

## Chapter 11

# PHEROMONES AND OTHER BEHAVIOR-MODIFYING CHEMICALS IN COTTON PEST MANAGEMENT

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## INTRODUCTION

The importance of behavior-modifying chemicals in cotton insect management lies in their potential to contribute to more effective control measures while reducing reliance upon insecticides. These materials can increase the efficiency of insecticide applications and can provide alternative means of suppression that may be more effective, more economical, and more environmentally and socially acceptable than the use of insecticides alone. Practical uses of behavior-modifying chemicals generally involve surveillance or suppression tactics. Surveillance tactics usually involve trapping and can be used for detection, monitoring and prediction. Suppression tactics may act: (a) directly on the pest population (e.g., mass trapping, mating disruption and feeding or oviposition deterrents); (b) indirectly by augmenting or manipulating the behavior of natural enemies; or (c) in conjunction with conventional pesticides as attracticides or bioirritants. To be successful, practical application of behavior-modifying chemicals requires consideration of a wide range of factors. These factors include the behavior, dispersal, distribution, host range and density of the pest insect; the nature of the pest complex; the identity, composition and formulation of the chemicals; the timing of applications; and the environmental, economic and social consequences of their use. Pheromones and other behavior-modifying chemicals are being used in a variety of cotton insect management programs.

Semiochemicals are a group of behavior-modifying chemicals defined as naturally occurring substances that mediate interactions between organisms (Law and Regnier, 1971). Unlike hormones or neurotransmitters, which are produced by and act within an organism, these chemicals are emitted by one organism and effect interactions with other organisms of the same or different species. Chemicals effecting intraspecific interactions are referred to as pheromones (Karlson and Butenandt, 1959; Nordlund

and Lewis, 1976), while those that mediate interspecific interactions have been termed allelochemicals (Whittaker and Feeny, 1971) or, more recently, allelochemicals. Allelochemicals, in turn, are classified on the basis of whether the response evoked favors the emitter or the receiver of the chemical. A kairomone elicits a response favorable to the receiver (Brown *et al.*, 1970); the response to an allomone benefits the emitter (Brown, 1968); and the response to a synomone is favorable to both organisms (Nordlund and Lewis, 1976). These terms are not mutually exclusive. For example, a substance emitted by a female insect that is used by the male in finding a mate is a pheromone. If the same substance is also involved in the mechanism whereby a parasite or predator of that insect locates its prey, it is a kairomone. A synthetic copy of a semiochemical is referred to by the same name as the natural material; e.g., a synthetic pheromone is the synthesized version of the natural compound emitted by the insect. However, some synthetic compounds that affect insect behavior are not known to occur naturally in the organisms involved and therefore are not semiochemicals. Among these are the parapheromones, which are compounds that mimic pheromones in their activity but have not been shown to be emitted by the insect. Synthetic attractants and synthetic repellents are other examples of behavior-modifying chemicals that are not classed as semiochemicals. The practical application of pheromones on a wide range of crops has been reviewed in some detail elsewhere (Ridgway *et al.*, 1990a). The behavior-modifying chemicals most frequently associated with cotton insects in the United States are pheromones and kairomones, and the chief focus of this chapter will be on these semiochemicals.

## DELIVERY SYSTEMS

To use behavior-modifying chemicals effectively in the management of cotton pests, careful thought must be given to the development of appropriate delivery systems. A controlled-release formulation is usually necessary, because most of these chemicals are used at very low dose rates, are volatile and are subject to environmental degradation. For active materials made up of several components, the ratio at which these components are emitted may need to be kept constant despite differences in their volatility. The type of formulation and its method of use will affect the design parameters of the delivery system, as will the behavior patterns of the insect. For example, many of the factors that must be considered in developing an attractant for a trap may be different from those involved in formulating a dispenser for use in preventing mating through communication disruption.

The delivery system should be compatible with regular agricultural practices. For baits in traps or for dispensers that must be hand-placed, ease of handling is a major factor. For material to be broadcast, it is desirable to have a sprayable formulation, with dispensers of appropriate particle size, together with compatible stickers and other adjuvants. For some types of delivery systems, a sprayable formulation has not been practical. It has been necessary to develop special dispersal systems for some larger non-sprayable solid particles and fibers.

Most controlled-release systems may be classified as belonging to one of four basic types (Zeoli *et al.*, 1982; Leonhardt, 1990): (a) reservoir systems without a rate-controlling membrane, e.g., hollow, open-ended fibers or capillaries; (b) reservoir systems surrounded by a rate-controlling membrane, such as capsules; (c) monolithic systems in which the active chemical is dispersed throughout an inert matrix; and (d) laminates, in which an inner reservoir containing the active material is sandwiched between two outer polymeric layers. In the first type, the active material evaporates from the liquid surface within the tube and diffuses to the end of the tube, where it is released; the rate of release is determined by the rate of evaporation and the rate of diffusion to the end of the tube. In reservoir systems with a rate-controlling membrane, all or part of the wall of the reservoir is made of a permeable polymer through which the active material diffuses. The release rate is determined to a great extent by the nature of the polymer and the thickness and surface area of the wall. A variety of these systems are in use, including sealed polyethylene tubes, bags, or vials and polymer-coated microcapsules of various types. In the third type of system, the active material is dispersed in an inert matrix; emission rates are dependent on the rate of diffusion within the matrix to the surface. A common example is a rubber cap or septum impregnated with pheromone, but these require precautions against degradation of pheromone components by substances used in the manufacture of the rubber. In the laminate dispensers, the rate of emission is controlled by the dimensions of the outer polymer layers, the nature of the polymer and the concentration of the active ingredient in the reservoir layer. With variations in particle size and in dispenser shape, systems representing these four types have been used in a wide range of applications. Suitability of a system for a given application must be determined in the field.

In order to obtain meaningful data when using different delivery systems and to assure activity for the desired length of time, performance criteria for the controlled-release dispensers must be specified (Leonhardt *et al.*, 1990). Important factors are the concentration and purity of the active material, the rate of emission, the ratio in which the components of a mixture are emitted, and the duration of effectiveness of the dispenser. Performance standards developed in laboratory and field studies give assurance of the reliability of a delivery system. A number of specific controlled studies are available that illustrate approaches to developing controlled-release dispensers for behavior-modifying chemicals (Coppedge *et al.*, 1973; Hendricks *et al.*, 1989; Leonhardt *et al.*, 1985, 1987, 1988, 1989).

## ARTHROPOD PESTS

The major research emphasis on behavior-modifying chemicals of arthropod pests of cotton in the United States has been on the sex and aggregating pheromones of the boll weevil, *Anthonomus grandis grandis* Boheman, and the sex pheromones of three lepidopterous insects, the pink bollworm, *Pectinophora gossypiella* (Saunders), the bollworm, *Helicoverpa* (= *Heliothis*) *zea* (Boddie), and the tobacco budworm, *Heliothis virescens* (F.). Significant, but more limited, efforts have been directed

towards pheromones of *Lygus* bugs, stink bugs and mites and towards kairomones for parasites and predators. More recently, some potentially important research on allelochemicals that may be very useful as attractants and feeding stimulants for the boll weevil and the bollworm is receiving increased attention.

## BOLL WEEVIL

The boll weevil is a serious pest of cotton that occurs in most cotton growing states in the United States. However, areawide management or eradication programs have essentially eliminated the boll weevil from the Carolinas, most of Georgia, north Florida, southeastern Alabama, California and Arizona. Adults, which overwinter in crop remnants or other debris near cotton fields, emerge in the spring and feed on cotton plants, doing their greatest economic damage when the squares and bolls appear. Females oviposit (lay eggs) into the squares or bolls, where the larvae hatch, feed and then pupate. Adults emerge, feed and oviposit to continue the cycle. In some areas there may be seven or more generations per year.

Observations made in a simple but elegant experiment conducted in 1963 (Cross and Mitchell, 1966) suggested the presence of a male-produced, wind-borne boll weevil pheromone. In subsequent laboratory studies (Keller *et al.*, 1964), an active airborne substance emitted by males was obtained by drawing air over caged males and through a column of activated charcoal for three weeks. Extraction of the charcoal and evaporation of the solvent yielded a residue that stimulated and attracted female weevils.

The boll weevil sex pheromone was later identified (Tumlinson *et al.*, 1969) as a mixture of four components (Figure 1). In laboratory tests, the optimum ratio of these components was found to be 9:7:12:12 (Tumlinson *et al.*, 1969). However, it was shown that the omission of the third compound had no significant effect on attractancy in the field (Dickens and Prestwich, 1989), and that the ratios could be varied considerably without significantly affecting attractancy in the field (Hardee *et al.*, 1974). Depending on the time of year, this boll weevil pheromone functions both as a sex pheromone and as an aggregating pheromone. In the spring and fall, traps baited with males attract both sexes of overwintered adults. In mid-season (during the fruiting season), mostly females are attracted (Mitchell and Hardee, 1974; Hardee, 1975).

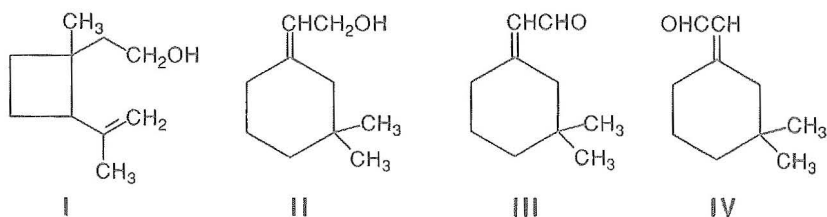


Figure 1. Chemical structures of the four grandlure components: (I), *cis*-2-isopropenyl-1-methylcyclobutaneethanol; (II), (*Z*)-3,3-dimethyl- $\text{-}^1\text{-}^b$ -cyclohexaneethanol; (III), (*Z*)-3,3-dimethyl- $\text{-}^1\text{-}^a$ -cyclohexaneacetaldehyde; and (IV), (*E*)-3,3-dimethyl- $\text{-}^1\text{-}^a$ -cyclohexaneacetaldehyde.



Furthermore, the attractancy of the pheromone is increased in the presence of host plants or plant chemicals (Coppedge and Ridgway, 1973; Dickens, 1989).

The synthetic pheromone, grandlure, has been used, or can potentially be used, in a variety of ways to assist in boll weevil management. It is used in traps to detect the presence of boll weevils (Dickerson *et al.*, 1987a) and, in areas where the pest is already established, to monitor population densities (Ridgway *et al.*, 1985). Traps have also been used in attempts to suppress populations through mass trapping of adults, although this technique shows promise only at low population densities (Leggett *et al.*, 1988). Other potential population suppression techniques using grandlure include mating disruption (Huddleston *et al.*, 1977); trap cropping, i.e., use of the pheromone to attract weevils to a small portion of the crop where they can be destroyed (Gilliland *et al.*, 1974); and attracticides, which combine the pheromone and/or host-plant chemicals with an insecticide (McKibben *et al.*, 1985; Lusby *et al.*, 1987; Ridgway *et al.*, 1990b). Large scale field trials are under way in Mississippi to evaluate the use of grandlure with a toxicant applied to a wooden surface (bait stick) and distributed in the field as point sources (Personal communication, James W. Smith, USDA, ARS, Boll Weevil Research Unit, Mississippi State, Mississippi).

Grandlure is currently in widespread use in traps for both monitoring and mass trapping. Although a range of commercial dispensers is available, an improved plastic laminate dispenser and a polyvinyl chloride dispenser (Dickerson *et al.*, 1987b; Leonhardt *et al.*, 1988), each containing 10 milligrams of grandlure, are used predominately. Monitoring with pheromone traps as a guide to application of insecticides for overwintered boll weevil control is in use in a number of states (Ridgway *et al.*, 1985). Pheromone traps also are utilized for detection, monitoring and/or mass trapping in a number of areawide boll weevil population suppression programs, including ones in the Southeast, Southwest, and Texas. The general use of grandlure in traps for detection, monitoring and mass trapping has been reviewed elsewhere (Ridgway *et al.*, 1990b).

Operationally, the most extensive use of boll weevil pheromone traps has been in the Southeastern Boll Weevil Eradication Program which began in 1978. The program has essentially proceeded in three phases: (a) eradication trial in North Carolina and Virginia; (b) expanded program into southern North Carolina and South Carolina; and (c) expanded program into Georgia, Alabama and Florida (Figure 2).

The boll weevil eradication trial was conducted in North Carolina and Virginia in 1978-1980. The technology applied included pheromone traps for surveillance and suppression, release of sterile insects and insecticide treatments of overwintering adults on a mandatory basis (USDA, 1981a). The cotton acreage involved in the trial area (See Figure 2) was about 12,000 acres (4,800 hectares) in 1978; after the initial trial was completed, the program was continued and the area covered was expanded. The acreage planted to cotton in the area covered by the initial trial had increased to 70,000 acres (28,000 hectares) by 1987 (Planer, 1988). The trial was generally considered to be an economic (Carlson and Suguiyama, 1985) and biological (USDA, 1981b) success, although there was some disagreement about the interpretation of biological results (National Research Council, 1981; USDA, 1981b).

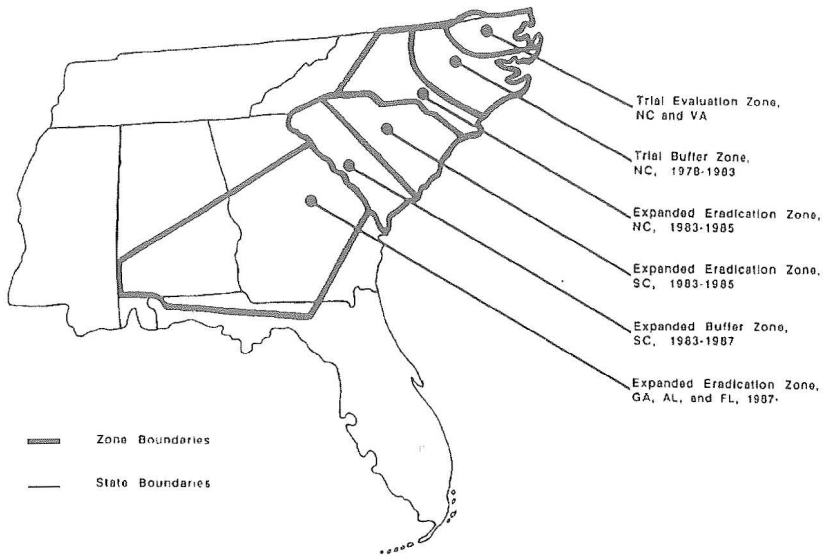


Figure 2. Diagram of the state boundaries (light line) and zone boundaries (heavy line) within the Southeastern Boll Weevil Eradication Program. (From Ridgway *et al.*, 1990b.)

In the eradication trial, traps were initially deployed at the rate of one per 8 to 10 acres (3 to 4 hectares) around fields to aid in scheduling fall diapause boll weevil applications. In the spring of 1979 and 1980, one trap per acre was placed around fields to monitor populations. After cotton was growing two traps per acre were placed in the fields to maximize detection and for possible suppression through mass trapping. In the fall, traps were again placed around fields at one trap per acre. When reproduction of the boll weevil had been eliminated in an area, the trap density was reduced to one trap per 5 to 10 acres (2 to 4 hectares), and the traps were used primarily to detect possible reintroductions. The extremely low numbers of boll weevils that were detected in the original trial evaluation area in North Carolina reflected the efficacy of the program in eliminating reproducing boll weevil populations (Table 1). The increased trap captures in the buffer area in 1982 and 1983 and overall increases in boll weevil populations outside the program area in southeastern North Carolina during those years probably reflect the reduced boll weevil suppression efforts in the buffer area. The value of the pheromone traps in detecting reintroduced boll weevils so that measures can be taken to prevent reestablishment of boll weevil populations has been demonstrated repeatedly in the trial evaluation area. Specific cases for 1984 and 1985 are discussed by Dickerson *et al.* (1986). Results of reductions in boll weevils in the expanded eradication zones in North Carolina and South Carolina indicated that the program also was effective in those areas (Dickerson *et al.*, 1986, 1987a). Further, an

Table 1. Boll weevil capture in fields in the Southeastern Boll Weevil Eradication Trial Evaluation Zone, 1979-1989. (From Ridgway *et al.*, 1985; Dickerson *et al.*, 1987a; W. A. Dickerson, personal communication<sup>1</sup>.)

Year	Acres	No. of fields trapped	Percent of fields at three weevil capture levels		
			no. of weevils per field		
			0	1-5	>5
1979	15,200	1,020	99.12	0.88	0.00
1980	26,700	1,775	99.98	0.06	0.06
1981	35,700	2,600	99.00	0.96	0.04
1982	37,800	3,000	91.47	6.66	1.87
1983	35,900	2,500	95.60	4.00	0.40
1984	63,000	4,300	99.95	0.00	0.05
1985	64,600	4,500	99.93	0.00	0.07 <sup>2</sup>
1986	50,500	4,100	99.98	0.02 <sup>3</sup>	0.00
1987	71,090	4,400	99.96	0.04 <sup>4</sup>	0.00
1988	91,800	5,680	>99.98	0.02 <sup>5</sup>	0.00
1989	64,100	3,966	100.0	0.00	0.00

<sup>1</sup>Willard A. Dickerson, North Carolina Department of Agriculture, Raleigh, North Carolina.

<sup>2</sup>66 weevils in 3 fields

<sup>3</sup>1 weevil

<sup>4</sup>1 weevil in each of 2 fields

<sup>5</sup>9 weevils in 1 field

economic assessment indicates that the total benefits resulting from the program exceeded \$75 per acre in both North Carolina and South Carolina (Carlson *et al.*, 1989). The southeastern program was expanded, beginning in 1983 (Figure 2). Pheromone traps continued to play a prominent role in detection, monitoring and suppression of boll weevil populations (Ridgway *et al.*, 1990b), with several hundred thousands of traps and several million pheromone dispensers being used annually.

An organized areawide boll weevil management/eradication program was initiated in southern California, southwestern Arizona and part of Mexico in 1985. Extensive trapping, insecticide applications and cultural controls led to elimination of reproducing populations in these areas by 1987 (National Cotton Council of America, 1989). In 1988, the program was expanded to cover the remainder of Arizona and adjoining areas of Mexico. In this southwestern program, the boll weevil pheromone trap was used primarily for detection and to aid in decision-making related to insecticide application (Anonymous, 1989). About 50,000 traps, deployed at one or two traps per 10 acres (4 hectare) and 1,200,000 pheromone dispensers were used in 1988 (Personal communication, Frank Myers, retired, Phoenix, Arizona).

## PINK BOLLWORM

The pink bollworm is a serious pest of cotton in much of the western cotton growing region of the United States. Overwintering occurs by larvae within cotton seeds, bolls or plant remnants in the field or at the gin. Damage in the form of yield loss and reduction in quality occurs from larval feeding on seeds within green bolls. There may be as many as six generations each year in areas with long growing seasons.

Behavioral studies apparently played only a limited role in the discovery of the pink bollworm pheromone, since original studies utilized primarily empirical screening in an effort to discover attractants for the pink bollworm (Jacobson, 1969; Keller, 1969). However, efforts to confirm the presence of some of these attractants in the insect led to the discovery of the natural sex pheromone. The sex pheromone of the pink bollworm (Hummel *et al.*, 1973; Bierl *et al.*, 1974) is a 60:40 blend of the *Z,Z* and *Z,E* isomers of 7,11-hexadecadien-1-ol acetate.

The synthetic pheromone, gossypure, is commercially formulated in a 50:50 mixture. It is currently used in traps for population surveillance, as a mating disruptant and, along with an insecticide, as an attracticide. The development and use of gossypure in surveillance and suppression has been recently reviewed by Staten *et al.* (1988) and Baker *et al.* (1990). The quality of gossypure used for monitoring and the development of different delivery systems for use in control programs are worthy of special note. However, since gossypure is the only pheromone currently in use for control of a cotton insect by mating disruption, emphasis will be placed on this aspect. Use of gossypure for control of the pink bollworm had its beginning with the landmark research of Shorey *et al.* (1976) and Gaston *et al.* (1977), utilizing a hollow-fiber dispensing system. Although these original experiments were criticized for the lack of untreated controls, they were responsible for launching a series of events over the next decade that has led to the widespread acceptance of gossypure as a pink bollworm management "tool".

Although the original hollow-fiber dispensing system (NoMate® PBW) was approved for commercial use in the United States (Tinsworth, 1990) in 1978, uncertainty about its efficacy and difficulties with application hindered its acceptance. Then in 1982, following several years of declining yields and increased pesticide use, with its associated secondary pest problems, cotton growers in California's Imperial Valley established a Pest Abatement District that mandated at least four pheromone (gossypure) disruption sprays. A total of 45,600 acres (18,226 hectares) was treated with gossypure; insecticide use was postponed until later in the season. The program was successful in that average yields increased from 2.2 bales/acre (5.4 bales/hectare) in 1981 to 2.7 bales/acre (6.7 bales/hectare) in 1982, and secondary pest problems early in the season were greatly reduced. While the mandatory program was not continued, most growers voluntarily continued to use pheromone treatments the next year (Baker *et al.*, 1990).

Further evaluation of the hollow-fiber and laminate flake dispensing systems (Disrupt® PBW) and of a wire-reinforced sealed polyethylene tube (PB-ROPE®) (Table 2) (Staten *et al.*, 1987) and subsequent studies (Staten *et al.*, 1988) have led to

improved confidence in mating disruption. Although difficult to quantify, the use of the pheromone, gossypure, with a toxicant in an attracticide approach has also had a significant impact (Baker *et al.*, 1990). A review of the percentage of acreage treated with gossypure products from 1982 to 1986 reveals a trend towards increased uses of this pheromone, with the percentage of acreage treated increasing from 15 to 29 percent (Baker *et al.*, 1990). More recently, three different sprayable bead formulations (Checkmate® PBW, Decoy® PBW Beads and NoMate® PBW MEC) and another point-source dispenser (Decoy® PBW Stakes) have been developed (Brosten and Simmonds, 1990). Indications are that the number of acres treated with a pink bollworm pheromone-based product in 1990 substantially exceeded that treated in any previous year (Personal communication, Charles C. Doane, Scentry, Inc., Goodyear, Arizona).

In addition to the control programs in southern California and Arizona, the California Department of Food and Agriculture (CDFA) has also maintained an aggressive suppression/eradication program in the nearly 300,000 acres of cotton grown in the San Joaquin Valley. This is a cooperative program involving cotton producers, CDFA and USDA. When pink bollworm moths are detected by a grid of pheromone traps, the infested area is treated with releases of sterile males and with aerially applied gossypure disruptant-attracticide (Baker *et al.*, 1990). This program is widely recognized as being successful in preventing establishment of pink bollworm populations in the San Joaquin Valley.

Table 2. Effects of PB-ROPE® treatment on pink bollworm damage (number of larvae in bolls) and insecticide use in the Imperial Valley of California and Mexicali Valley of Mexico in 1985. (From Staten *et al.*, 1987.)

Treatment	No. of fields	Pink bollworm <u>Larvae/100 bolls</u>		Average no. of insecticide treatments per field
		August	September	
Imperial Valley <sup>1</sup>				
Conventional insecticide	8	0.85	0.88	11.4 a
Conventional pheromone	8	0.90	2.1	10.4 a
PB-ROPE pheromone	7	0.32	0.39	6.6 b
Mexicali Valley <sup>2</sup>				
Conventional insecticide	14	1.72 a	1.55 a	4.9 a
PB-ROPE pheromone	16	0.7 b	0.72 b	2.9 b

<sup>1</sup>The eight conventional pheromone fields were treated with Nomate PBW® or Disrupt®. Means in same column having no letters in common are significantly different according to ANOVA followed by Duncan's multiple range test ( $P=0.01$ ).

<sup>2</sup>Means in same column having no letters in common are significantly different according to Student's *t* test ( $P=0.01$ ).

## BOLLWORM AND TOBACCO BUDWORM

The world-wide *Helicoverpa/Heliiothis* complex includes a number of major pests of agricultural crops. In the United States, two species from this group, the bollworm, and the tobacco budworm are among the most important insects attacking field crops, accounting for annual losses and costs for control of hundreds of millions of dollars (Sparks *et al.*, 1988). Crops damaged by these two insects include cotton, corn, beans, garden peas, peppers, tomatoes, lettuce, sorghum, alfalfa, clover, vetch, tobacco and peanuts (Davidson and Lyon, 1979). In cotton, the bollworm was recognized as an important pest as early as 1841 (Quaintance and Brues, 1905), while the tobacco budworm did not achieve prominence until much later (Sparks *et al.*, 1988). For some time, control was achieved by use of insecticides, but development of resistance to the chlorinated hydrocarbons, followed by the organophosphates and carbamates (Harris *et al.*, 1972), and more recently by the pyrethroids (Miller, 1985) has intensified the need for other methods for management of these two pests.

Both the bollworm and the tobacco budworm are nocturnal (active at night), so direct field observations of mating behavior were limited until the development of night-vision methodology (Lingren *et al.*, 1978). Field analysis of behavior also is difficult because of the tendency of the females to change locations and the often fierce competition between males for an individual female (Sparks *et al.*, 1988). Nevertheless, understanding of the behavior patterns and the interactions of the various influences affecting the bollworm and tobacco budworm is important in assessing the potential role of pheromones in the management of these insects. Most early behavioral studies involved laboratory-reared insects and/or laboratory or cage tests. In 1962 and 1963, Gentry *et al.* (1964) showed that traps baited with laboratory-reared female tobacco budworm moths or with extracts from the females captured released-male moths, thus demonstrating the presence of a sex attractant emitted by the females. Teal *et al.* (1981) reported details of the precourtship and courtship behaviors of male and female tobacco budworm moths in wind tunnel and cage tests.

Although the sex pheromones are the primary means of mating communication for the tobacco budworm and the bollworm, there is evidence that visual communication may be a supplementary short-range mate-detection mechanism (Sparks *et al.*, 1988). For example, male bollworm moths flying toward a cotton wick impregnated with a pheromone source were observed to move instead toward a mock female constructed of brown paper at distances of 6.3 to 8.7 inches (16 to 22 centimeters) (Carpenter and Sparks, 1982). The actual production of the pheromones is influenced by a number of external factors, including photoperiod and host plant (Raina, 1988). It is regulated internally by one or more neurohormones (Raina *et al.*, 1989a). Further, the role of host plant attractants and feeding stimulants should be recognized, since these materials could potentially be useful in suppression programs (Lingren *et al.*, 1990).

The chemistry of the pheromones of the bollworm/tobacco budworm complex has been reviewed by Sparks *et al.* (1988) and Lopez *et al.* (1990). Initial efforts to identify the pheromones of the bollworm and tobacco budworm were hampered by the lack

of adequate bioassays and the low sensitivity of analytical instrumentation and methodology. Thus, initial identifications were inaccurate or incomplete (McDonough *et al.*, 1970; Roelofs *et al.*, 1974; Tumlinson *et al.*, 1975). A number of subsequent studies were conducted with pheromone gland extracts. The presence and importance of multiple component mixtures—4 and 7 components from the pheromone glands of the bollworm and tobacco budworm, respectively—were reported by Klun *et al.* (1979) (Table 3). Subsequent studies of pheromone gland extracts yielded information on the pheromones of five additional species in the *Helicoverpa/Heliothis* complex (Table 3) (Sparks *et al.*, 1988). Although the components vary from species to species, (Z)-11-hexadecenal is the major pheromone component in all species of the complex that have been studied. There is considerable variation in the reported compositions of the pheromone blends for the different species. Differences associated with many factors can give rise to a substantial range in the numbers of components found or in the reported component ratios. These factors include: (a) methodology and the sensitivity of the analytical technique; (b) the source of the pheromone, whether from an extract or from emitted volatiles; (c) laboratory-reared vs. wild insects (Raina *et al.*, 1989b); (d) insect strains (Ramaswamy and Roush, 1986); and (e) individual variations among insects. Variation is also encountered in studies to determine the behavioral responses to the various pheromone components. Flight tunnel studies and field trapping studies do not always give comparable results. Data obtained are affected by many factors, such as the pheromone dispenser system, the trap design, the presence of host plants, and environmental conditions such as temperature.

With the tobacco budworm, the binary mixture of (Z)-11-hexadecenal and (Z)-9-tetradecenal (often referred to as virelure) is an effective trap lure, but the addition of (Z)-11-hexadecen-1-ol has been demonstrated to improve trap captures (Ramaswamy *et al.*, 1985; Shaver *et al.*, 1987). Lures containing this alcohol at a level of 0.25 to 1 percent of that of (Z)-11-hexadecenal gave optimum trap captures while higher levels of the alcohol suppressed captures. With the bollworm, a binary mixture of two C-16 aldehydes, (Z)-11-hexadecenal and (Z)-9-hexadecenal, is an effective trap lure, but there is some indication that the quaternary mixture of the four components identified for this insect (Table 3) is a more effective lure. Addition of (Z)-11-hexadecen-1-ol, which increased trap captures with the tobacco budworm, reduced captures of the bollworm when used with this four-component mixture (Teal *et al.*, 1984). Differences in the ratios of major components and the presence of various other components, often in trace quantities, seem to be responsible for pheromone specificity in these insects, although the roles of the individual components are not fully understood.

As with pheromones and other behavior-modifying chemicals of other insects, those associated with the bollworm and tobacco budworm theoretically could be used for surveillance or suppression. Research related to practical applications has been concentrated primarily on use of the sex pheromones (Sparks *et al.*, 1988; Lopez *et al.*, 1990). The availability of more complete pheromone blends raised the expectation that suppression with pheromones might be possible through mass trapping, mating disruption or use in attracticides. However, review of available information indicates

Table 3. Female pheromonal components for four species of *Heliothis* and three species of *Helicoverpa* determined by analyses of extracts of the pheromone glands. (Modified from Sparks *et al.*, 1988.)

Compound	Species of <i>Heliothis</i>				Species of <i>Helicoverpa</i>		
	<i>virescens</i> <sup>1</sup>	<i>subflexa</i>	<i>phloxiphaga</i>	<i>peltigera</i> <sup>2</sup>	<i>zea</i> <sup>1</sup>	<i>punctigera</i> <sup>3</sup>	<i>amigera</i>
	percent of total pheromone content						
(Z)-9-tetradecenal	2.0	0.2	-	9.2	-	-	-
tetradecanal	1.6	0.3	-	0.5	-	-	-
(Z)-9-tetradecen-1-ol	-	-	-	4.1	-	-	-
(Z)-9-tetradecen-1-ol acetate	-	-	-	1.3	-	-	-
(Z)-7-hexadecenal	1.0	2.0	-	0.7	1.1	-	-
(Z)-9-hexadecenal	1.3	15.1	0.5	0.9	1.7	-	3.0
(Z)-11-hexadecenal	81.4	40.5	91.8	62.8	92.4	60	87.0
hexadecanal	9.5	1.3	4.8	2.3	4.4	-	4.0
(Z)-11-hexadecen-1-ol	3.2	5.2	2.9	15.2	-	-	-
hexadecanol	-	-	-	-	-	-	6.0
(Z)-7-hexadecen-1-ol acetate	-	2.7	-	-	-	-	-
(Z)-9-hexadecen-1-ol acetate	-	6.2	-	-	-	-	-
(Z)-11-hexadecen-1-ol acetate	-	25.5	-	3.0	-	25	-
hexadecanol acetate	-	-	-	-	-	-	6.0

<sup>1</sup>*Heliothis virescens* = tobacco budworm; *Helicoverpa zea* = bollworm.

<sup>2</sup>(Dunkelblum and Kehat, 1989)

<sup>3</sup>(Rothschild *et al.*, 1982) Identification of pheromone components was not complete.



a number of major limitations. Mass trapping is limited by trap efficiency, which may vary from 3 to 55 percent, based on the percentage of males responding to the vicinity of a trap (Sparks *et al.*, 1979a, 1979b). Also, the most efficient traps are large and complicated, thus limiting their practical use in large numbers. Considerable research on mating disruption (or communication disruption) has been done with the bollworm and the tobacco budworm, but results are not promising (Sparks *et al.*, 1988). Reduction in mating was achieved in some studies, but it is questionable whether any practical reduction in populations can be achieved. The high mobility of the bollworm and tobacco budworm, with the consequent immigration into treated areas, and the role of vision in close-range orientation of males to females are factors that may prevent development of mating disruption into a viable means of bollworm/tobacco budworm control. Similarly, in tests of insecticidal baits laced with pheromones, satisfactory results were not obtained, even when a feeding stimulant was incorporated in the attracticidal bait, because contact of the insects with the insecticide in the bait was not sufficient to be of biological significance (Sparks *et al.*, 1988).

A number of plant products have been explored as feeding stimulants to enhance the efficacy of microbial agents against cotton bollworm and tobacco budworm larvae. At least one, derived from cottonseed flour, has shown enough promise to be commercially marketed (Stamps, 1981).

Because of the limited success in the use of pheromones for control of the bollworm and tobacco budworm, major research efforts in recent years have emphasized the use of pheromones in traps for monitoring populations. However, the large number of variables influencing trap capture and its relation to field infestations often complicates the practical use of traps. These many variables include the pheromone blend, the dispenser, trap design, characteristics of individual species and all the abiotic and biotic factors that influence the fate of the pheromone and the behavior, fecundity and mortality of the insect. The status of the development of dispensers and trap designs has been reviewed elsewhere (Lopez *et al.*, 1990), therefore, only some highlights will be provided here. Although a number of dispensers are available commercially, a plastic laminate dispenser for the bollworm pheromone and a black molded polyvinyl chloride dispenser for the tobacco budworm pheromone or its major components appear to be the dispensers of choice. Preliminary performance criteria have been developed for these dispensers (Leonhardt *et al.*, 1987). Of the many trap designs evaluated, the modified wire cone trap (Hartstack *et al.*, 1979) continues to be the preferred trap of researchers, although some alternatives are commercially available (Lopez *et al.*, 1990).

Pheromone-baited traps have been used in monitoring with at least four different objectives: (a) collection; (b) detection; (c) population estimation; and (d) prediction. Examples particularly worthy of note from those reviewed by Lopez *et al.* (1990) include: collection of insects to monitor the level of insecticide resistance in field populations (Plapp *et al.*, 1987); detection of bollworms near high-value crops; successful measurement of field populations (Hartstack *et al.*, 1978; Johnson, 1983; Witz *et al.*, 1985); and population prediction (Hartstack *et al.*, 1983; Witz *et al.*, 1985). It should

be emphasized that the results from the use of traps for population estimation and prediction have been highly variable, but research is continuing to reduce this variability. Therefore, with further refinements of pheromone trap inputs into population models to increase the accuracy of both timing and density of field populations, pheromone traps could become an invaluable tool in the management of the bollworm and tobacco budworm (Hayes and Coleman, 1989).

## PLANT BUGS

Three *Lygus* species (Heteroptera: Miridae) that are pests of cotton are the tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), the pale legume bug, *Lygus elisus* Van Duzee, and the western lygus bug, *Lygus hesperus* Knight. These bugs cause shedding of cotton squares and young bolls by puncturing and feeding with their piercing-sucking mouth parts. Older bolls may be damaged but are less likely to be shed. Scales (1968) observed that caged female tarnished plant bugs attract males. Subsequent findings have shown that this also occurs with other mirids (Aldrich, 1988a, 1995). This attraction is temporarily lost upon mating. Male tarnished plant bugs, as well as a few males of other mirid species, were captured in traps baited with virgin females (Slaymaker and Tugwell, 1984). Cross attraction of males by females occurred between the tarnished plant bug and the pale legume bug, but western lygus bug males were attracted only by conspecific females (e.g., females of the same species) (Graham, 1987). The source of the attractive material has not been determined.

A variety of compounds have been identified in volatile material from females of these three *Lygus* species (Aldrich, 1988a), including a number of acetates, butyrates and other aliphatic esters, as well as (*E*)-2-hexenal, (*E*)-4-oxo-2-hexenal and (*E*)-hexenol. As yet, no significant attraction to any combination of these compounds has been demonstrated (Aldrich, 1988a, 1995), although traps baited with virgin female tarnished plant bugs have been used for monitoring (Slaymaker and Tugwell, 1984). Elucidation of the attractive compounds would provide more efficient trapping methods and improved management of these pests.

## PHYTOPHAGOUS STINK BUGS

Phytophagous (plant feeding) stink bugs such as the southern green stink bug, *Nezara viridula* (L.) (Heteroptera: Pentatomidae), are occasional pests of cotton. Mitchell and Mau (1971) noted that adult males of this insect were attractive to virgin females in olfactometer and field tests. Subsequently, it was shown that males and nymphs of the southern green stink bug also were attracted to males in the field (Harris and Todd, 1980). Aldrich *et al.* (1987) demonstrated that males emitted a volatile material that was attractive to adult insects and nymphs in the field. The site of production of this pheromone has not been determined. It appears that this aggregation pheromone serves as a long-range attractant for mate location but is not involved in close-range courtship (Todd, 1989). Numerous male-specific compounds, including (*Z*)- $\alpha$ -bisabolene [(*Z*)-1-methyl-4-(1,5-dimethyl-1,4-hexadienyl)cyclohexene] and *cis* and *trans*-(*Z*)- $\alpha$ -bisabolene epoxides, have been identified from male-produced air-

borne volatile material (Figure 3) (Aldrich, 1995; Baker *et al.*, 1987). Some of these compounds have been shown to be attractive to females in laboratory bioassays (Aldrich, 1988a). Southern green stink bugs from different geographic locations produce pheromone blends with different ratios of major components, indicating the existence of different strains of the insect (Aldrich *et al.*, 1989). Tests have not established which of these compounds are required for pheromonal activity in the field (Aldrich, 1995). Volatiles from males of another occasional pest of cotton, the green stink bug, *Acrosternum hilare* (Say), contain many of the same components isolated from the southern stink bug, but there are marked differences in the relative abundance of some of these components (Aldrich *et al.*, 1989). When the male-specific compounds required for field attraction of these phytophagous pentatomids have been determined, they should be useful in traps for monitoring populations (Aldrich, 1988b).

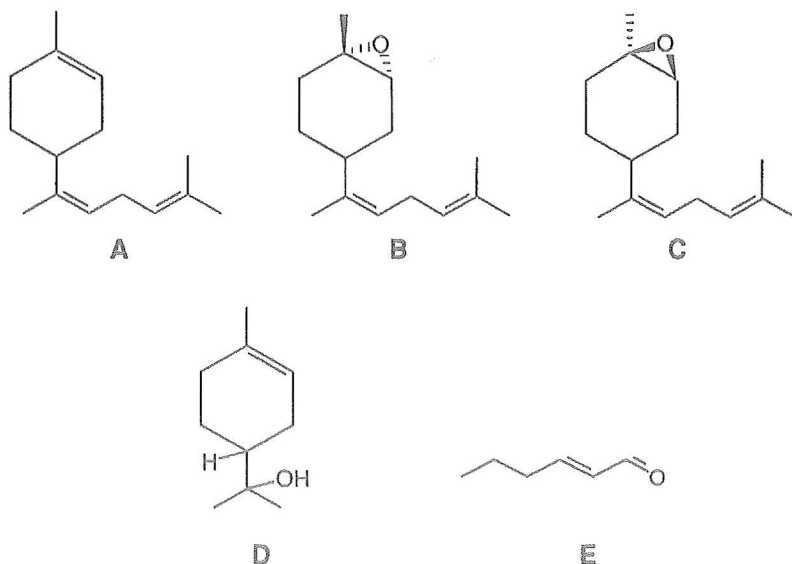


Figure 3. Primary components of pheromones of the pentatomids, southern green stink bug (A, B), green stink bug (A, C), and spined soldier bug (D, E). A, (Z)-α-bisabolene; B, trans-(Z)-α-bisabolene epoxide; C, cis-(Z)-α-bisabolene epoxide; D, (+)-R-α-terpineol; E, (E)-2-hexenal ("leaf-aldehyde") (Modified from Aldrich, 1995).

## PHYTOPHAGOUS MITES

Spider mites (Acari: Tetranychidae) often become a problem in cotton when insecticides kill the predator insects and mites that regulate their numbers. The twospotted spider mite, *Tetranychus urticae* Koch, is widely distributed. It feeds on many hosts and perhaps is the most abundant species on cotton. At least 32 additional species of tetranychid mites are reported to be pests of cotton (Leigh, 1985).

Ewing (1914) first recorded the observation that male twospotted spider mites were attracted to quiescent (inactive) females prior to their final molt and remained nearby until the adult females emerged, at which time mating occurred. Cone *et al.* (1971a, 1971b) showed that extracts of the deutonymphs were attractive to males in laboratory bioassays. Further studies (Penman and Cone, 1972, 1974) demonstrated that tactile (sense of touch) stimuli from the web produced by the female deutonymphs played a role in the attraction of males and that the volatile material was a short-range attractant or an arrestant that maintains male interest in the female.

Regev and Cone (1975, 1976) identified the sesquiterpene alcohol, farnesol (3,7,11-trimethyl-2,6,10-dodecatrien-1-ol), as the attractive material in extracts of quiescent female twospotted spider mites; the *Z,E* isomer was more attractive than the *Z,Z* isomer. Another sesquiterpene alcohol, nerolidol (3,7,11-trimethyl-1,6-10-dodecatrien-3-ol), found in the extract also showed attractancy. Subsequently, a monoterpene alcohol, citronellol (3,7-dimethyl-6-octen-1-ol), was identified from pharate females and was highly attractive to males in bioassays (Regev and Cone, 1980).

Because it is an arrestant or short-range attractant, the pheromone would not be effective in attracting the mites to monitoring traps. However, a mixture of (*Z,E*)-farnesol and nerolidol, under the trade name Stirup-M®, was approved for commercial use (Tinsworth, 1990) in 1987 as a selective mite pheromone for use against the twospotted spider mite; the carmine spider mite *Tetranychus cinnabarius* (Boisduval); other *Tetranychus* species; and the European red mite, *Panonychus ulmi* (Koch). It is intended to be mixed with a conventional miticide to increase the time mites remain on treated crop surfaces, thereby increasing the efficacy of the miticide and making it possible to reduce the quantities used and the frequency of applications.

## PARASITES AND PREDATORS

A variety of behavior-modifying chemicals influence the actions of beneficial insects in cotton, and the interactions of these factors are very complex (Jones *et al.*, 1976). Consequently, identification of specific chemicals has proceeded slowly. Sex pheromones have been demonstrated for a few parasites and predators, and some parasites have been shown to deposit marking pheromones that prevent repeated searches over the same area or that prevent superparasitization. Pheromones or other substances from the host insect frequently are found to serve as kairomones, stimulating the parasite or predator to search for a host or serving as an attractant. In addition to these chemicals from the parasite or predator and from its host or prey, cues from the preferred habitat of the host also affect the behavior of beneficial insects. Phytochemicals from the host's food plant may serve as attractants or stimulants.

The phenomenon of "learning" is another unique characteristic encountered in the study of these behavioral chemicals. Frequently, exposure of a parasite to a host or to host-derived kairomones increases the efficiency of searching for other hosts. This "success-motivated searching" (Vinson, 1977) must be considered in designing experimental studies on applications of behavior-modifying chemicals of beneficial insects.

Various types of behavior-modifying chemicals, primarily kairomones, have been reported for a wide range of natural enemies of pests associated with cotton. Some examples are summarized in Table 4. The natural enemies listed in the table include: parasites that attack eggs (four genera), larvae (five genera) and adults (one genus); and four genera of predators. Some of these natural enemies are host-specific, while others attack a wide range of hosts. The hosts listed in Table 4 are generally those reported in the references cited.

## EGG PARASITES

The behavioral chemicals affecting egg parasites include various kairomones left by ovipositing lepidopterous host females. With *Trichogramma pretiosum* Riley, for example, bollworm moth scale extracts increased parasitization, apparently by stimulating increased searching (Jones *et al.*, 1976). From bollworm scale extracts, Jones *et al.* (1973) identified four straight-chain hydrocarbons having kairomonal activity for *Trichogramma evanescens* Westwood; of these, tricosane was the most active. Increased rates of parasitization of bollworm eggs were also observed with *Trichogramma achaeae* Nagaraja and Nagarkatti after exposure to tricosane (Gross *et al.*, 1975). Although *Trichogramma pretiosum* responded similarly to the bollworm moth scale extracts, tricosane produced no significant response with *Trichogramma pretiosum*, and while dotriacontane increased parasitism, it has not been shown to be present in moth scales (Jones *et al.*, 1976).

Another type of kairomone, which is present in material from the accessory gland of female bollworm moths, stimulated ovipositor probing by *Trichogramma pretiosum* (Nordlund *et al.*, 1987). Two proteins from the accessory gland of female tobacco budworm moths, apparently involved in adhesion of eggs, serve as egg recognition kairomones for *Telenomus heliothidis* Ashmead. Glass beads coated with these proteins were examined and probed by the parasite (Strand and Vinson, 1983). This recognition kairomone induced the parasite to oviposit and develop in nonhost eggs (Strand and Vinson, 1982), which could prove useful in artificial rearing of such parasites.

Pheromones of the host insect can also serve as kairomones. Gossyplure, the synthetic pheromone of the pink bollworm, caused increased parasitization of pink bollworm eggs by *Trichogramma pretiosum* (Zaki, 1985). The synthetic pheromone blend of the bollworm increased rates of parasitization of the bollworm eggs by this same parasite (Lewis *et al.*, 1982; Noldus, 1988).

Searching or ovipositing parasites leave marking pheromones around or within the host eggs (Salt, 1937; Gardner and van Lenteren, 1986; Okuda and Yeorgan, 1988). These marking pheromones increase the efficiency of searching and reduce superparasitization.

## LARVAL AND ADULT PARASITES

As with the egg parasites, kairomones from the host affect the behavior of larval parasites. Mixtures of methyl-branched hydrocarbons that stimulate searching of *Cardiochiles nigriceps* Viereck, *Microplitis croceipes* (Cresson) and *Microplitis*

Table 4. Behavior-modifying chemicals affecting parasites and predators of cotton pests.

Insect	Host	Source and/or stimulus	Action	Reference
<u>EGG PARASITES (Hymenoptera: Trichogrammatidae)</u>				
<i>Trichogramma achaeae</i>	bollworm	moth scales, tricosane and other hydrocarbons	search stimulating kairomone	(Gross <i>et al.</i> , 1975)
<i>Trichogramma evanescens</i>	bollworm, wide range of hosts	moth scales, tricosane and other hydrocarbons odors from another female <i>T. evanescens</i> host egg	search stimulating kairomone marking pheromone arrestment (contact pheromone)	(Jones <i>et al.</i> , 1973) (Salt, 1937) (Gardner and van Lenteren, 1986)
<i>Trichogramma pretiosum</i>	pink bollworm bollworm, other moths	host sex pheromone (gossypure) moth scale extracts accessory gland of female bollworm bollworm pheromone	kairomone, increased parasitization search stimulating kairomone oviposition stimulating kairomone host seeking kairomone	(Zaki, 1985) (Jones <i>et al.</i> , 1976) (Nordlund <i>et al.</i> , 1987) (Lewis <i>et al.</i> , 1982, Noldus, 1988)
<u>EGG PARASITES (Hymenoptera: Scelionidae)</u>				
<i>Telenomus heliothidis</i>	tobacco budworm	tobacco budworm eggs (two proteins)	host egg recognition kairomone	(Strand and Vinson, 1983)
<i>Telenomus podisi</i>	pentatomids	female parasite on parasitized eggs	host egg marking pheromone	(Okuda and Yeargan, 1988)
<i>Trissolcus euschisti</i>	pentatomids	female parasite on parasitized eggs	host egg marking pheromone	(Okuda and Yeargan, 1988)
<u>EGG PARASITES (Hymenoptera: Braconidae)</u>				
<i>Chelonus curvimaculatus</i>	pink bollworm	moth scales	search stimulating kairomone	(Chiri and Legner, 1982)
<u>LARVAL PARASITES (Hymenoptera: Ichneumonidae)</u>				
<i>Campoletis sonorensis</i>	tobacco budworm	cotton plant  female Dufours gland female oviducts (water soluble material)	attractant and search stimulating synomones host marking pheromone oviposition deterrent pheromone	(Elzen <i>et al.</i> , 1984a) (Guillot and Vinson, 1972) (Guillot and Vinson, 1972)
<u>LARVAL PARASITES (Hymenoptera: Braconidae)</u>				
<i>Bracon mellitor</i>	boll weevil	frass (diet-specific component)	oviposition probing stimulant	(Vinson <i>et al.</i> , 1976)
<i>Cardiochiles nigriceps</i>	tobacco budworm	larval mandibular gland, frass, methyl-branched hydrocarbons  female in cocoon female Dufours gland (unidentified hydrocarbons)	host-seeking stimulant kairomone  short-range sex pheromone host marking pheromone	(Vinson <i>et al.</i> , 1975)  (Vinson, 1978) (Guillot <i>et al.</i> , 1974)

Table 4. Continued.

Insect	Host	Source and/or stimulus	Action	Reference
<i>Microplitis croceipes</i>	bollworm	frass hydrocarbons, 13-methylhentriacontane plant compounds in larval frass increased female Dufours gland females	host-seeking stimulant kairomone host searching host-marking pheromone sex attractant pheromone	(Jones <i>et al.</i> , 1971) (Nordlund and Sauls, 1981) (Vinson and Guillot, 1972) (Elzen and Powell, 1988, 1989)
<i>Microplitis demolitor</i>	bollworm	frass hydrocarbons, 13-methylhentriacontane	host-seeking stimulant kairomone	(Nordlund and Lewis, 1985)
<u>LARVAL PARASITES (Diptera: Tachinidae)</u>				
<i>Archytas marmoratus</i>	tobacco budworm	larval, frass (in most noctuid larvae) (a protein)	larviposition stimulant kairomone	(Nettles and Burks, 1975)
<u>ADULT PARASITE (Diptera: Tachinidae)</u>				
<i>Trichopoda pennipes</i>	southern green stink bug	male host pheromone	attractant kairomone	(Mitchell and Mau, 1971)
<u>PREDATORS (Neuroptera: Chrysopidae)</u>				
<i>Chrysoperla carnea</i>	bollworm	moth scales accessory gland secretion (egg adhesive) b-caryophyllene from cotton	search stimulant kairomone prey acceptance kairomone attractant synomone (for adults)	(Lewis <i>et al.</i> , 1977) (Nordlund <i>et al.</i> , 1977) (Flint <i>et al.</i> , 1979)
<u>PREDATORS (Coleoptera: Malachiidae)</u>				
<i>Collops vittatus</i>	large variety of insects	caryophyllene oxide from cotton	attractant in traps	(Flint <i>et al.</i> , 1979)
<u>PREDATORS (Heteroptera: Pentatomidae)</u>				
<i>Podisus maculiventris</i>	large variety of insects	males, $\alpha$ -terpineol and ( <i>E</i> )-2-hexenal	sex attractant pheromone	(Aldrich <i>et al.</i> , 1984)
<u>PREDATORS (Acari: Phytoseiidae)</u>				
<i>Phytoseiulus persimilis</i>	tetranychid mites	mites on plants	attractant kairomones	(Sabelis and Dicke, 1985)

*demolitor* Wilkinson have been identified from frass (excrement) or larvae of the tobacco budworm (Vinson *et al.*, 1975) and the bollworm (Jones *et al.*, 1971; Nordlund and Lewis, 1985), respectively; 13-methylhentriacontane was one of the more active components. A proteinaceous material found in the frass or hemolymph of most noctuid larvae stimulates larviposition (deposition of living larvae) in the tobacco budworm larva by the tachinid parasite *Archytas marmoratus* (Townsend) (Nettles and Burks, 1975). Also, the pheromone of the male southern green stink bug is a kairomone that attracts the parasite *Trichopoda pennipes* (F.) (Mitchell and Mau, 1971, Todd and Lewis, 1976).

Like the egg parasites, larval parasites also employ marking pheromones. Vinson and Guillot (1972) demonstrated that material from the Dufours gland permits *Microplitis croceipes*, *Cardiochiles nigriceps* or *Campoletis sonorensis* (= *perdistinctus*) (Cameron) to distinguish between nonparasitized and parasitized larvae of the tobacco budworm. The existence of sex pheromones in some parasites has also been demonstrated. Vinson (1978) presented evidence for a short-range pheromone emitted by females while still in the cocoon. Elzen and Powell (1988) have reviewed the evidence for a volatile sex pheromone emitted by female *Microplitis croceipes*; they have shown that male *Microplitis croceipes* can be caught in traps baited with virgin females.

Parasites also are affected by chemical cues originating from the habitat frequented by their hosts. These chemicals are classed as synomones since they facilitate location of the host by the parasite and are therefore of mutual benefit to the parasite and the host plant. Williams *et al.* (1988) have reviewed such parasite—plant interactions, with particular reference to cotton and to *Campoletis sonorensis*. *Campoletis sonorensis* females have been shown to orient to and search cotton plants that are host-free (Elzen *et al.*, 1983); in this case, both volatile and contact chemicals were involved. Certain compounds from cotton that are attractive to *Campoletis sonorensis* are not found in larval frass from diet-reared tobacco budworm larvae, but feeding cotton to diet-reared larvae increased the kairomonal activity of the larvae and their frass (Elzen *et al.*, 1984b). Similarly, in laboratory experiments, *Microplitis croceipes* females responded to the extracts of frass from bollworm larvae reared on cotton, but not to frass from larvae reared on corn. This lack of response was shown to be the result of the absence of some chemicals in the corn (Nordlund and Sauls, 1981).

## PREDACEOUS INSECTS

Predators respond to many of the same types of chemical cues as do the parasites. The rate of predation by the common green lacewing, *Chrysoperla carnea* (Stephens), on eggs of the bollworm was increased when bollworm moth scales or extracts of the scales were applied to the search area (Lewis *et al.*, 1977). Another kairomone for lacewing larvae appears to be present in the accessory gland secretion of the bollworm that causes adhesion of eggs to leaves (Nordlund *et al.*, 1977). The authors suggest that the scale kairomone is a search stimulant while that in the accessory gland secretion is involved in prey acceptance. A compound in cotton, *b*-caryophyllene, is attrac-



tive to adult female green lacewings, while another predator, *Collops vittatus* Say, a beetle, is caught in traps baited with caryophyllene oxide, another compound found in cotton (Flint *et al.*, 1979).

With the spined soldier bug, *Podisus maculiventris* (Say) (Heteroptera: Pentatomidae), which preys upon a large variety of insects and is the most widespread pentatomid predator in the United States, it has been demonstrated that males call a mate with pheromone from dorsal abdominal glands that open just under the wings. Females, males and immature nymphs respond to calling males. Although six compounds have been identified in volatiles from the male dorsal abdominal glands (Aldrich *et al.*, 1978), only two compounds are necessary for long-range attraction: (+)-*R*- $\alpha$ -terpineol and (*E*-2-hexenal. The compound (-)-*R*- $\alpha$ -terpineol has no adverse affect on attractancy so the cheaper racemic  $\alpha$ -terpineol can be used for trapping (Aldrich, 1995).

A number of parasites and predators of the spined soldier bug were caught on or near traps baited with live males or with the synthetic pheromone of the spined soldier bug (Aldrich, 1985). These included the tachinid flies, *Hemyda aurata* Robineau-Desvoidy and *Euclytia flava* (Townsend); an ectoparasitic biting midge, *Forcipomyia crinita* Saunders; two species of scelionid egg parasitoids, *Telenomus calvus* and *Telenomus podisi* Ashmead; and eastern yellowjackets, *Vespula maculifrons* (Buysson).

In addition to the use of the synthetic pheromone of the spined soldier bug for monitoring population levels of the predator, it has been suggested (Aldrich *et al.*, 1984) that it might be useful for: (a) luring these predators to pest infestations; (b) establishing them in areas where they are not now present; (c) moving them out of fields before applying an insecticide; or (d) assessing potential rates of parasitism.

## PREDACEOUS MITES

Predatory phytoseiid mites such as *Phytoseiulus persimilis* Athias-Henriot prey upon spider mites. In an extensive review, Sabelis and Dicke (1985) summarize the many experiments demonstrating that prey location by these mites is facilitated by kairomones that may be prey-specific or may be derived from the host plant. The nature and chemical composition of these kairomones have not been elucidated.

## OPPORTUNITIES

The highly successful use of the boll weevil pheromone in traps and the pink bollworm pheromone in mating disruption or attracticides should provide considerable impetus for exploiting opportunities for expanding the practical use of pheromones and other behavior-modifying chemicals in cotton pest management. Further, the ever-increasing need to reduce insecticide use and insect control costs provides strong justification to continue and expand research and development activities. The past successes have been associated with diverse research and development efforts involving chemistry, behavior, population ecology and delivery systems. Future successes undoubtedly

will require similar efforts. As attempts are made to manipulate more complex systems, increased emphasis should be placed on strategy definition and scientific integration.

Existing control technologies clearly will benefit from further refinements, and additional attention to development of new and improved pheromone-based surveillance methods will lead to additional practical uses. However, in terms of population suppression, future major advances may be associated with allelochemicals. The plant-derived kairomones for pests, such as attractants and feeding stimulants, often have the advantage of being active against both sexes, while the pheromones often are sex-specific. For this reason, the potential for suppression of the bollworm and tobacco budworm may rest with plant-derived chemicals, since movement of mated females clearly limits the use of pheromones for mating disruption. Additionally, fundamental new knowledge on hormonal regulation of pheromone production in Lepidoptera could lead to entirely new methods of disrupting the mating process (Ridgway *et al.*, 1990c).

Kairomones for natural enemies continue to be a very fertile field for research, for much is still to be learned. However, if this area of research is to have practical impact in the foreseeable future, major efforts on one or more model systems are needed, with a focus on the identification of useful chemical compounds and of the specific natural enemies to be manipulated.

## SUMMARY AND CONCLUSION

Aggregation and/or sex pheromones have been identified and are in practical use for surveillance and/or suppression of the boll weevil, pink bollworm, cotton bollworm, and tobacco budworm. Boll weevil pheromone traps are used for surveillance related to the management of insecticides for overwintered boll weevil control in most areas of the United States where the boll weevil occurs. They are used as integral components of a number of areawide management programs. Boll weevil traps are used most intensively for both surveillance and suppression in the six states in the Southeastern Boll Weevil Eradication Program. The pink bollworm pheromone is used in the western United States for both surveillance and suppression; suppression is accomplished through mating disruption or use of attracticides, rather than mass trapping. The pheromones for both the bollworm and tobacco budworm are used primarily for monitoring in research programs. However, there is some commercial use, including the use of pheromone traps to sample tobacco budworms as part of a cooperative insecticide resistance management program.

The existence of sex pheromones in *Lygus* spp. has been demonstrated under field conditions by using live insects in traps as the source of the chemicals. The elucidation of the specific pheromone is complicated by the production in the scent glands of behavioral chemicals that are not attractants. Therefore, the chemical identities of the pheromones are not yet known. Pheromones of phytophagous stink bugs that attack cotton are known, as are pheromones for phytophagous mites. The latter pheromones are available commercially and are used to enhance the efficacy of miticides.

Chemicals produced from both insects and plants have been demonstrated to influence the behavior of natural enemies of cotton insects. The potential exists for utilizing these chemicals in a program involving mass rearing, pre-release behavioral modification and field behavioral manipulation to consistently provide adequate levels of pest protection.

Finally, in view of the selectivity of pheromones and other behavior-modifying chemicals, markets are often small and the incentives for private investment are limited. Also, expensive large-scale experimentation over a period of several years is often necessary to demonstrate efficacy and to develop practical management programs. Therefore, to take advantage of future opportunities, close cooperation between the public and private sectors, with a major resource commitment by the public sector, is essential.

### AUTHORS' NOTE

The literature review for this chapter was essentially completed in July 1990. Some of the important events since that time include substantial advancement of the Southeastern Boll Weevil Eradication Program, development of improved formulations of gossypure for use in suppression of the pink bollworm, and evaluation of the boll weevil bait stick for use in suppression of the boll weevil.

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