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CHIRAL ESTERS: SEX PHEROMONE OF THE BAGWORM, *Oiketicus kirbyi* (LEPIDOPTERA: PSYCHIDAE)

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Abstract—Gas chromatographic-electroantennographic detection (GC-EAD) analyses of pheromone extract of female bagworms, *Oiketicus kirbyi* (Guilding), revealed five EAD-active compounds. Retention index calculations, GC-mass spectrometry in both full-scan and selected-ion monitoring modes and GC-EAD analyses of authentic standards identified the compounds as 1-methylbutyl octanoate (MBO), 1-methylbutyl nonanoate (MBN), 1-methylbutyl decanoate (MBD), 1-methylpentyl decanoate (MPD), and 1-methylbutyl dodecanoate (MBDD). Of these five chiral esters, MBD was most abundant in extracts and elicited the strongest antennal response. In field experiments in Costa Rica, (*R*)-MBD attracted *O. kirbyi* males, whereas (*S*)-MBD in combination with (*R*)-MBD inhibited response. *R* but not *S* enantiomers of MBO, MBN, and MBDD strongly synergized attraction to (*R*)-MBD. (*S*)-MBO and (*S*)-MBDD were inactive, whereas (*S*)-MBN was inhibitory. (*R*)-, (*S*)- and racemic MPD were inactive. Blends of (*R*)-MBD in ternary combination with either (*R*)-MBO and (*R*)-MBN or (*R*)-MBN and (*R*)-MBDD were as attractive as the five-ester blend. Five- and four-ester blends were equally attractive, suggesting redundancy of pheromone components for attraction of males. The multiple sex pheromone component blend of chiral esters in *O. kirbyi* may have evolved to maintain species-specific communication in bagworm communities of tropical Americas.

Key Words—Lepidoptera, Psychidae, *Oiketicus kirbyi*, bagworm, sex pher-

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omone, pheromone chirality, 1-methylbutyl octanoate, 1-methylbutyl nonanoate, 1-methylbutyl decanoate, 1-methylbutyl dodecanoate.

INTRODUCTION

The bagworm, *Oiketicus kirbyi* (Guilding) (Lepidoptera: Psychidae), is a major defoliator of oil palm plantations in the tropical Americas (Genty et al., 1978). As with other bagworms, *O. kirbyi* has an unusual life history (Stephens, 1962; Ponce et al., 1979; Villanueva and Granda Paz, 1986; Campos Arce et al., 1987; Rhainds et al., 1995). Upon encountering a suitable host, wind-dispersed larvae envelop themselves in a self-constructed bag, which they enlarge throughout their development. Following eclosion, vermiform, apterous females stay within their pupal case and protecting bag, awaiting the arrival of winged males. To copulate, the male inserts his extensible abdomen through the bag into the female pupal case. Mated females lay a single egg mass within their pupal case.

As in other bagworms (Leonhardt et al., 1983; Bosman and Brand, 1971; Boguang, 1981), female *O. kirbyi* expel pheromone-impregnated scales (hairs) out of the pupal case into the lower part of the bag for attraction of males (Acosta, 1986). (1*R*)-1-Methylbutyl decanoate (MBD) has been identified as a sex pheromone component of *Thyridopteryx ephemeraeformis* (Haworth) (Leonhardt et al., 1983), but sex pheromones of other bagworms are as yet unknown. We report the identification and field testing of the sex pheromone of *O. kirbyi*.

METHODS AND MATERIALS

Laboratory Analysis. Bags containing *O. kirbyi* pupae were collected in commercial oil palm plantations in Coto, Costa Rica, and sent to Simon Fraser University. Pupae were removed from their bags and kept separately in Petri dishes (9 cm diameter) at 25°C under a photoperiod of 12L:12D. Pheromone-impregnated scales expelled by a female out of the pupal case were extracted in 150 μl of hexane for 10 min. Extracts of 100 females were combined and subjected to gas chromatographic–electroantennographic detection analyses (GC-EAD) (Arn et al., 1975) on three fused silica columns (30 × 0.25 or 0.32 mm ID) coated with DB-23, DB-210 (J&W Scientific, Folsom, California 95630), or SP-1000 (Supelco, Bellafonte, Pennsylvania 16823). Coupled GC-mass spectrometry (MS) (Hewlett-Packard 5985B) in selected ion monitoring (SIM) mode, using a DB-210 column with isobutane for chemical ionization (CI), was conducted to confirm the identification of EAD-active components in scale extracts. Full-scan CI mass spectra of synthetic candidate compounds were obtained to select diagnostic ions. In sequence, 200 pg of synthetic compounds, a hexane blank, and a concentrated pheromone extract were then analyzed in SIM mode,

each time scanning for the diagnostic ions. Synthetic candidate pheromone components were further subjected to GC-EAD analyses to compare their EAD activity with those of female-produced compounds.

Synthesis of Pheromone Components. Chiral esters were synthesized with >90% yield from chiral alcohols and alkanoyl chlorides in pyridine. Final products were purified by silica gel chromatography using hexane–ether (10%) as eluents. Enantiomeric excess of (1*R*)- and (1*S*)-1-methylbutanol (each ≥96%), as well as (1*R*)- and (1*S*)-1-methylpentanol (each ≥96%) (Aldrich Chemical Co., Milwaukee, Wisconsin), was determined by derivatization (Slessor et al., 1985) and GC analyses [fused silica, DB-5 coated column (30 × 0.25 mm); temperature: 90°C and 100°C isothermal for 2-pentanol and 2-hexanol derivatives, respectively]. Mass spectra of synthetic compounds were obtained on a Hewlett Packard 5895B mass spectrometer equipped with a fused silica column (30 m × 0.25 mm ID) coated with DB-210. NMR spectra (Bruker WU-400 spectrometer) were taken in $CDCl_3$ at 400 MHz (*J* values in hertz).

(1R)-1-Methylbutyl Octanoate ((R)-MBO). EI-MS [*m/z*] (%)]: 214 (M^+, 1), 171 (10), 145 (87), 144 (40), 128 (14), 127 (100), 101 (16), 87 (19), 85 (10), 84 (20), 73 (12), 71 (25), 70 (58), 60 (12), 57 (45), 55 (30), 43 (42), 42 (13), 41 (27). ^1H NMR ($CDCl_3$): δ: 4.91 (1H, hex, J = 7 Hz), 2.26 (2H, t, J = 7 Hz), 1.60 (3H, m), 1.45 (1H, m), 1.30 (10H, m), 1.17 (3H, d, J = 7 Hz), 0.90 (3H, t, J = 7 Hz), 0.80 (3H, t, J = 7 Hz). (*S*)-MBO gave almost identical spectra.

(1R)-1-Methylbutyl Nonanoate ((R)-MBN). EI-MS [*m/z* (%)]: 228 (M^+, 1), 159 (79), 158 (50), 142 (17), 141 (100), 129 (18), 115 (15), 98 (15), 87 (17), 73 (13), 71 (44), 70 (53), 69 (13), 60 (11), 57 (25), 55 (30), 43 (37), 42 (12), 41 (23). ^1H NMR ($CDCl_3$): δ: 4.90 (1H, hex, J = 7 Hz), 2.26 (2H, t, J = 7 Hz), 1.60 (3H, m), 1.42 (1H, m), 1.28 (12H, m), 1.17 (3H, d, J = 7 Hz), 0.89 (3H, t, J = 7 Hz), 0.86 (3H, t, J = 7 Hz). (*S*)-MBN gave almost identical spectra.

(1R)-1-Methylbutyl Decanoate ((R)-MBD). EI-MS [*m/z* (%)]: 242 (M^+, 1), 173 (83), 172 (44), 156 (11), 155 (100), 143 (10), 129 (25), 87 (11), 85 (11), 71 (31), 70 (39), 69 (10), 57 (12), 55 (16), 43 (30), 41 (18). ^1H NMR ($CDCl_3$): δ: 4.89 (1H, hex, J = 7 Hz), 2.24 (2H, t, J = 7 Hz), 1.59 (3H, m), 1.40 (1H, m), 1.26 (14H, m), 1.16 (3H, d, J = 7 Hz), 0.88 (3H, t, J = 7 Hz), 0.84 (3H, t, J = 7 Hz). (*S*)-MBD gave almost identical spectra. Spectroscopic data were consistent with those previously reported (Leonhardt et al., 1983).

(1R)-1-Methylpentyl Decanoate ((1R)-MPD). EI-MS [*m/z* (%)]: 256 (M^+, 1), 173 (73), 172 (49), 156 (15), 155 (100), 129 (26), 101 (12), 85 (33), 84 (55), 83 (11), 73 (11), 71 (22), 69 (22), 57 (20), 56 (14), 55 (23), 43 (32), 41 (20). ^1H NMR ($CDCl_3$): δ: 4.86 (1H, hex, J = 7 Hz), 2.26 (2H, t, J = 7 Hz), 1.60 (3H, m), 1.46 (1H, m), 1.26 (16H, m), 1.20 (3H, d, J = 7 Hz), 0.95

(3H, t, J = 7 Hz), 0.86 (3H, t, J = 7 Hz). (*S*)-MPD gave almost identical spectra.

(1R)-1-Methylbutyl Dodecanoate ((1R)-MBDD). EI-MS [*m/z* (%)]: 270 (M^+, 1), 202 (13), 201 (100), 200 (66), 184 (11), 183 (86), 157 (16), 129 (14), 85 (11), 83 (12), 71 (21), 70 (31), 57 (14), 55 (15), 43 (22), 41 (13). ^{1}H NMR ($CDCl_3$): δ: 4.90 (1H, hex, J = 7 Hz), 2.25 (2H, t, J = 7 Hz), 1.60 (3H, m), 1.44 (1H, m), 1.24 (18H, m), 1.20 (3H, d, J = 7 Hz), 0.90 (3H, t, J = 7 Hz), 0.87 (3H, t, J = 7 Hz). (*S*)-MBDD gave almost identical spectra.

Field Bioassay. Experiments were conducted in commercial oil palm plantations in Coto, Costa Rica. Green Unitraps (Phero Tech Inc., Delta, British Columbia) were suspended from oil palms 3 m above ground in randomized complete blocks, with traps and blocks at 18 to 27-m intervals. Traps were baited with cotton balls impregnated with hexane solutions of candidate pheromone components. A small Diclorvos cube (Green Cross, Division of Ciba Geigy Canada Ltd., Mississauga, Ontario) placed on the bottom of traps assured retention of captured moths. After 1 to 2 days, baits were changed and captured male *O. kirbyi* counted. Blocks were rerandomized when a predetermined number of males had been captured.

The first experiment compared attraction of (*R*)- and (*S*)-MBD (1000 μg), alone and in combination. The second experiment tested (*R*)-MBD (10,000 μg) alone and combined with (*S*)-MBD at respective ratios of 1:1, 1:0.1, 1:0.01, 1:0.001, and 1:0.0001. Experiment 3 tested (*R*)-MBD (1000 μg) alone and combined with either one or both enantiomers of MBO at 1:0.1 and 1:0.01 ratios. Experiments 4–6 tested (*R*)-MBD (1000 μg) alone and in 1:0.1 ratio with either one or both enantiomers of MBN (experiment 4), MPD (experiment 5), and MBDD (experiment 6). Experiments 7–9 each tested (*R*)-MBD in pentanary combination with (*R*)-MBO, (*R*)-MBN, (*R*)-MPD, and (*R*)-MBDD, and in all binary (experiment 7), ternary (experiment 8), and quaternary combinations (experiment 9) with these chiral esters. Experiment 10 tested (*R*)-MBD (1000 μg) alone and in ternary combinations with (*R*)-MBN and (*R*)-MBO at respective ratios of 1:1, 1:0.1, 1:0.01 and 1:0.001. A final dose–response experiment tested (*R*)-MBD alone and in ternary combinations with both (*R*)-MBO and (*R*)-MBN at a 1:1:1 ratio, employing doses of 10, 100, 1000, and 10,000 μg.

Statistical Analysis. Statistical analyses were conducted with the SAS statistical package (SAS Institute Inc., Cary, North Carolina). Numbers of male *O. kirbyi* captured in Unitraps were compared using a nonparametric analysis of variance (Friedman's test) followed by the Student-Newman-Keul's (SNK) test. In all analyses, $P < 0.05$ levels of significance were used.

RESULTS

Laboratory Analysis. GC-EAD analyses of female *O. kirbyi* pheromone extract on a DB-210 column consistently revealed five EAD-active compounds (Figure 1). Coupled GC-MS of the most abundant and major EAD-active com-

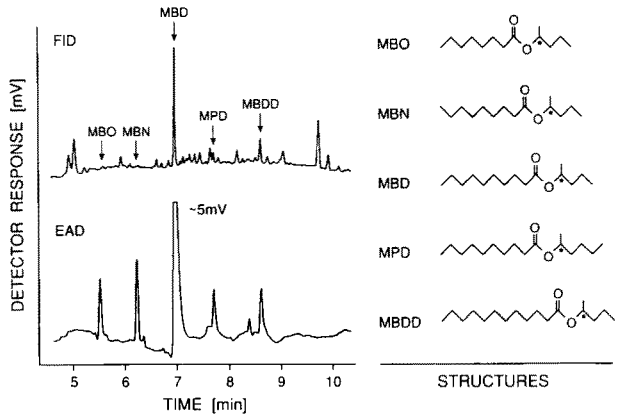

FIG. 1. Flame ionization detector (FID) and electroantennographic detector (EAD: male *O. kirbyi* antenna) responses to female *O. kirbyi* pheromone extract, chromatographed on a DB-210 column (1 min at 100°C, 15°C/min to 180°C, 2°C/min to 220°C). MBO = 1-methylbutyl octanoate; MBN = 1-methylbutyl nonanoate; MBD = 1-methylbutyl decanoate; MPD = 1-methylpentyl decanoate; MBDD = 1-methylbutyl dodecanoate. Retention indices of MBO, MBN, MBD, MPD, and MBDD were respectively: 1643, 1745, 1846, 1942, 2050 (DB-210); 1651, 1756, 1858, 1949, 2064 (DB-23); 1588, 1688, 1788, 1876, 1990 (SP-1000). *Indicates chiral center of molecule.

ponent gave the same mass spectrum as MBD, a previously identified pheromone component of *T. ephemeraeformis* (Leonhardt et al., 1983). Identical retention and mass spectrometric characteristics of and comparable antennal responses to synthetic and female-produced MBD confirmed the presence of this compound in female *O. kirbyi* pheromone extract.

Retention indices of the four minor EAD-active compounds (Figure 1) suggested they were homologous MBO, MBN, MPD, and MBDD. Equivalent amounts of synthetic and female-produced esters elicited similar antennal responses. GC-MS-CI-SIM analyses of pheromone extract and synthetic MBO, MBN, MPD, and MBDD resulted in retention time and ion ratio matches of synthetic and female-produced compounds, except for MBN; synthetic MBO [*m/z* (%)]: 145 (100), 215 (M+1, 63), extract: 145 (100), 215 (64); synthetic MPD: 173 (100), 257 (M+1, 45), extract: 173 (100), 257 (40); synthetic MBDD: 201 (100), 271 (M+1, 53), extract: 201 (100), 271 (49). Diagnostic ions *m/z* 159 and 229 for MBN were detected at the correct retention time, but the ion ratio could not be accurately determined due to a coeluting compound also containing *m/z* 229 (but not *m/z* 159).

Field Bioassay. In a 12-replicate experiment, (*R*)-MBD attracted on average 11.7 bagworm males per trap, while the *S* enantiomer was unattractive and in combination with (*R*)-MBD inhibited response. Unbaited traps did not attract

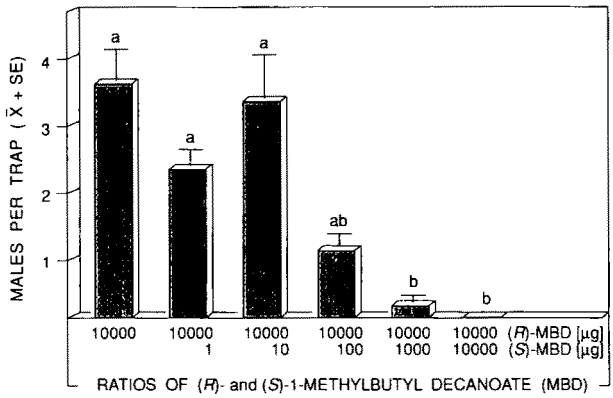

FIG. 2. Mean number and standard error (SE) of male *O. kirbyi* captured in Unitraps baited with different ratios of (*R*)- and (*S*)-MBD. April 5–9, 1993, Coto, Costa Rica, $N = 8$. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$.

any males. Attraction of males to (*R*)-MBD proportionally decreased as the amount of (*S*)-MBD in the lure increased (Figure 2). The *R* but not *S* enantiomers of either MBO, MBN, or MBDD strongly enhanced attraction to (*R*)-MBD (Figure 3). (*S*)-MBO and (*S*)-MBDD were inactive, whereas (*S*)-MBN added to its antipode reduced attraction (Figure 3). (*R*)-, (*S*)-, and racemic MPD were behaviorally benign. A five-ester blend was more attractive than any of four binary blends containing (*R*)-MBD (Figure 4). Blends of (*R*)-MBD in ternary combination with either (*R*)-MBO and (*R*)-MBN or (*R*)-MBN and (*R*)-MBDD were as attractive as the five-ester blend (Figure 5). Five- and four-ester blends were equally attractive (Figure 6). Increasing the amount of synergistic (*R*)-MBO and (*R*)-MBN relative to (*R*)-MBD increased attraction (Figure 7); attraction increased as the amount of pheromone increased from 10 to 10,000 µg (Figure 8).

DISCUSSION

Chiral lepidopteran sex pheromone components comprise mono- and diene epoxides in geometrids, noctuids, and arctiids (Mayer and McLaughlin, 1991; Arn et al., 1992; Gries et al., 1993a; Szöcs et al., 1993), methyl-branched hydrocarbons in lyonetiids (Francke et al., 1987, 1988) and geometrids (Gries et al., 1991, 1993b,c, 1994), a methyl-branched epoxide in lymantriids (Bierl et al., 1970, 1975), and a methylbutyl ester in psychids (Leonhardt et al., 1983). While chirality of female-produced pheromone components has rarely been

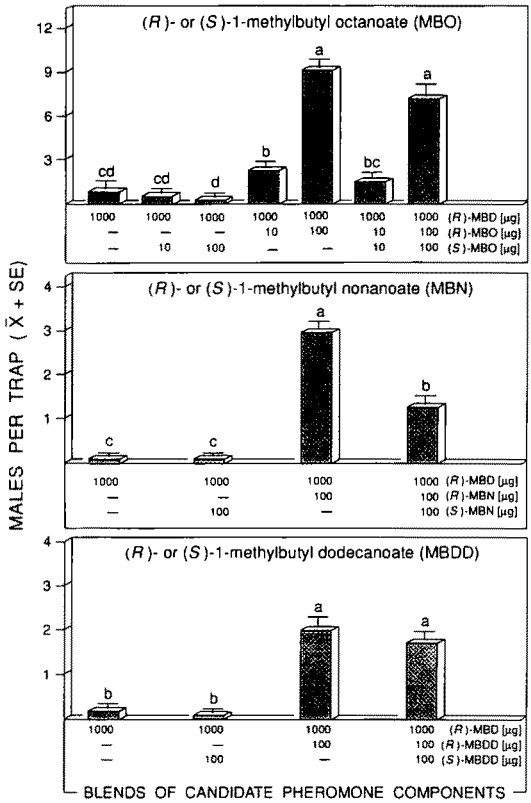

FIG. 3. Mean number of male *O. kirbyi* captured in Unitraps baited with (*R*)-MBD alone and in combination with optical isomers of MBO (November 1–15, 1992, $N = 15$), MBN (October 15–23, 1993, $N = 10$), and MBDD (October 14–28, 1993, $N = 10$), Coto, Costa Rica. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$. Compound abbreviations as in Figure 1.

determined (Szöcs et al., 1993), electroantennogram, wind-tunnel, and field bioassays of synthetic optical isomers alone and in combination indicate that usually one isomer is attractive, whereas the antipode is inactive (Li et al., 1993a,b; Klimetzek et al., 1976), synergistic (Millar et al., 1991) or inhibitory (Cardé et al., 1977; Plimmer et al., 1977; Millar et al., 1991; Szöcs et al., 1993). Blends of two or three chiral components of sex pheromone have been documented in geometrids. (3*Z*,9*Z*,6*R*,7*S*)-Epoxy-nonadecadiene and (6*Z*,9*Z*,3*S*,4*R*)-epoxy-nonadecadiene synergistically attract *Probole amicaria* (Herrich-Schäffer) (Millar et al., 1990). (5*R*,11*S*)-5,11-Dimethylheptadecane,

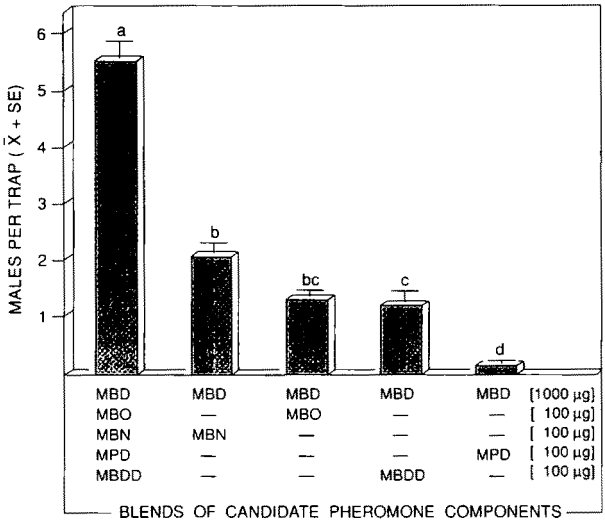

FIG. 4. Mean number of male *O. kirbyi* captured in Unitraps baited with (*R*)-MBD in binary and pentanary combinations with (*R*)-MBO, (*R*)-MBN, (*R*)-MPD, and (*R*)-MBDD. November 1–8, 1993, Coto, Costa Rica, $N = 10$. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$. Compound abbreviations as in Figure 1.

(2,5*R*)-2,5-dimethylheptadecane, and (7*R*)-7-methylheptadecane comprise the ternary sex pheromone blend of the western hemlock looper, *Lambdina fiscellaria lugubrosa* (Hulst) (Li et al., 1993a,b). Of the four chiral esters in *O. kirbyi*, *R* enantiomers are attractive, whereas *S* enantiomers are behaviorally benign (MBO, MBDD) or inhibitory (MBD, MBN).

Even though both *T. ephemeraeformis* and *O. kirbyi* bagworms utilize (*R*)-MBD as a major sex pheromone component, their pheromones are distinct. While (*S*)-MBD is behaviorally benign in *T. ephemeraeformis* (Leonhardt et al., 1983), it inhibits response of *O. kirbyi* (Figure 2). Contrasting with the single ester sex pheromone of *T. ephemeraeformis*, female *O. kirbyi* produce a blend of four chiral esters. Distinct communication channels of *T. ephemeraeformis* in the eastern United States (Sheppard and Stairs, 1976) and *O. kirbyi* in Central and South America (Genty et al., 1978) may be attributed to reproductive isolation and different environmental conditions (Cardé and Baker, 1984). The likely more diverse bagworm fauna in the tropical Americas may have provided selective forces for *O. kirbyi* to evolve a multiple component blend of chiral esters for species-specific communication.

Enhanced attraction to (*R*)-MBD when combined in either two-, three-,

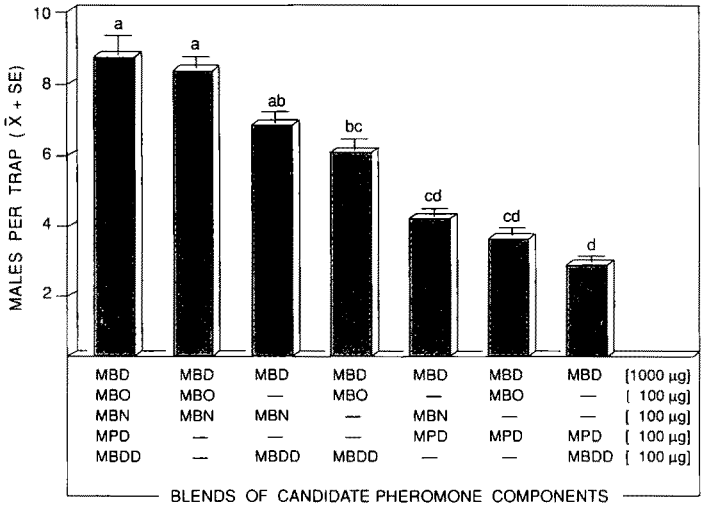

FIG. 5. Mean number of male *O. kirbyi* captured in Unitraps baited with (*R*)-MBD in ternary and pentanary combinations with (*R*)-MBO, (*R*)-MBN, (*R*)-MPD, and (*R*)-MBDD. November 2–22, 1993, Coto, Costa Rica, $N = 20$. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$. Compound abbreviations as in Figure 1.

four-, and five-component blends with (*R*)-MBO, (*R*)-MBN, (*R*)-MPD, and (*R*)-MBDD (Figures 3–6) indicated that all compounds except MPD are sex pheromone components. Equal attraction of two ternary and all four- and five-component blends suggests redundancy of pheromone components for male attraction. Redundancy of sex pheromone components was first documented in the cabbage looper moth, *Trichoplusia ni* (Hubner), with various pheromone blends compensating for the lack of one or more components (Linn et al., 1984). While individual components may be redundant for the attraction of males, they may serve to inhibit response by sympatric congeners.

Most female moths actively release sex pheromone from abdominal glands for attraction of males (Percy-Cunningham and MacDonald, 1987). Cessation of calling behavior and decline of pheromone production after mating (Richerson and Cameron, 1974; Raina, 1984; Webster and Cardé, 1984; Giebultowicz et al., 1991) has been associated with transfer of sperm [*Lymantria dispar* (L.)] (Giebultowicz et al., 1991) or male accessory gland secretion [*Heliothis zea* (Boddie)] (Raina, 1984) into the spermetheca. Calling female *O. kirbyi*, in contrast, expel their pheromone-impregnated scales at once out of the pupal case into the lower part of the bag (Rhainds, unpublished). As pheromone dissipation from these scales is independent of the female's mating status, it is unclear

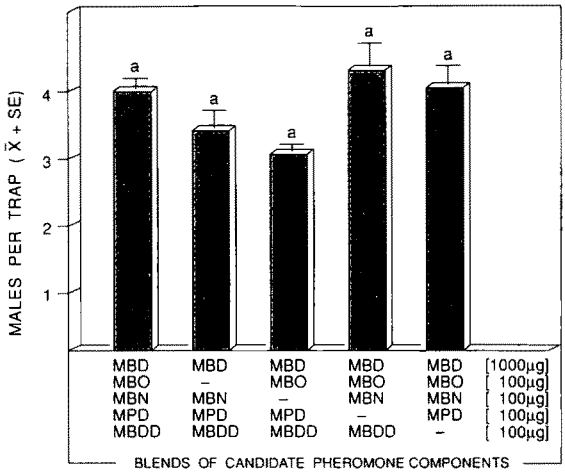

FIG. 6. Mean number of male *O. kirbyi* captured in Unitraps baited with (*R*)-MBD in quaternary and pentanary combinations with (*R*)-MBO, (*R*)-MBN, (*R*)-MPD, and (*R*)-MBDD. November 4–15, 1993, Coto, Costa Rica, $N = 10$. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$. Compound abbreviations as in Figure 1.

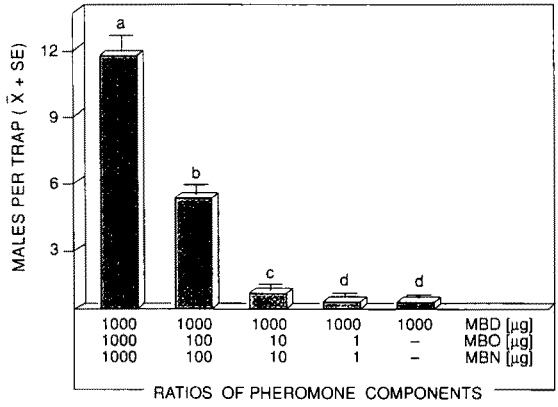

FIG. 7. Mean number of male *O. kirbyi* captured in Unitraps baited with (*R*)-MBD, (*R*)-MBO, and (*R*)-MBN in different ratios. November 12–21, 1993, Coto, Costa Rica, $N = 10$. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$. Compound abbreviations as in Figure 1.

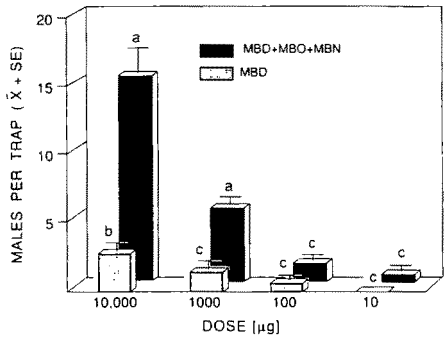

FIG. 8. Mean number of male *O. kirbyi* captured in Unitraps baited with (*R*)-MBD alone and in combination with (*R*)-MBO and (*R*)-MBN (1 : 1 : 1) at increasing doses. November 19–27, 1993, Coto, Costa Rica, $N = 10$. Bars superscripted by the same letter are not significantly different, SNK test, $P < 0.05$. Compound abbreviations as in Figure 1.

whether or how mate-seeking males discriminate between bags containing virgin or mated females. We hypothesize that females produce an anti-sex pheromone after mating, that males mark mated females with an inhibitory compound, or that the pheromone rapidly dissipates from scales, rendering the female attractive for a short duration.

Assessment of bagworm populations in oil palm plantations currently involves counting larvae on one leaf per tree per hectare (Chinchilla, 1992). This approach is not reliable or cost-effective (Mackenzie, 1976; Wan and Hoh, 1992; Chinchilla, 1992). If proven to be efficacious, future monitoring of *O. kirbyi* populations could employ pheromone-based trapping with a multiple-ester lure. Successful use of MBD for biorational control of *T. ephemeraeformis* (Klun et al., 1986) indicates excellent potential for pheromone-based mating disruption of *O. kirbyi* populations.

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