

Electronic Supplementary Material

Circadian rhythms of insect pheromone titre, calling, emission, and response: a review

Anat Levi-Zada¹ and John A. Byers²

¹Department of Entomology, Institute of Plant Protection, Agricultural Research Organization,
Volcani Institute, Rishon LeZion 7505101, Israel

²Semiochemical Solutions, Beer Yaakov 7030476, Israel

Author for correspondence E-mail: anatzada@volcani.agri.gov.il; <http://orcid.org/0000-0001-8951-4769>)

Table S1. Number and percentage of 224 research papers on diel (circadian) rhythms regarding pheromones of various taxonomic groups.

| Order | Families | Number of genera ¹ | Number of papers | Percent of papers |
|---------------------------------------|-----------------------|-------------------------------|------------------|-------------------|
| Order Lepidoptera (moths) | | | 152 | 67.9 |
| | Batrachedridae | <i>Batrachedra</i> | 1 | 0.4 |
| | Bombycidae | <i>Bombyx</i> | 4 | 1.8 |
| | Coleophoridae | <i>Coleophora</i> | 2 | 0.9 |
| | Cossidae | <i>Isoceras</i> | 1 | 0.4 |
| | Crambidae | 5 | 8 | 3.6 |
| | Erebidae/Lymantriidae | 5 | 15 | 6.7 |
| | Gelechiidae | 4 | 5 | 2.2 |
| | Geometridae | <i>Lambdina</i> | 1 | 0.4 |
| | Gracillariidae | 2 | 4 | 1.8 |
| | Limacodidae | 3 | 1 | 0.4 |
| | Noctuidae | 11 | 64 | 28.6 |
| | Pterophoridae | <i>Platyptilia</i> | 3 | 1.3 |
| | Pyalidae | 10 | 15 | 6.7 |
| | Saturniidae | 2 | 2 | 0.9 |
| | Sesiidae | <i>Synanthedon</i> | 3 | 1.3 |
| | Sphingidae | <i>Manduca</i> | 3 | 1.3 |
| | Tortricidae | 10 | 21 | 9.4 |
| | Zygaenidae | 2 | 1 | 0.4 |
| Order Coleoptera (beetles) | | | 19 | 8.5 |
| | Bostrichidae | 3 | 4 | 1.8 |
| | Cerambycidae | 7 | 4 | 1.8 |
| | Chrysomelidae | <i>Diabrotica</i> | 1 | 0.4 |
| | Curculionidae | 2 | 3 | 1.3 |
| | Dermestidae | 2 | 3 | 1.3 |
| | Scarabaeidae | 2 | 2 | 0.9 |
| | Tenebrionidae | <i>Tribolium</i> | 2 | 0.9 |
| Order Hemiptera = Homoptera (sucking) | | | 18 | 8.0 |
| | Aphididae | 6 | 6 | 2.7 |
| | Diaspididae | 2 | 2 | 0.9 |
| | Miridae | 2 | 2 | 0.9 |
| | Pentatomidae | <i>Euschistus</i> | 3 | 1.3 |
| | Pseudococcidae | 3 | 3 | 1.3 |
| | Reduviidae | <i>Triatoma</i> | 1 | 0.4 |
| | Triozidae | <i>Bactericera</i> | 1 | 0.4 |
| Order Diptera (flies) | | | 14 | 6.3 |
| | Agromizidae | <i>Agromiza</i> | 1 | 0.4 |
| | Cecidomyiidae | <i>Sitodiplosis</i> | 1 | 0.4 |
| | Culicidae | <i>Culex</i> | 1 | 0.4 |

| | | | |
|---------------------------------|--------------------|---|-----|
| Drosophilidae | <i>Drosophila</i> | 2 | 0.9 |
| Tephritidae | 4 | 9 | 4.0 |
| Order Hymenoptera (wasps, bees) | | 6 | 2.7 |
| Apidae | <i>Apis</i> | 4 | 1.8 |
| Brachonidae | <i>Aphidius</i> | 1 | 0.4 |
| Platygastridae | <i>Telenomus</i> | 1 | 0.4 |
| Trichogrammatidae | <i>Lathromeris</i> | 1 | 0.4 |
| Order Dictyoptera (cockroaches) | | 6 | 2.7 |
| Acanthopidae | <i>Acanthops</i> | 1 | 0.4 |
| Blaberidae | <i>Leucophaea</i> | 1 | 0.4 |
| Blattidae | <i>Periplaneta</i> | 1 | 0.4 |
| Ectobiidae=Blattellidae | 2 | 3 | 1.3 |
| Order Trichoptera (caddisflies) | | 1 | 0.4 |
| Limnephilidae | <i>Dicosmoecus</i> | 1 | 0.4 |
| Sericostomatidae | <i>Gumaga</i> | 1 | 0.4 |
| Order Ixodida (ticks) | | 2 | 0.9 |
| Ixodidae | 2 | 2 | 0.9 |
| Order Acarina (mites) | | 1 | 0.4 |
| Tetranychidae | <i>Tetranychus</i> | 1 | 0.4 |
| Order Araneae (spiders) | | 1 | 0.4 |
| Araneidae | <i>Mastophora</i> | 1 | 0.4 |

¹Number of different genera given for each family unless only one genus which in that case is named

Table S2. Number and percentage of 224 research papers on diel (circadian) rhythms regarding various aspects of pheromone amounts (titre/titer) in glands/bodies, calling behavior, pheromone release/emission rates, and response to pheromones.

| Pheromone-related keywords ¹ | Number of papers | Percent of papers |
|---|------------------|-------------------|
| Titre (OR titer) | 52 | 23.2 |
| Calling | 82 | 36.6 |
| Release | 41 | 18.3 |
| Release (but was actually calling) | 14 | 6.3 |
| Release (actual release rates) ² | 27 | 12.1 |
| Response | 104 | 46.4 |
| Mating | 39 | 17.4 |
| Temperature | 17 | 7.6 |
| Antenna OR EAG | 14 | 6.3 |
| Titre + Calling | 25 | 11.2 |
| Titre + Release | 5 | 2.2 |
| Titre + Response | 6 | 2.7 |
| Calling + Release | 5 | 2.2 |
| Calling + Response | 20 | 8.9 |
| Release + Response | 6 | 2.7 |
| Titre + Calling + Release | 2 | 0.9 |
| Titre + Calling + Response | 4 | 1.8 |
| Titre + Release + Response | 1 | 0.4 |
| Calling + Release + Response | 0 | 0 |
| Titre + Calling + Release + Response | 0 | 0 |

¹Articles were found initially by means of key words in title but some articles were then discounted when they did not contain data as suggested by title.

²Articles that reported pheromone release/emitting rates (quantity/time unit). Earlier reports sometimes considered “calling” behavior the same as “release” of pheromone.

Table S3 (gives more details on photoperiods and source figures from literature used in analysis in Table 1 in manuscript, this is a more detailed version).

Mean time (hours) and SD in photophase or scotophase of pheromone activity rhythms calculated from graphical data in literature on non-lepidopteran insects (more details). Data were fit to a normal equation from the mean time (b) and SD (c) by computer iteration to obtain the scaling coefficient a, allowing estimation of Y activity (emission, calling, or response) at any hour X (from eq. 1 in text).

| Species - Circadian activity | Source | Mean hour \pm SD | a^I | R^2 (N) |
|--|------------------|--------------------------------|-------|-----------|
| Coleoptera (beetles) | | | | |
| <i>Rhyzopertha dominica</i> (Bostrichidae) - male emission of dominicalure-1 aggregation pheromone, $\mu\text{g}/\text{male}/\text{h}$ | (1) ² | 7.94 \pm 4.9 photophase | 0.475 | 0.29 (7) |
| <i>Trogoderma variabile</i> (Dermestidae) - % female calling | (2) | 3.98 \pm 2.45 photophase | 233.2 | 0.82 (27) |
| <i>Trogoderma variabile</i> (Dermestidae) - % male response to diluted female sex pheromone extract | (2) | 4.1 \pm 3.7 photophase | 566.8 | 0.55 (8) |
| <i>Diabrotica barberi</i> (Chrysomelidae) - mean male catch/h on traps with synthetic female sex pheromone | (3) | 4.23 \pm 1.07 photophase | 62.9 | 0.80 (14) |
| <i>Sitophilus granaries</i> (Curculionidae) - % male response to male aggregation pheromone extract | (4) | 6.0 \pm 4.94 photophase | 444.9 | 0.34 (6) |
| <i>Sitophilus granaries</i> (Curculionidae) - % female response to male aggregation pheromone extract | (4) | 6.7 \pm 4.64 photophase | 588.4 | 0.49 (6) |
| <i>Hedypathes betulinus</i> (Cerambycidae) - μg (E)-6,10-dimethyl-5,9-undecadien-2-yl acetate emission per male-day | (5) | 6.49 \pm 1.98 photophase | 696 | 0.76 (6) |
| <i>Anthonomus grandis</i> (Curculionidae) - μg aggregation pheromone (sum four-components) in frass per male-hour | (6) | 7.25 \pm 4.23 photophase | 24.7 | 0.97 (9) |
| <i>Anomala albopilosa albopilosa</i> (Scarabaeidae) - ng sex pheromone buibuilactone component emission per male-hour | (7) | 2.20 \pm 2.05 scotophase | 45.95 | 0.58 (6) |
| Hemiptera (mealybugs, aphids, sucking bugs) | | | | |
| <i>Planococcus citri</i> (Pseudococcidae) virgin mealybug sex pheromone emission ng/female/h (8-10 days age) | (8) | 11.93 \pm 2.26 scotophase | 6.34 | 0.99 (11) |
| <i>Planococcus ficus</i> (Pseudococcidae) virgin mealybug sex pheromone emission ng/female/h (13-15 days age) | (8) | 2.53 \pm 5.05 photophase | 6.02 | 0.90 (11) |
| <i>Nipaecoccus viridis</i> (Pseudococcidae) virgin mealybug sex pheromone (ester) relative emission (12-14 days age) | (9) | | | |
| <i>Dysaphis plantaginea</i> (Aphididae) % oviparae calling (14 days age) | (10) | 5.87 \pm 2.94 photophase | 858.5 | 0.48 (12) |
| <i>Dysaphis plantaginea</i> (Aphididae) oviparae sex pheromone nepeta-(lactone+lactol) emission ng/adult/h (7 days age) | (10) | 7.72 \pm 4.27 photophase | 69.7 | 0.84 (16) |
| Diptera (flies) | | | | |
| <i>Anastrepha suspensa</i> (Tephritidae) emission anastrephin aggregation-lek pheromone ng/male/h (12 days age) | (11) | 11.36 \pm 1.60 photophase | 587.4 | 0.95 (8) |
| <i>Ceratitis catoirii</i> (Diptera: Tephritidae) number males calling in field cage (age > 12 days) | (12) | 2.97 \pm 1.23 photophase | 85.95 | 0.90 (13) |
| <i>Ceratitis catoirii</i> (Tephritidae) number males observed mating in lab cage (age > 12 days) | (12) | 5.27 \pm 1.39 photophase | 12.67 | 0.82 (12) |
| <i>Bactrocera zonata</i> (Tephritidae) relative emission of DMSU (spiroacetal) female sex component (3-8 days age) | (13) | 10.06 \pm 2.87 photophase | 221.4 | 0.80 (6) |
| <i>Bactrocera zonata</i> (Tephritidae) relative emission of 2,3,5-trimethylpyrazine male sex component (8-13 days age) | (13) | 7.97 \pm 3.38 photophase | 92.7 | 0.17 (9) |
| Hymenoptera (bees, ants, wasps) | | | | |

| | | | | |
|---|------|--------------|-------|-----------|
| <i>Apis mellifica ligustica</i> (Apidae) titre queen pheromone 9-keto-2-decenoic acid µg/head (virgin female 15-18 days age) | (14) | 7.42 ± 4.36 | 9110 | 0.90 (6) |
| <i>Aphidius nigripes</i> (Brachonidae) male catch on virgin female traps in field | (15) | 4.09 ± 2.95 | 80.3 | 0.50 (7) |
| Dictyoptera (cockroaches) | | | | |
| <i>Supella longipalpa</i> (Blattellidae) % females calling (8 days age) | (16) | 6.58 ± 2.80 | 665.9 | 0.83 (14) |
| <i>Supella longipalpa</i> (Blattellidae) % males responding to 0.01 female extract, males entrained then dark continuous 72 h | (17) | 6.98 ± 4.11 | 1124 | 0.92 (9) |
| <i>Blattella germanica</i> (Blattellidae) % females calling (7 days age) | (18) | 1.25 ± 5.78 | 1175 | 0.76 (24) |
| <i>Blattella germanica</i> (Blattellidae) % females mating (7 days age) | (18) | 11.44 ± 4.22 | 101.9 | 0.73 (23) |

¹Scaling coefficient *a*, mean hour *b*, and SD *c* are used to calculate *Y* of activity (described in first column) at any hour *X* of photophase or scotophase according to the normal curve eq. (1) in text.

²(1) Bashir et al. (2003), Figs. 1 and 2 (12L:12D); (2) Cross et al. (1977), Fig. 2 (16L:8D); (3) Dobson and Teal (1986), Fig. 1A (14.5L:9.5D); (4) Faustini et al. (1982), Fig. 2 (16L:8D); (5) Fonseca et al. (2010), Fig. 4C (12L:12D); (6) Gueldner and Wiygul (1978), Fig. 1 (16L:8D); (7) Leal et al. (1996), Fig. 5 (16L:8D); (8) Levi-Zada et al. (2014b), Figs. 2 and 3 (12L:12D); (9) Levi-Zada et al. (2019), Fig. 1 (14L:10D); (10) Stewart-Jones et al. (2007), Fig. 4 (12L:12D); (11) Nation (1990), Fig. 3 (14L:10D); (12) Quilici et al. (2002), Fig. 2 (12.5L:11.5D); (13) Levi-Zada et al. (2020b), Figs. 1 and 3 (14L:10D); (14) Pain and Roger (1978), Fig. 1 (16L:8D); (15) McNeil and Brodeur (1995), Fig. 6 (16L:8D); (16) Smith and Schal (1991) (12L:12D); (17) Liang and Schal (1990), Fig. 5 (12L:12D); (18) Liang and Schal (1993), Fig. 2 (12L:12D).

References used in analysis of literature presented in Tables S1 and S2

- Alford AR, Hammond AMJr (1982) Temperature modification of female sex pheromone release in *Trichoplusia ni* (Hubner) and *Pseudoplusia includens* (Walker) (Lepidoptera: Noctuidae). *Environ Entomol* 11:889–892
- Ameline A, Frérot B (2011) Oddity in diel periodicity of *Ditula angustiorana* (Haw.) (Lepidoptera: Tortricidae) female calling behaviour, pheromone titre and reproductive activity. *Int J Entomol* 47:209–213
- Babilis NA, Mazomenos BE (1992) Pheromone production in *Sesamia nonagrioides*: diel periodicity and effect of age and mating. *J Insect Physiol* 38:561–564
- Baker TC, Cardé, RT (1979) Endogenous and exogenous factors affecting periodicities of female calling and male sex pheromone response in *Grapholitha molesta* (Busck). *J Insect Physiol* 25:943–950
- Bashir T, Birkinshaw LA, Farman D, Hall DR, Hodges RJ (2003) Pheromone release by *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) in the laboratory: daily rhythm, inter-male variation and association with body weight and/or boring activity. *J Stored Prod Res* 39:159–169
- Bento JMS, Parra JRP, Vilela EF, Walder JM, Leal WS (2001) Sexual behavior and diel activity of citrus fruit borer *Ecdytolopha aurantiana*. *J Chem Ecol* 27:2053–2065
- Bestmann HJ, Erler J, Vostrowsky O (1988) Determination of diel periodicity of sex pheromone release in three species of Lepidoptera by 'closed-loop-stripping'. *Experientia* 44:797–799
- Birch MC (1977) Response of both sexes of *Trichoplusia ni* (Lepidoptera: Noctuidae) to virgin females and to synthetic pheromone. *Ecol Entomol* 2:99–104
- Bober R, Rafaeli A (2010) Gene-silencing reveals the functional significance of pheromone biosynthesis activating neuropeptide receptor (PBAN-r) in a male moth. *Proc Nat Acad Sci Wash* 107:16858–16862
- Bollinger JF, Shorey HH, Gaston LK (1977) Effect of several temperatures on the development and timing of responsiveness of males of *Trichoplusia ni* to the female sex pheromone. *Environ Entomol* 6:311–314
- Borges M, Mori K, Costa MLM, Sujii ER (1998) Behavioural evidence of methyl-2,6,10-trimethyltridecanoate as a sex pheromone of *Euschistus heros* (Het., Pentatomidae). *J Appl Entomol* 122, 335–338.
- Borges M, Schmidt FGV, Sujii ER, Medeiros MA, Mori K, Zarbin PHG, Ferreira JTB (2019) Field responses of stink bugs to the natural and synthetic pheromone of the neotropical brown stink bug, *Euschistus heros* (Heteroptera: Pentatomidae). *Physiol Entomol* 23:202–207
- Byers JA, Fefer D, Levi-Zada A (2013) Sex pheromone component ratios and mating isolation among three *Lygus* plant bug species of North America. *Naturwissenschaften* 100:1115–1123
- Bäckman AC, Bengtsson M, Witzgall P (1997) Pheromone release by individual females of codling moth, *Cydia pomonella*. *J Chem Ecol* 23:807–815
- Calvert I, Corbet SA (1973) Reproductive maturation and pheromone release in the flour moth *Anagasta kuehniella* (Zeller). *J Entomol* 47:201–209
- Camerini G, Groppali R, Rama F, Maini S (2015) Semiochemicals of *Ostrinia nubilalis*: diel response to sex pheromone and phenylacetaldehyde in open field. *Bull Insectology* 68:45–50
- Cardé RT (1974) Diel periodicities of female calling and male pheromone attraction in *Holomelina aurantiaca* (Lepidoptera: Arctiidae). *Can Entomol* 106:933–944
- Cardé RT, Doane CC, Roelofs WL (1974) Diel periodicity of male sex pheromone response and female attractiveness in the gypsy moth (Lepidoptera: Lymantriidae). *Can Entomol* 106:479–484
- Cardé RT, Charlton RE, Wallner WE, Baranchikov YN (1996) Pheromone-mediated diel activity rhythms of male Asian gypsy moths (Lepidoptera: Lymantriidae) in relation to female eclosion and temperature. *Ann Entomol Soc Am* 89:745–753
- Carrière Y, McNeil JN (1988) Observations on the mating behavior of the alfalfa blotch leafminer, *Agromyza frontella* (Rondani) (Diptera: Agromyzidae), and evidence of a female sex pheromone. *J Insect Behav* 1:291–306

- Castrejón-Gómez VR (2010) Evidence of a sex pheromone and daily calling pattern of females of *Zamagiria dixolophella* (Lepidoptera: Pyralidae). *Fla Entomol* 93:147–152
- Castrovillo PJ, Cardé RT (1979) Environmental regulation of female calling and male pheromone response periodicities in the codling moth (*Laspeyresia pomonella*). *J Insect Physiol* 25:659–667
- Charlton RE, Cardé RT (1982) Rate and diel periodicity of pheromone emission from female gypsy moths, (*Lymantria dispar*) determined with a glass-adsorption collection system. *J Insect Physiol* 28:423–430
- Cheng WJ, Zheng XL, Wang P, Zhou LL, Lei CL, Si SY, Wang XP (2015) The circadian rhythm of flight activity of *Spodoptera exigua* males in response to sex pheromone. *Entomol Exp Appl* 154:154–160
- Choi MY, Tatsuki S, Boo KS (1998) Regulation of sex pheromone biosynthesis in the oriental tobacco budworm, *Helicoverpa assulta* (Lepidoptera: Noctuidae). *J Insect Physiol* 44:653–658
- Chon TS, Liang D, Schal C (1990) Effects of mating and grouping on oocyte development and pheromone release activities in *Supella longipalpa* (Diptera: Blattellidae). *Environ Entomol* 19:1716–1721
- Christensen TA, Lehman HK, Teal PEA, Itagaki H, Tumlinson JH, Hildebrand JG (1992) Diel changes in the presence and physiological actions of octopamine in the female sex-pheromone glands of heliothine moths. *Insect Biochem Molec Biol* 22:841–849
- Cibrian-Tovari J, Mitchell ER (1991) Courtship behavior of *Heliothis subflexa* (gn.) (Lepidoptera: Noctuidae) and associated backcross insects obtained from hybridization with *H. virescens* (F.). *Environ Entomol* 20:419–426
- Coffelt JA, Sower LL, Vick KW (1978) Quantitative analysis of identified compounds in pheromone gland rinses of *Plodia interpunctella* and *Ephesia cautella* at different times of day. *Environ Entomol* 7:502–505
- Cross JH, Byler RC, Silverstein RM, Greenblatt RE, Gorman JE, Burkholder WE (1977) Sex pheromone components and calling behavior of the female dermestid beetle, *Trogoderma variabile* Ballion (Coleoptera: Dermestidae). *J Chem Ecol* 3:115–125
- Debarr GL, Berisford CW (1981) Attraction of webbing coneworm males to female sex pheromone. *Environ Entomol* 10:119–121
- Delisle J, McNeil JN (1987) Calling behaviour and pheromone titre of the true armyworm *Pseudaletia unipuncta* (Haw.) (Lepidoptera: Noctuidae) under different temperature and photoperiodic conditions. *J Insect Physiol* 33:315–324
- Delisle J, Royer L (1994) Changes in pheromone titer of oblique banded leafroller, *Choristoneura rosaceana*, virgin females as a function of time of day, age, and temperature. *J Chem Ecol* 20:45–66
- Delisle J, Picimbon JF, Simard J (1999) Physiological control of pheromone production in *Choristoneura fumiferana* and *C. rosaceana*. *Arch Insect Biochem Physiol* 42:253–265
- Dobson ID, Teal PEA (1986) Field studies of the temporal response patterns of male *Diabrotica virgifera virgifera* LeConte and *D. barberi* Smith and Lawrence to 8R-methyl-2R-decyl propanoate. *Physiol Entomol* 11:405–410
- Dong SL, Du JW (2001) Diel rhythms of calling behavior and sex pheromone production of beet armyworm, *Spodoptera exigua* (Lepidoptera: Noctuidae). *Entomol Sinica* 8:89–96
- Duff CM, Gries G, Mori K, Shirai Y, Seki M, Takikawa H, Sheng T, Slessor KN, Gries R, Maier CT, Ferguson DC (2001) Does pheromone biology of *Lambdina athasaria* and *L. pellucidaria* contribute to their reproductive isolation? *J Chem Ecol* 27, 431–442.
- Dunkelblum E, Kehat M, Harel M, Gordon D (1987) Sexual behaviour and pheromone titre of the *Spodoptera littoralis* female moth. *Entomol Exp Appl* 44:241–247
- Dusbabek F, Leonovich SA (1988) Circadian basis of assembly pheromone response in *Argas (Percicargas) persicus*. *Exp Appl Acarol* 4:319–334
- Eban-Rothschild A, Shemesh Y, Bloch G (2012) The colony environment, but not direct contact with conspecifics, influences the development of circadian rhythms in honey bees. *J Biol Rhythm* 27:217–225
- Eisenbach J, Mittler TE (1980) An aphid circadian rhythm: factors affecting the release of sex pheromone by oviparae of the greenbug, *Schizaphis graminum*. *J Insect Physiol* 26:511–515

- Epsky ND, Heath RR (1993) Pheromone production by male *Anastrepha suspensa* (Diptera: Tephritidae) under natural light cycles in greenhouse studies. *Environ Entomol* 22:464–469
- Fatzinger CW (1973) Circadian rhythmicity of sex pheromone release by *Dioryctria abietella* (Lepidoptera: Pyralidae (Phycitinae)) and the effect of a diel light cycle on its precopulatory behavior. *Ann Entomol Soc Am* 66:1147–1153
- Faustini DL, Giese WL, Phillips JK, Burkholder WE (1982) Aggregation pheromone of the male granary weevil, *Sitophilus granarius* (L.). *J Chem Ecol* 8:679–686
- Fiaboe MK, Chabi-Olaye A, Gounou S, Smith H, Borgemeister C, Schulthess F (2003) *Sesamia calamistis* calling behavior and its role in host finding of egg parasitoids *Telenomus busseolae*, *Telenomus isis*, and *Lathromeris ovicida*. *J Chem Ecol* 29:921–929
- Figueiras ANL, Kenigsten A, Lazzari CR (1994) Aggregation in the bug *Triatoma infestans*: chemical signals and temporal pattern. *J Insect Physiol* 40:311–316
- Flecke C, Dolzer J, Krannich S, Stengl M (2006) Perfusion with cGMP analogue adapts the action potential response of pheromone-sensitive sensilla trichoidea of the hawkmoth *Manduca sexta* in a daytime-dependent manner. *J Exp Biol* 209:3898–3912
- Flores MF, Romero A, Oyarzun MS, Bergmann J, Zaviezo T (2015) Monitoring *Pseudococcus calceolariae* (Hemiptera: Pseudococcidae) in fruit crops using pheromone-baited traps. *J Econ Entomol* 108:2397–2406
- Fonseca MG, Vidal DM, Zarbin PHG (2010) Male-produced sex pheromone of the cerambycid beetle *Hedypathes betulinus*: chemical identification and biological activity. *J Chem Ecol* 36:1132–1139
- Foster SP (2000) Periodicity of sex pheromone biosynthesis, release and degradation in the lightbrown apple moth, *Epiphyas postvittana* (Walker). *Arch Insect Biochem Physiol* 43:125–136
- Foster SP, Roelofs WL (1994) Regulation of pheromone production in virgin and mated females of two tortricid moths. *Arch Insect Biochem Physiol* 25:271–285
- Francis A, Bloem KA, Roda AL, Lapointe SL, Zhang A, Onokpise O (2007) Development of trapping methods with a synthetic sex pheromone of the pink hibiscus mealybug, *Maconellicoccus hirsutus* (Hemiptera: Pseudococcidae). *Fla Entomol* 90:440–446
- Free JB, Ferguson AW, Simpkins JR (1992) The behaviour of queen honeybees and their attendants. *Physiol Entomol* 17:43–55
- Gatellier L, Nagao T, Kanzak R (2004) Serotonin modifies the sensitivity of the male silkworm to pheromone. *J Exp Biol* 207:2487–2496
- Gemeno C, Haynes KF (2000) Periodical and age-related variation in chemical communication system of black cutworm moth, *Agrotis ipsilon*. *J Chem Ecol* 26:329–342
- Gemeno C, Haynes KF (2001) Impact of photoperiod on the sexual behavior of the black cutworm moth (Lepidoptera: Noctuidae). *Environ Entomol* 30:189–195
- Gerber GH, Howlader MA (1987) The effects of photoperiod and temperature on calling behaviour and egg development of the bertha armyworm, *Mamestra configurata* (Lepidoptera: Noctuidae). *J Insect Physiol* 33:429–436
- Giebultowicz JM, Webb RE, Raina AK, Ridgway RL (1992) Effects of temperature and age on daily changes in pheromone titer in laboratory-reared and wild gypsy moth (Lepidoptera: Lymantriidae). *Environ Entomol* 21:822–826
- Gorsuch CS, Karandinos MG, Koval CF (1975) Daily rhythm of *Synanthedon pictipes* (Lepidoptera: Aegeriidae) female calling behavior in Wisconsin: temperature effects. *Entomol Exp Appl* 18:367–376
- Graham HM (1973) Hourly response of laboratory-reared and native male pink bollworms to traps baited with hexalure. *Environ Entomol* 2, 965.
- Greenfield MD, Karandinos MG (1979) Resource partitioning of the sex communication channel in clearwing moths (Lepidoptera: Sesiidae) of Wisconsin. *Ecol Monogr* 49:403–426
- Gries G, Schaefer PW, Gries R, Liska J, Gotoh T (2001) Reproductive character displacement in *Lymantria monacha* from northern Japan? *J Chem Ecol* 27:1163–1176
- Groot AT (2014) Circadian rhythms of sexual activities in moths: a review. *Frontiers in Ecology and Evolution* 2:article 43, 1–21

- Guedot C, Horton DR, Landolt PJ (2012) Age at reproductive maturity and effect of age and time of day on sex attraction in the potato psyllid *Bactericera cockerelli*. *Insect Sci* 19:585–594
- Gueldner RC, Wiygul G (1978) Rhythms in pheromone production of the male boll weevil. *Science* 199:984–986
- Guldmond JA, Tigges WT, De Vrijer PWF (1994) Circadian rhythm of sex pheromone production and male activity of coexisting sibling species of *Cryptomyzus* aphids (Homoptera: Aphididae). *Eur J Entomol* 91:85–89
- Hammack L, Bukkholder WE (1976) Circadian rhythm of sex pheromone-releasing behaviour in females of the dermestid beetle, *Trogoderma glabrum*: regulation by photoperiod. *J Insect Physiol* 22:385–388
- Hanin O, Azrielli A, Zakin V, Applebaum S, Rafaeli A (2011) Identification and differential expression of a sex-peptide receptor in *Helicoverpa armigera*. *Insect Biochem Molec Biol* 41:537–544
- Haynes KF, Birch MC (1984) The periodicity of pheromone release and male responsiveness in the artichoke plume moth, *Platyptilia carduidactyla*. *Physiol Entomol* 9:287–295
- Haynes KF, Birch MC (1986) Temporal reproductive isolation between two species of plume moths (Lepidoptera: Pterophoridae). *Ann Entomol Soc Am* 79:210–215
- Haynes KF, Gaston LK, Mistrot Pope M, Baker TC (1983) Rate and periodicity of pheromone release from individual female artichoke plume moths, *Platyptilia carduidactyla* (Lepidoptera: Pterophoridae). *Environ Entomol* 12:1597–1600
- Haynes KF, Gemeno C, Yeargan KV, Millar JG, Johnson KM (2002) Aggressive chemical mimicry of moth pheromones by a bolas spider: how does this specialist predator attract more than one species of prey? *Chemoecology* 12:99–105
- Heath RR, McLaughlin JR, Proshold F, Teal PEA (1991) Periodicity of female sex pheromone titer and release in *Heliothis subflexa* and *H. virescens* (Lepidoptera: Noctuidae). *Ann Entomol Soc Am* 84:182–189
- Heath RR, Manukian A, Epsky ND, Sivinski J, Calkins CO, Landolt PJ (1993) A bioassay system for collecting volatiles while simultaneously attracting tephritid fruit flies. *J Chem Ecol* 19:2395–2410
- Hendrichs J, Hendrichs MA (1990) Mediterranean fruit fly (Diptera: Tephritidae) in nature: location and diel pattern of feeding and other activities on fruiting and nonfruiting hosts and nonhosts. *Ann Entomol Soc Am* 83:632–641
- Hendricks DE (1985) Portable electronic detector system used with inverted-cone sex pheromone traps to determine periodicity and moth captures. *Environ Entomol* 14:199–204
- Hirashima A, Eiraku T, Watanabe Y, Kuwano E, Taniguchi E, Eto M (2001) Identification of novel inhibitors of calling and in vitro [14 c]acetate incorporation by pheromone glands of *Plodia interpunctella*. *Pest Manag Sci* 57:713–720
- Hrabar M, Danci A, McCann S, Schaefer PW, Gries G (2014) New findings on life history traits of *Xenos peckii* (Strepsiptera: Xenidae). *Can Entomol* 146:514–527
- Hunt RE, Haynes KF (1990) Periodicity in the quantity and blend ratios of pheromone components in glands and volatile emissions of mutant and normal cabbage looper moths, *Trichoplusia ni*. *J Insect Physiol* 36:769–774
- Ichikawa T (1998) Activity patterns of neurosecretory cells releasing pheromonotropic neuropeptides in the moth *Bombyx mori*. *Proc Nat Acad Sci Wash* 95:4055–4060
- Ichikawa T, Kamimoto S (2003) Heteronomous rhythmic activity of neurosecretory cells in the silkworm. *Neurosci Lett* 347:73–76
- Iglesias F, Jacquín-Joly E, Marco MP, Camps F, Fabrias G (1999) Temporal distribution of PBAN-like immunoreactivity in the hemolymph of *Mamestra brassicae* females in relation to sex pheromone production and calling behavior. *Arch Insect Biochem Physiol* 40:80–87
- Itagaki H, Conner WE (1988) Calling behavior of *Manduca sexta* (L.) (Lepidoptera: Sphingidae) with notes on the morphology of the female sex pheromone gland. *Ann Entomol Soc Am* 81:798–807
- Jackson JK, Resh VH (1991) Periodicity in mate attraction and flight activity of three species of caddisflies (Trichoptera). *J N Am Benthol Soc* 10:198–209

- Jones MDR, Gubbins SJ (1979) Modification of female circadian flight-activity by a male accessory gland pheromone in the mosquito, *Culex pipiens quinquefasciatus*. *Physiol Entomol* 4:345–351
- Kamimura M, Tatsuki S (1993) Diel rhythms of calling behavior and pheromone production of oriental tobacco budworm moth, *Helicoverpa assulta* (Lepidoptera: Noctuidae). *J Chem Ecol* 19:2953–2963
- Kamimura M, Tatsuki S (1994) Effects of photoperiodic changes on calling behavior and pheromone production in the oriental tobacco budworm moth, *Helicoverpa assulta* (Lepidoptera: Noctuidae). *J Insect Physiol* 40:731–734
- Kanaujia KR, Sidhu HS (1980) Factors affecting the responsiveness of males to female sex pheromone in angoumois grain moth, *Sitotroga cerealella* (Olivier). *J Appl Entomol* 89:387–390
- Kaneko J (1986) Effect of temperature on the timing of calling of the yellow peach moth *Conogethes punctiferalis* (Guenée) (Lepidoptera: Pyralidae). *Jpn J Appl Entomol Z* 30:239–246
- Kanno H (1981a) Mating behaviour of the rice stem borer moth, *Chilo suppressalis* Walker (Lepidoptera: Pyralidae) VI. Effects of photoperiod on the diel rhythms of mating behaviours. *Appl Entomol Zool* 16:406–411
- Kanno H (1981b) Seasonal variation in periodicity of mating behaviour in the rice stem borer, *Chilo suppressalis* (Walker) (Lepidoptera: Pyralidae). *Bull Entomol Res* 71:631–637
- Kaster LV, Showers WB, Mulder PG (1989) Seasonality in the hourly reproductive behavior of adult *Agrotis ipsilon* (Lepidoptera: Noctuidae) in Iowa. *Environ Entomol* 18:674–677
- Katsoyannos BI (1982) Male sex pheromone of *Rhagoletis cerasi* L. (Diptera, Tephritidae): Factors affecting release and response and its role in the mating behavior. *J Appl Entomol* 94:187–198
- Kawasaki K (1986) Activity rhythms and behavior of adult *Spodoptera litura* F. (Lepidoptera: Noctuidae) at night: factors determining male attraction time by females. *Appl Entomol Zool* 21:493–499
- Kawasaki K, Tamaki Y, Nakamura K (1983) Seasonal difference in diel periodicity of male attraction of the smaller tea tortrix moth *Adoxophyes*-sp (Lepidoptera: Tortricidae) to synthetic sex pheromones and virgin females. *Jpn J Appl Entomol Z* 27:106–111
- Kim Y, Jung S, Kim Y, Lee Y (2011) Real-time monitoring of oriental fruit moth, *Grapholita molesta*, populations using a remote sensing pheromone trap in apple orchards. *J Asia-Pac Entomol* 14:259–262
- Kipp LR, Lonergan GC, Bell WJ (1995) Male periodicity and the timing of mating in the spruce budworm (Lepidoptera: Tortricidae): influences of population density and temperature. *Environ Entomol* 24:1150–1159
- Knight AL, Light DM (2005) Factors affecting the differential capture of male and female codling moth (Lepidoptera: Tortricidae) in traps baited with ethyl (*E,Z*)-2,4-decadienoate. *Environ Entomol* 34:1161–1169
- Koblos G, Danko T, Sipos K, Geiger Á, Szlanka T, Fodor J, Fonagy A (2015) The regulation of $\Delta 11$ -desaturase gene expression in the pheromone gland of *Mamestra brassicae* (Lepidoptera; Noctuidae) during pheromonogenesis. *Gen Comp Endocrinol* 221:217–227
- Kochansky JP, Cardé RT, Taschenberg EF, Roelofs WL (1977) Rhythms of male *Antheraea polyphemus* attraction and female attractiveness, and an improved pheromone synthesis. *J Chem Ecol* 3:419–427
- Kondo A, Sano T, Tanaka F (1994) Automatic record using camera of diel periodicity of pheromone trap catches. *Jpn J Appl Entomol Z* 38:197–199
- Konno Y (1986) Time-lag between sex pheromone content and the calling behavior in the yellow peach moth, *Conogethes punctiferalis* (Guenée) (Lepidoptera: Pyralidae). *Appl Entomol Zool* 21:622–624
- Konstantopoulou MA, Pratsinis H, Kletsas D, Mazomenos BE (2006) Pheromone-binding protein and general odorant binding protein of *Sesamia nonagrioides*: sex- and diel-dependent expression. *Entomol Exp Appl* 119:129–136
- Kontev C, Zdarek J, Kalvoda L (1984) Epigamic behaviour of the cereal pest *Cnephasia pumicana* (Lepidoptera, Tortricidae) investigated with pheromone traps. *Acta Entomol Bohemos* 81:90–98
- Kou R, Chow YS (1987) Calling behavior of the cotton bollworm, *Heliothis armigera* (Lepidoptera: Noctuidae). *Ann Entomol Soc Am* 80:490–493
- Krupke CH, Jones VP, Brunner JF (2006) Diel periodicity of *Euschistus conspersus* (Heteroptera: Pentatomidae) aggregation, mating, and feeding. *Ann Entomol Soc Am* 99:169–174

- Krupp JJ, Kent C, Billeter JC, Azanchi R, So AKC, Schonfeld JA, Smith BP, Lucas C, Levine JD (2008) Social experience modifies pheromone expression and mating behavior in male *Drosophila melanogaster*. *Curr Biol* 18:1373–1383
- Krupp JJ, Billeter JC, Wong A, Choi C, Nitabach MN, Levine JD (2013) Pigment-dispersing factor modulates pheromone production in clock cells that influence mating in *Drosophila*. *Neuron* 79:54–68
- Kumara ADNT, Chandrashekharaiah M, Subaharan K, Chakravarthy AK (2015) Periodicity of adult emergence and sexual behaviour of coconut black headed caterpillar, *Opisina arenosella* Walker (Lepidoptera: Oecophoridae). *Phytoparasitica* 43:701–712
- Landolt PJ, Heath RR (1987) Seasonal and diel patterns of sex attraction of male *Harrisina americana* and *Acoloitus falsarius* (Lepidoptera: Zygaenidae). *Fla Entomol* 70:392–396
- Landolt PJ, Heath RR (1988) Effects of age, mating, and time of day on behavioral responses of female papaya fruit fly, *Toxotrypana curvicauda* Gerstaecker (Diptera: Tephritidae), to synthetic sex pheromone. *Environ Entomol* 17:47–51
- Landolt PJ, Gonzalez M, Chambers DL, Heath RR (1991) Comparison of field observations and trapping of papaya fruit fly in papaya plantings in central America and Florida. *Fla Entomol* 74:408–414
- Leal WS, Sawada M, Matsuyama S, Kuwahara Y, Hasegawa M (1993) Unusual periodicity of sex pheromone production in the large black chafer *Holotrichia parallela*. *J Chem Ecol* 19:1381–1391
- Leal WS, Hasegawa M, Sawada M, Ono M, Tada S (1996) Scarab beetle *Anomala albopilosa albopilosa* utilizes a more complex sex pheromone system than a similar species *A. cuprea*. *J Chem Ecol* 22:2001–2010
- Leos-Martinez J, Granovsky TA, Willlams HJ, Vinson SB, Burkholder WE (1986) Estimation of aerial density of the lesser grain borer (Coleoptera: Bostrichidae) in a warehouse using dominicalure traps. *J Econ Entomol* 79:1134–1138
- Levi-Zada, A, Nestel D, Fefer D, Nemni-Lavy E, Deloya-Kahane I, David M (2012) Analyzing diurnal and age-related pheromone emission of the olive fruit fly, *Bactrocera oleae* (Diptera: Tephritidae) by sequential SPME–GCMS analysis. *J Chem Ecol* 38:1036–1041
- Levi-Zada A, Sadowsky A, Dobrinin S, David M, Ticuchinski T, Fefer D, Greenberg A, Blumberg D (2013) Reevaluation of the sex pheromone of the lesser date moth, *Batrachedra amydraula*, using autosampling SPME-GC/MS and field bioassays. *Chemoecology* 23:13–20
- Levi-Zada A, David M, Fefer D, Seplyarsky V, Sadowsky A, Dobrinin S, Ticuchinski T, Harari D, Blumberg D, Dunkelblum E (2014a) Circadian release of male-specific components of the greater date moth, *Aphomia (Arenipses) sabella*, using sequential SPME/GC/MS analysis. *J Chem Ecol* 40:236–243
- Levi-Zada A, Fefer D, David M, Eliyahu M, Franco JC, Protasov A, Dunkelblum E, Mendel Z (2014b) Diel periodicity of pheromone release by females of *Planococcus citri* and *Planococcus ficus* and the temporal flight activity of their conspecific males. *Naturwissenschaften* 101:671–678
- Levi-Zada A, Sadowsky A, Dobrinin S, Ticuchinski T, David M, Fefer D, Dunkelblum E, Byers JA (2018) Monitoring and mass-trapping methodologies using pheromones: the lesser date moth *Batrachedra amydraula*. *Bull Entomol Res* 108:58–68
- Levi-Zada A, Levy A, Rempoulakis P, Fefer D, Steiner S, Gazit Y, Nestel D, Yuval B, Byers JA (2020b) Diel rhythm of volatile emissions of males and females of the peach fruit fly *Bactrocera zonata*. *J Insect Physiol* 120: *in press*
- Liang D, Schal C (1990) Circadian rhythmicity and development of the behavioural response to sex pheromone in male brown-banded cockroaches, *Supella longipalpa*. *Physiol Entomol* 15:355–361
- Liang D, Schal C (1993) Calling behavior of the female German cockroach, *Blattella germanica* (Dictyoptera: Blattellidae). *J Insect Behav* 6:603–614
- Linn CEJr, Roelofs WL (1986) Modulatory effects of octopamine and serotonin on male sensitivity and periodicity of response to sex pheromone in the cabbage looper moth, *Trichoplusia ni*. *Arch Insect Biochem Physiol* 3:161–171
- Linn CEJr, Roelofs WL (1992) Role of photoperiod cues in regulating the modulatory action of octopamine on pheromone-response thresholds in the cabbage looper moth. *Arch Insect Biochem Physiol* 20:285–302

- Linn CE Jr, Campbell MG, Roelofs WL (1992) Photoperiod cues and the modulatory action of octopamine and 5-hydroxytryptamine on locomotor and pheromone response in male gypsy moths, *Lymantria dispar*. Arch Insect Biochem Physiol 20:265–284
- Linn CE, Campbell MG, Poole KR, Wu WQ, Roelofs WL (1996) Effects of photoperiod on the circadian timing of pheromone response in male *Trichoplusia ni*: relationship to the modulatory action of octopamine. J Insect Physiol 42:881–891
- Liu H, Zhao W, Yang M, Liu J, Zhang J (2013) Diel rhythms of sexual behavior and pheromone titers in *Isoceras sibirica* Alpheraky (Lepidoptera, Cossidae). Arch Insect Biochem Physiol 84:15–26
- Lu Q, Huang LY, Liu FT, Wang XF, Chen P, Xu J, Deng JY, Ye H (2017) Sex pheromone titre in the glands of *Spodoptera litura* females: circadian rhythm and the effects of age and mating. Physiol Entomol 42:156–162
- Löfstedt C, Van Der Pers JNC, Löfqvist J, Lanne BS, Appelgren M, Bergström G, Thelin B (1982) Sex pheromone components of the turnip moth, *Agrotis segetum*: chemical identification, electrophysiological evaluation and behavioral activity. J Chem Ecol 8:1305–1321
- Ma M, Burkholder WE (1978) Sex pheromone releasing behavior of *Anthrenus flavipes* (furniture carpet beetles) females (Coleoptera: Dermestidae). Ann Entomol Soc Am 71:129–133
- Ma T, Zhang Y, Wang S, Lan L, Lin N, Wang C, Wu Y, Chang M, Sun Z, Wang C, Wen X (2018) Reproductive behavior and sex pheromone production in *Eutectona machaeralis* (Lepidoptera: Crambidae). Fla Entomol 101:189–194
- Margaritopoulos JT, Malarky G, Tsitsipis JA, Blackman RL (2007) Microsatellite DNA and behavioural studies provide evidence of host-mediated speciation in *Myzus persicae* (Hemiptera: Aphididae). Biol J Linn Soc 91:687–702
- Marsh D (1975) Responses of male aphids to the female sex pheromone in *Megoura viciae* Buckton. J Entomol 50:43–64
- Martinez T, Camps F (1988) Stimulation of sex pheromone production by head extract in *Spodoptera littoralis* at different times of the photoperiod. Arch Insect Biochem Physiol 9:211–220
- Mazo-Cancino A Del, Malo EA, Cruz-López L, Rojas JC (2004) Diel periodicity and influence of age and mating on female sex pheromone titre in *Estigmene acrea* (Lep., Arctiidae). J Appl Entomol 128:459–463
- Mazor M, Dunkelblum E (2005) Circadian rhythms of sexual behavior and pheromone titers of two closely related moth species *Autographa gamma* and *Cornutiplusia circumflexa*. J Chem Ecol 31:2153–2168
- Mbata GN, Ramaswamy SB (1990) Rhythmicity of sex pheromone content in female *Heliothis virescens*: impact of mating. Physiol Entomol 15:423–432
- McLaughlin JR, Heath RR, Ashley TR (1990) Periodicity of pheromone release from female white peach scale. Physiol Entomol 15:193–197
- McNeil JN, Brodeur J (1995) Pheromone-mediated mating in the aphid parasitoid, *Aphidius nigripes* (Hymenoptera: Aphididae). J Chem Ecol 21:959–971
- Meagher RL, Epsky ND, Cherry R (2007) Mating behavior and female-produced pheromone use in tropical sod webworm (Lepidoptera: Crambidae). Fla Entomol 90:304–308
- Merlin C, Lucas P, Rochat D, François MC, Maïbèche-Coisne M, Jacquín-Joly E (2007) An antennal circadian clock and circadian rhythms in peripheral pheromone reception in the moth *Spodoptera littoralis*. J Biol Rhythm 22:502–514
- Ming QL, Yan YH, Wang CZ (2007) Mechanisms of premating isolation between *Helicoverpa armigera* (Hübner) and *Helicoverpa assulta* (Guenée) (Lepidoptera: Noctuidae). J Insect Physiol 53:170–178
- Mitchell RF, Reagel PF, Wong JCH, Meier LR, Silva WD, Mongold-Diers J, Millar JG, Hanks LM (2015) Cerambycid beetle species with similar pheromones are segregated by phenology and minor pheromone components. J Chem Ecol 41:431–440
- Monti L, Lalanne-Cassou B, Lucas P, Malosse C, Silvain JF (1995) Differences in sex pheromone communication systems of closely related species: *Spodoptera latifascia* (Walker) and *S. descoinsi* Lalanne-Cassou, Silvain (Lepidoptera: Noctuidae). J Chem Ecol 21:641–660

- Mori BA, Evenden ML (2015) Challenges of mating disruption using aerosol-emitting pheromone puffers in red clover seed production fields to control *Coleophora deauratella* (Lepidoptera: Coleophoridae). *Environ Entomol* 44:34–43
- Morse D, Szittnerg R, Grant GG, Meighen EA (1982) Rate of pheromone release by individual spruce budworm moths. *J Insect Physiol* 28:863–866
- Mozuraitis R, Buda V, Borg-Karlson AK, Ivinskis P (1997) Chemocommunication in *Phyllonorycter ulmifoliella* (Hbn.) (Lepidoptera: Gracillariidae): periodicity, sex pheromone, and inhibitors. *J Chem Ecol* 23:175–189
- Mozuraitis R, Buda V, Jonušaitė V, Borg-Karlson AK, Noreika R (2000) Sex pheromones of *Phyllonorycter acerifoliella* and *Ph. heegerella* and communication peculiarities in three species of leafmining moths. *Entomol Exp Appl* 94:15–23
- Mozuraitis R, Liblikas I, Noreika R (2008) Sex pheromone communication of tentiform leaf-miners *Phyllonorycter insignitella* and *Ph. nigrescentella* from two related species groups. *Chemoecology* 18:171–176
- Nagari M, Szyszka P, Galizia G, Bloch G (2017) Task-related phasing of circadian rhythms in antennal responsiveness to odorants and pheromones in honeybees. *J Biol Rhythm* 32:593–608
- Nammour D, Huignard J, Pouzat J (1988) A female sex pheromone in *Bruchidius atrolineatus* (Pic)(Coleoptera, Bruchidae): analysis of the factors affecting production or emission of this pheromone. *Physiol Entomol* 13:185–192
- Nation JL (1990) Biology of pheromone release by male Caribbean fruit flies, *Anastrepha suspensa* (Diptera: Tephritidae). *J Chem Ecol* 16:553–571
- Nojima S, Classen A, Groot AT, Schal C (2018) Qualitative and quantitative analysis of chemicals emitted from the pheromone gland of individual *Heliothis subflexa* females. *Plos One* 13, e0202035
- O'Ceallachain DP, Ryan MF (1977) Production and perception of pheromones by the beetle *Tribolium confusum*. *J Insect Physiol* 23:1303–1309
- Obeng-Ofori D, Coaker TH (1990) Some factors affecting responses of four stored product beetles (Coleoptera: Tenebrionidae, Bostrichidae) to pheromones. *Bull Entomol Res* 80:433–441
- Odell TM (1978) Periodicity of eclosion and pre-mating behavior of gypsy moth. *Ann Entomol Soc Am* 71:748–751
- Odell DR, Lance TM, Mastro VC, Schwalbe CP (1988) Temperature-mediated programming of activity rhythms in male gypsy moths (Lepidoptera: Lymantriidae): implications for the sterile male technique. *Environ Entomol* 17:649–653
- Ono T, Charlton RE, Cardé RT (1990) Variability in pheromone composition and periodicity of pheromone titer in potato tuberworm moth, *Phthorimaea operculella* (Lepidoptera: Gelechiidae). *J Chem Ecol* 16:531–542
- Pain J, Roger B (1978) Circadian rhythm of 9-ketodec-2-enoic acid, queen pheromone, and 10-hydroxydec-2-enoic acid of worker bees, *Apis mellifica lingustica* S. *Apidologie* 9:263–272
- Park KC, Cork A, Boo KS (1996) Intrapopulational changes in sex pheromone composition during scotophase in oriental tobacco budworm, *Helicoverpa assulta* (Guenée) (Lepidoptera: Noctuidae). *J Chem Ecol* 22:1201–1210
- Pashley DP, Hammond AM, Hardy TN (1992) Reproductive isolating mechanisms in fall armyworm host strains (Lepidoptera: Noctuidae). *Ann Entomol Soc Am* 85:400–405
- Pats P, Wiktelius S (1992) Diel flight periodicity of *Chilo partellus*. *Entomol Exp Appl* 65:165–170
- Pierce AM, Pierce HDJr, Oehlschlager AC, Czyzewska E, Borden JH (1987) Influence of pheromone chirality on response by *Oryzaephilus surinamensis* and *Oryzaephilus mercator* (Coleoptera: Cucujidae). *J Chem Ecol* 13:1525–1542
- Pivnick KA (1993) Response of males to female sex pheromone in the orange wheat blossom midge, *Sitodiplosis mosellana* (Gehin) (Diptera: Cecidomyiidae). *J Chem Ecol* 19:1677–1689
- Pope MM, Gaston LK, Baker TC (1982) Composition, quantification, and periodicity of sex pheromone gland volatiles from individual *Heliothis virescens* females. *J Chem Ecol* 8:1043–1055

- Pope MM, Gaston LK, Baker TC (1984) Composition, quantification, and periodicity of sex pheromone volatiles from individual *Heliothis zea* females. *J Insect Physiol* 30:943–945
- Quartey GK, Coaker TH (1996) Periodicity of activity and sexual response of adult *Ephestia cautella* (Walk.) (Lep., Phycitidae). *J Appl Entomol* 120:335–339
- Quilici S, Franck A, Peppuy A, Correia E Dos Reis, Mouniama C, Blard F (2002) Comparative studies of courtship behavior of *Ceratitis* spp. (Diptera: Tephritidae) in reunion island. *Fla Entomol* 85:138–142
- Rafaeli A, Klein Z (1994) Regulation of pheromone production by female pink bollworm moths *Pectinophora gossypiella* (Sanders) (Lepidoptera: Gelechiidae). *Physiol Entomol* 19:159–164
- Rafaeli A, Soroker V (1989) Influence of diel rhythm and brain hormone on pheromone production in two Lepidopteran species. *J Chem Ecol* 15:447–445
- Raina AK, Klun JA, Stadelbacher EA (1986) Diel periodicity and effect of age and mating on female sex pheromone titer in *Heliothis zea* (Lepidoptera: Noctuidae). *Ann Entomol Soc Am* 79:128–131
- Raina AK, Davis JC, Stadelbacher EA (1991) Sex pheromone production and calling in *Helicoverpa zea* (Lepidoptera: Noctuidae): effect of temperature and light. *Environ Entomol* 20:1451–1456
- Ramaswamy SB, Ma PWK, Pitre HN (1988) Calling rhythm and pheromone titers in *Spodoptera frugiperda* (JE Smith) (Lep., Noctuidae) from Mississippi and Honduras. *J Appl Entomol* 106:90–96
- Rasmy AH, Hussein HE (1993) Effect of day time on release of female sex pheromone and male response in the two-spotted spider mite (Acari, Tetranychidae). *J Appl Entomol* 115:214–216
- Rechav Y (1978) Lack of daily rhythm in the release of assembly pheromones by the tick *Amblyomma hebraeum* (Koch). *Experientia* 34:478–479
- Rice RE, Moreno DS (1970) Flight of male California red scale. *Ann Entomol Soc Am* 63:91–96
- Robinson MH, Robinson B (1979) By dawn's early light: matutinal mating and sex attractants in a neotropical mantid. *Science* 205:825–827
- Rosén W (2002) Endogenous control of circadian rhythms of pheromone production in the turnip moth, *Agrotis segetum*. *Arch Insect Biochem Physiol* 50:21–30
- Rosén WQ, Han GB, Löfstedt C (2003) The circadian rhythm of the sex-pheromone-mediated behavioral response in the turnip moth, *Agrotis segetum*, is not controlled at the peripheral level. *J Biol Rhythm* 18:402–408
- Rothschild GHL, Minks AK (1974) Time of activity of male oriental fruit moths at pheromone sources in the field. *Environ Entomol* 3:1003–1007
- Rymer J, Bauernfeind AL, Brown S, Page TL (2007) Circadian rhythms in the mating behavior of the cockroach, *Leucophaea maderae*. *J Biol Rhythm* 22:43–57
- Saario CA, Shorey HH, Gaston LK (1970) Sex pheromones of noctuid moths. XIX. Effect of environmental and seasonal factors on captures of males of *Trichoplusia ni* in pheromone-baited traps. *Ann Entomol Soc Am* 63:667–672
- Sadek MM, Wowerm G, Von, Löfstedt C, Rosén WQ, Anderson P (2012) Modulation of the temporal pattern of calling behavior of female *Spodoptera littoralis* by exposure to sex pheromone. *J Insect Physiol* 58:61–66
- Sasaerila Y, Gries G, Gries R, Boo TC (2000) Specificity of communication channels in four limacodid moths: *Darna bradleyi*, *Darna trima*, *Setothosea asigna*, and *Setora nitens* (Lepidoptera: Limacodidae). *Chemoecology* 10:193–199
- Schaefer PW, Gries G, Gries R, Holden D (1999) Pheromone components and diel periodicity of pheromonal communication in *Lymantria fumida*. *J Chem Ecol* 25:2305–2312
- Schal C, Charlton RE, Cardé RT (1987) Temporal patterns of sex pheromone titers and release rates in *Holomelina lamae* (Lepidoptera: Arctiidae). *J Chem Ecol* 13:1115–1129
- Schlamp KK, Brown K, Gries R, Hart M, Gries G, Judd GGR (2006) Diel periodicity of sexual communication in *Anarsia lineatella* (Lepidoptera: Gelechiidae). *Can Entomol* 138:384–389
- Schofl G, Heckel DG, Groot AT (2009) Time-shifted reproductive behaviours among fall armyworm (Noctuidae: *Spodoptera frugiperda*) host strains: evidence for differing modes of inheritance. *J Evol Biol* 22:1447–1459

- Schuckel J, Siwicki KK, Stengl M (2007) Putative circadian pacemaker cells in the antenna of the hawkmoth *Manduca sexta*. *Cell Tissue Res* 330:271–278
- Silvegren G, Löfstedt C, Rosén WQ (2005) Circadian mating activity and effect of pheromone pre-exposure on pheromone response rhythms in the moth *Spodoptera littoralis*. *J Insect Physiol* 51:277–286
- Skabeikis DD, Teale SA, Fierke MK (2016) Diel rhythms in *Monochamus* (Coleoptera: Cerambycidae): production of and response to a male-produced aggregation pheromone. *Environ Entomol* 45:1017–1021
- Smith AF, Schal C (1991) Circadian calling behavior of the adult female brown-banded cockroach, *Supella longipalpa* (F.) (Dictyoptera: Blattellidae). *J Insect Behav* 4:1–14
- Sollai G, Solari P, Crnjar R (2018) Olfactory sensitivity to major, intermediate and trace components of sex pheromone in *Ceratitis capitata* is related to mating and circadian rhythm. *J Insect Physiol* 110:23–33
- Sower LL, Shorey HH, Gaston LK (1971) Sex pheromones of noctuid moths. XXV. Effects of temperature and photoperiod on circadian rhythms of sex pheromone release by females of *Trichoplusia ni*. *Ann Entomol Soc Am* 64:488–492
- Stelinski LL, Rogers ME (2008) Factors affecting captures of male citrus leafminer, *Phyllocnistis citrella* Stainton, in pheromone-baited traps. *J Appl Entomol* 132:143–150
- Stelinski LL, Il'ichev AL, Gut LJ (2006) Antennal and behavioral responses of virgin and mated oriental fruit moth (Lepidoptera: Tortricidae) females to their sex pheromone. *Ann Entomol Soc Am* 99:898–904
- Stevenson DE, Harris MK (2009) Determining circadian response of adult male *Acrobasis nuxvorella* (Lepidoptera: Pyralidae) to synthetic sex attractant pheromone through time-segregated trapping with a new clockwork timing trap. *Environ Entomol* 38:1690–1696
- Stewart-Jones A, Dewhurst SY, Durrant L, Fitzgerald JD, Hardie J, Hooper AM, Pickett JA, Poppy GM (2007) Structure, ratios and patterns of release in the sex pheromone of an aphid, *Dysaphis plantaginea*. *J Exp Biol* 210:4335–4344
- Strandh M, Johansson T, Löfstedt C (2009) Global transcriptional analysis of pheromone biosynthesis-related genes in the female turnip moth, *Agrotis segetum* (Noctuidae) using a custom-made cDNA microarray. *Insect Biochem Molec Biol* 39:484–489
- Tang JD, Charlton RE, Cardé RT, Yin CM (1992) Diel periodicity and influence of age and mating on sex pheromone titer in gypsy moth, *Lymantria dispar* (L.). *J Chem Ecol* 18:749–760
- Tawata M, Ichikawa T (2001) Circadian firing activities of neurosecretory cells releasing pheromonotropic neuropeptides in the silkworm, *Bombyx mori*. *Zool Sci* 18:645–649
- Teal PEA (1985) The effect of hybridization on the periodicity of sex pheromone release of *Euxoa* species (Lepidoptera: Noctuidae). *Physiol Entomol* 10:463–466
- Teal PEA, Byers JR, Philogene BJR (1978) Differences in female calling behavior of three interfertile sibling species of *Euxoa* (Lepidoptera: Noctuidae). *Ann Entomol Soc Am* 71, 630–634.
- Teixeira LAF, Grieshop MJ, Gut LJ (2010) Effect of pheromone dispenser density on timing and duration of approaches by peachtree borer. *J Chem Ecol* 36:1148–1154
- Thieme T, Dixon AEG (1996) Mate recognition in the *Aphis fabae* complex: daily rhythm of release and specificity of sex pheromones. *Entomol Exp Appl* 79:85–89
- Tigar BJ, Key GE, Flores-S ME, Vazquez-A M (1993) Flight periodicity of *Prostephanus truncatus* and longevity of attraction to synthetic pheromone. *Entomol Exp Appl* 66:91–97
- Traynier RMM (1970) Sexual behaviour of the Mediterranean flour moth, *Anagasta kuhniella*: some influences of age, photoperiod, and light intensity. *Can Entomol* 102:534–540
- Valles SM, Capinera JL (1992) Periodicity of attraction of adult melonworm, *Diaphania hyalinata*. *Fla Entomol* 75:390–392
- Valles SM, Heath RR, Capinera JL (1992) Production and release of sex pheromone by *Diaphania nitidalis* (Lepidoptera: Pyralidae): periodicity, age, and density effects. *Ann Entomol Soc Am* 85:731–735
- Walgenbach CA, Phillips JK, Faustini DL, Burkholder WE (1983) Male-produced aggregation pheromone of the maize weevil, *Sitophilus zeamais*, and interspecific attraction between three *Sitophilus* species. *J Chem Ecol* 9:831–840

- Wan X, Qian K, Du Y (2015) Synthetic pheromones and plant volatiles alter the expression of chemosensory genes in *Spodoptera exigua*. *Sci Rep-UK* 5:17320
- Wang Q, Zeng W, Chen L, Li J, Yin X (2002) Circadian reproductive rhythms, pair-bonding, and evidence for sex-specific pheromones in *Nadezhdiella cantori* (Coleoptera: Cerambycidae). *J Insect Behav* 15:527–539
- Wang P, Chen GF, Zhang JS, Xue Q, Zhang JH, Chen C, Zhang QH (2017) Pheromone-trapping the nun moth, *Lymantria monacha* (Lepidoptera: Lymantriidae) in inner Mongolia, China. *Insect Sci* 24:631–639
- Webster RP, Cardé RT (1982a) Influence of relative humidity on calling behaviour of the female European corn borer moth (*Ostrinia nubilalis*). *Entomol Exp Appl* 32:181–185
- Webster RP, Cardé RT (1982b) Relationships among pheromone titre, calling and age in the omnivorous leafroller moth (*Platynota stultana*). *J Insect Physiol* 28:925–933
- Webster RP, Cardé RT (1984) The effects of mating, exogenous juvenile hormone and a juvenile hormone analogue on pheromone titre, calling and oviposition in the omnivorous leafroller moth (*Platynota stultana*). *J Insect Physiol* 30:113–118
- Wei H, Huang Y, Du J (2004) Sex pheromones and reproductive behavior of *Spodoptera litura* (Fabricius) moths reared from larvae treated with four insecticides. *J Chem Ecol* 30:1457–1466
- Worster AS, Seabrook WD (1989) Electrophysiological investigation of diel variations in the antennal sensitivity of the male spruce budworm moth *Choristoneura fumiferana* (Lepidoptera: Tortricidae). *J Insect Physiol* 35:1–5
- Xiang YY, Yang MF, Li ZZ (2010) Calling behavior and rhythms of sex pheromone production in the black cutworm moth in China. *J Insect Behav* 23:35–44
- Zarbin PHG, Lorini LM, Ambrogi BG, Vidal DM, Lima ER (2007) Sex pheromone of *Lonomia obliqua*: daily rhythm of production, identification, and synthesis. *J Chem Ecol* 33:555–565
- Závodská R, Wower G. Von, Löfstedt C, Rosén W, Sauman I (2009) The release of a pheromonotropic neuropeptide, PBAN, in the turnip moth *Agrotis segetum*, exhibits a circadian rhythm. *J Insect Physiol* 55:435–440
- Závodská R, Fexová S, Wower G Von, Han GB, Dolezel D, Sauman I (2012) Is the sex communication of two pyralid moths, *Plodia interpunctella* and *Ephestia kuehniella*, under circadian clock regulation? *J Biol Rhythm* 27:206–216
- Zhang QH, Priesner E, Chen GF, Chen QC, Zhao GL (1996) Diurnal and dose responses of male Chinese larch casebearer, *Coleophora sinensis* Yang (Lep., Coleophoridae) to synthetic sex-attractant. *J Appl Entomol* 120:327–333
- Zhang QH, Schlyter F, Chu D, Ma XY, Ninomiya Y (1998) Diurnal and seasonal flight activity of males and population dynamics of fall webworm moth, *Hyphantria cunea*, (Drury) (Lep., Arctiidae) monitored by pheromone traps. *J Appl Entomol* 122:523–532
- Zhang Z, Luo J, Lu C, Zhao B, Meng J, Chen L, Lei C (2011) Evidence of female-produced sex pheromone of *Adelphocoris suturalis* (Hemiptera: Miridae): effect of age and time of day. *J Econ Entomol* 104:1189–1194
- Zhang KS, Yang W, Zhuo ZH, Deng ZB, Yan CP, Yang H, Zhou JH, Xiao YB, Jia YZ (2012) Reproduction behavior and circadian rhythm of sex pheromone production and release in *Parocneria orientalis* (Lepidoptera: Lymantriidae). *Acta Entomol Sinica* 55:46–54
- Zhukovskaya MI (1995) Circadian rhythm of sex pheromone perception in the male American cockroach, *Periplaneta americana* L. *J Insect Physiol* 41:941–946