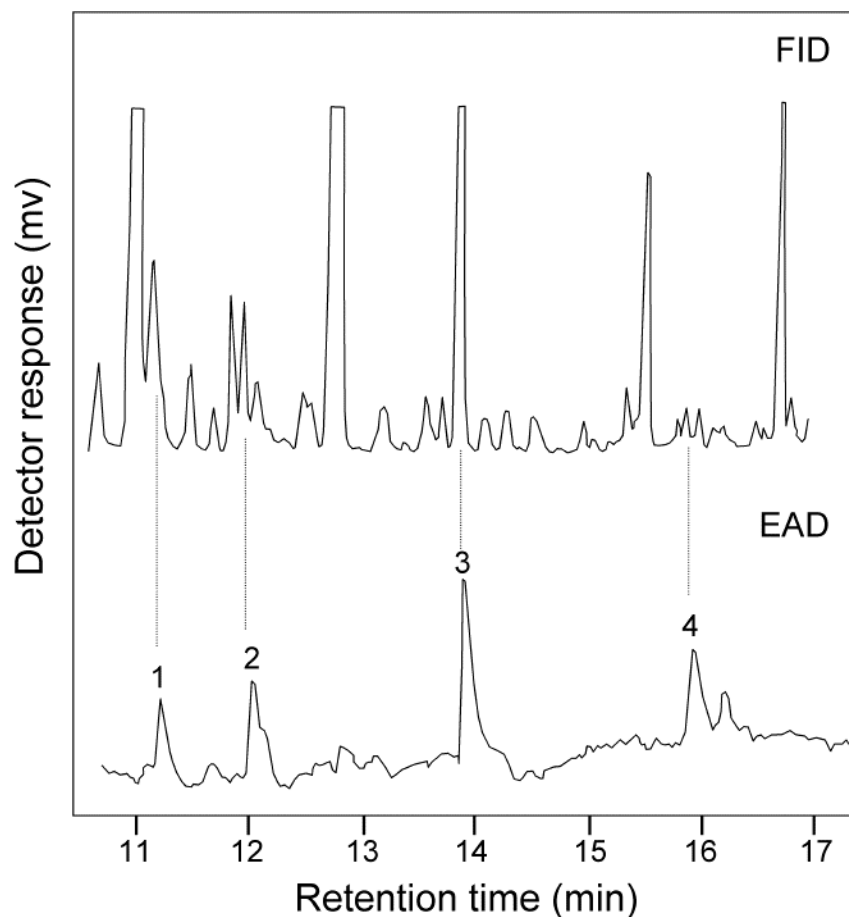


Figure 1. Flame ionization detector (FID) and electroantennographic detector (EAD: antenna of female *Scolytus amygdali*) responses to volatiles from female *S. amygdali* boring into plum branches. Chromatography: FFAP (30m x 0.25 mm ID) column; temperature program: 50⁰C (5 min), 5⁰C/min to 140⁰C, then 10⁰C/min to 220⁰C. EAD-active components were identified as follows: **SS-I** = (3*S*,4*S*)-4-methyl-3-heptanol; **SS-II**= (3*S*,4*S*)-4-methyl-3-hexanol; **III** = (5*S*,7*S*)-7-methyl-1,6-dioxaspiro[4,5]decane; and **IV** = 7-methyl-1,6-dioxaspiro [4,5] dec-8-ene.

Experiments 7, 8 (Table 3). The **SS-I** stereoisomer attracted significantly more beetles, and proportionately more males, than the stereoisomeric mixture of **I** (Ex.). Similarly, the blend of **SS-I** plus **SS-II** was significantly more attractive than blends in which **SS-I**, **SS-II** or both were replaced by **I** or **II** (Exp. 8)

Experiment 9-12 (Table 4). Ethanol, unlike methanol or propanol, attracted more beetles than did the control, but fewer than did the stereoisomeric pheromone mixture (Exp. 9). Addition of methanol to the pheromone strongly inhibited the response of

beetles, whereas addition of ethanol or propanol had no effect (Exps. 10-12). Ethanol, however, increased the percentage of captured males.

Table 2. Experiments 1-6 (at Kefar Tavor): Attraction of *Scolytus amygdali* to baits containing single stereoisomers or stereoisomeric pheromone mixtures.

Bait	Treatments		Captures	
	Components (μg)		Beetles per trap per week	%
Exp 1 (November 1996)				
A	SS-I	(50)	2.6 b	-
B	SS-I	(200)	8.0 a	-
C	SS-I	(500)	10.8 a	-
D	SS-I	(2000)	7.0 a	-
Exp. 2 (November 1996)				
A	SS-I	(50)	5.3 b	-
B	A + SS-II	(10)	7.3 ab	-
C	A + SS-II	(25)	8.8 ab	-
D	A + SS-II	(50)	14.4 a	-
Exp. 3 (November 1996)				
A	SS-I	(200)	27.4 b	-
B	A + SS-II	(20)	35.9 b	-
C	A + SS-II	(50)	39.7 ab	-
D	A + SS-II	(100)	74.3 a	-
E	A + SS-II	(200)	64.3 a	-
Exp. 4 (November- December 1996)				
A	SS-I (50) + SS-II (50)		15.9 a	-
B	A + IV	(10)	17.5 a	-
C	A + IV	(25)	16.7 a	-
D	A + IV	(50)	30.1 a	-
Exp. 5 (April 1997)				
A	SS-I (50) + SS-II (50)		61.8 a	26.4a
B	A + IV	(25)	75.3 a	25.7a
C	A + IV	(25)	67.7 a	29.5a
Exp. 6 (November 1997)				
A	SS-I	(500)	21.6 b	42.4 a
B	A + SS-II	(250)	31.8 a	45.9 a
C	A + IV	(250)	32.1 a	44.2 a

Table 3. Experiments 7, 8 (at Kefar Tavor): Attraction of *Scolytus amygdali* to baits containing single stereoisomers or mixtures of stereoisomeric pheromone components.

Bait	Treatment Components (μg)	Capture	
		Beetles per trap per week	%
Exp. 7 (July 1996)			
A	SS-I (200)	45.4 a	17.7 a
B	I (400)	21.9 b	2.3 b
C	I (800)	22.1 b	3.1 b
Exp. 8 (April 1998)			
A	SS-I (500) + SS-II (250)	192.5 a	44.90 a
B	SS-I (500) + II (1000)	161.7 a	40.49 a
C	I (2000) + SS-II (250)	112.7 b	24.11 b
D	I (2000) + II (1000)	106.0 b	20.77 b

Experiment 13-16 (Tables 5, 6). Methanol, unlike ethanol or propanol, significantly reduced numbers of ABB attacks on cut branches, both in the presence or absence of synthetic pheromone (Exps. 13-15). However, release of methanol in the crown of orchard trees failed to reduce the number of buds destroyed by beetles (Exp. 16).

Discussion

The alcohol **SS-I** is also the major pheromone component of *S. multistriatus* (Pearce et al. 1975) and *S. scolytus* (e.g. Blight et al. 1978). Other stereoisomers of 4-methyl-3-heptanol have been identified in ant species (Nacscimento et al. 1997 and literature cited therein). The second pheromone component of ABB, **SS-II**, is not known from other insects. However, (3*R*,4*S*)-4-methyl-3-hexanol was found in the head of the ant *Tetramorium impurum* (Pasteels et al. 1981). Unsaturated spiroacetal **IV** is reported for the first time. The saturated spiroacetal **III**, in contrast, had been identified in several coniferophagous bark beetles, including *Pityogenes chalcographus* (Francke et al. 1977), *Pityophthorus* spp. and *Cryphalus piceae* (Francke et al. 1995), *Conophthorus* spp. (de Groot et al. 1991, Birgersson et al. 1995, Pearce et al. 1995), and *Leperisinus varius* (Kohnle 1985). It repels male *C. coniperda* and *C. resinosae* (Birgersson et al. 1995, Pearce et al. 1995).

The identification of the aggregation pheromone of ABB enabled the preparation of pheromone-baited traps to monitor and possibly mass trap beetle populations. Because **SS-I** and **SS-II** were not commercially available and difficult to synthesize,

readily obtainable stereoisomeric mixtures of **I** and **II** were tested. Attractiveness of **I** and **II** was lower than that of **SS-I** plus **SS-II**, probably due to an inhibitory stereoisomer present in the mixture of **I**. In contrast, unnatural stereoisomers present in **I** are not inhibitory to *S. scolytus* and *S. multistriatus* (Blight *et al.*, 1979b). Similarly, attraction of *Rhynchophorus* palm weevils to their aggregation pheromones (5*S*,4*S*)-5-methyl-4-octanol, (3*S*,4*S*)-3-methyl-4-octanol and (4*S*,5*S*)-4-methyl-5-nonanol is not affected by unnatural stereoisomers (Perez *et al.* 1996; Giblin-Davis *et al.* 1996, and literature cited therein).

Table 4. Experiments 9-12 (at Kefar Tavor and Mishmar ha'Emeq): Effects of aliphatic alcohols on attraction of *Scolytus amygdali* to baits containing single stereoisomers or mixtures of stereoisomeric pheromone components.

Bait	Treatment Components (μ g)	Capture	
		Beetles per trap per week	%
Exp. 9 (September 1997)			
A	I (200) + II (100)	77.6	9.1
B	Methanol 10 cc	1.0	-
C	Ethanol 10 cc	9.7	40.1
D	Propanol 10 cc	1.1	-
E	Non-baited traps	0	-
Exp. 10 (October –November 1997)			
A	SS-I (500) + SS-II (250)	6.2 a	21.9 b
B	A + ethanol 10 cc	9.0 a	39.7 a
Exp. 11 (June-July 1998)			
A	I (200)	40.7 a	4.5 a
B	A + methanol 10 cc	5.2 b	>0.1 b
C	A + ethanol 10 cc	27.3 a	5.4 a
D	A + propanol 10cc	50.8 a	8.6 a
Exp. 12 (July 1998)			
A	SS-I (200) + SS-II (100)	30.4 a	25.1 a
B	A + methanol 10 cc	0.8 b	>0.1 b
C	A + ethanol 10 cc	32.3 a	27.3 a
D	A + propanol 10 cc	19.0 a	23.5 a

Ethanol released from decaying wood and stressed plants is a known attractant for ambrosia beetles and bark beetles, including *S. intricatus* (Moeck 1970; Klimetzek *et al.* 1986; Byers 1992; Markals and Kalapanida, 1997). It is a synergist with other host

kairomones and pheromones (Schroeder and Lindelöw 1989; Chénier and Philogéne 1989; Vite et al. 1976; Ross and Daterman 1995), and is used in Spain and Egypt for monitoring ABB. While ethanol was also weakly attractive to ABB in our study, neither ethanol nor propanol affected attractiveness of the pheromone. The lack of synergistic activity might have been due to high release rates (~380 mg/day) of the alcohol. Byers (1992) suggested that ethanol at low rather than high release rates attracted most *Tomicus piniperda* beetles. Unexpectedly, methanol strongly inhibited response of ABBs to pheromone-baited traps and reduced ABB colonization of branches. Similarly, when methanol was added to commercial pheromone lures of *Ips typographus*, it significantly reduced captures of the pine bark beetles *Orthotomicus erosus* and *Pityogenes calcaratus* (Mendel et al., unpublished). Despite the fact that methanol strongly reduced colonization of branches by ABB, it failed to disrupt bud feeding. Other repellents and/or release rates of repellents appear to be necessary to prevent colonization of plants and bud feeding, respectively.

Table 5. Experiments 13-15 (at Mishmar ha'Emeq): Effect of methanol on colonization of branches by *Scolytus amygdali*.

Bait	Treatment Components (μg)	Penetration holes per 5 cut branches	
		Plum	Almond
Exp. 13 (August 1998)			
A	Branches	4.1 a	-
B	Branches + methanol 10cc	0.9 b	-
Exp. 14 (October 1998)			
A	Branches + I (500) + II (250)	19.7 a	-
B	A + methanol 10cc	2.3 b	-
Exp. 15 (July 1998)			
A	Branches	1.6 b	0.8 b
B	A + I (500) + II (250)g	25.4 a	8.9 a
C	B + methanol 10 cc	1.3 b	0.6 b
D	B + ethanol 10 cc	19.2 a	14.1 a
E	B + propanol 10 cc	16.3 a	6.7 a

Our results indicate the possibility to establish a pheromone-based management of ABB. Traps baited with **I** and **II** have already been used to study the seasonal ABB flight, annual population trends, and occurrence of high populations in stone fruit plantations (Mendel et al., unpublished). We plan to investigate the relationship be-

tween numbers of captured beetles and damage caused by beetles, and to develop mass trapping of ABB, thereby providing growers with an alternative to insecticidal control of ABB.

Table 6. Experiment 16: Effect of methanol on bud feeding by *Scolytus amygdali*.

Bait	Treatment	Number of buds destroyed per 5 branches		
	Components (μg)	April 2000		May 2000
	Location ^a	a	b	c
A	Tree			1.4 ^b
B	A + methanol 10cc x 2			1.5
C	A + I (500) + II (250)	2.7	7.5	
D	C + methanol 10cc x 2	3.9	8.3	

^a Locations: 4-year-old plantations; two plum orchards at Yoqne'am (a) and Kerem Maharal (b), both near Mt Carmel; and a cherry orchard at Matat (c), in Upper Galilee. In each location, treatments were replicated 20 times. Timing of the experiment coincided with the major seasonal flight of ABB, according trap catch results obtained in 1999 (unpublished data).

^b Means within locations are not significantly different

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