Chapter 21

Use of pheromones in IPM

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During the past 68 years that have elapsed since the identification of the first insect pheromone (Butenandt, 1959) there has been a bourgeoning of basic and applied research that has resulted in an amazingly diverse and effective use of pheromones in IPM. Other behavior-modifying semiochemicals have had more limited success on a commercial level, although much research is continuing to try to find new ways to make such chemicals as host plant volatiles more useful in IPM settings as attractants or deterrents.

Although pheromones have established themselves in IPM systems, most end-users and even applied researchers do not realize how much work goes into identifying and optimizing pheromone blends so that they become highly species-specific and optimally attractive to the target species so that they can be used to the best effect. Research to determine the most effective pheromone blend compositions and dispenser dosages for monitoring and detection typically takes five to ten years to complete. Optimizing trap design targeting particular species can take several more years. Sometimes effective pheromones cannot be elucidated at all despite decades of intensive effort.

Delivery of effective commercial products presents another hurdle. For instance, applied pheromone researchers may spend years establishing that a particular mating disruption system is highly effective at disrupting mating and reducing crop damage after conducting experiments in which disruptant dispenser dosages and deployment densities have been varied. A mating disruption system may work successfully from a biological standpoint, but at the commercial level it may be too costly or not sufficiently user-friendly compared to standard practices, and the system will have been judged to "fail" at this level. It is important to distinguish between failure in the commercial arena versus biological failure of the mating disruption system itself.

21.1 | Monitoring established populations

The most widespread use of pheromones has been for monitoring endemic pest species' adult populations. Comprehensive apple IPM programs that were initiated in New York State and Michigan during the early 1970s were based on good, species-specific monitoring traps for the complex of tortricid moth pests that cause direct and indirect damage to fruit. Monitoring of leafroller pests coupled with computer assisted degree-day models (Riedl & Croft, 1974; Riedl *et al.*, 1976) allowed sprays to be timed for optimum efficacy against eggs and first instars on such key pests as the codling moth (*Cydia pomonella*) and

oriental fruit moth (*Grapholita molesta*). Spray-or-no-spray decisions based on abundance of adults in monitoring trap grids were also made possible by effective, standardized monitoring traps and deployment schemes developed against some pests such as the codling moth (Madsen, 1981). During the mid-1970s to late 1980s, insecticide applications were reduced by more than 50% in New York State, Michigan and the Pacific Northwest due to monitoring programs that improved decision making about the need to spray insecticides (Madsen, 1981) as well as their timing. Such programs have become even more refined over the years, with concomitant further reductions in insecticide applications being documented (Agnello *et al.*, 1994). On other crops in the USA as well as around the world, pheromone monitoring traps have asserted themselves in IPM programs as essential elements to the success of these programs. Their use is accepted as an integral and routine part of IPM. The chemical composition of thousands of pheromones can be readily accessed on the websites "Pherobase" (www.pherobase.com) and "Pherolist" (www.nysaes.cornell.edu/pheronet/). Many companies can be accessed on the web that provide pheromone monitoring trap kits for hundreds of pests.

21.2 | Detection and survey programs for invasive species

Pheromone traps have played a large role in detecting influxes of adult pest species from one region to another and also even from non-crop areas into crop areas. Survey programs involving grids of pheromone traps are used so routinely to report and track the yearly arrival of migrating adult populations of insects such as the black cutworm (*Agrotis ipsilon*) in the Midwest (Showers *et al.* 1989a, b) or the spread of expanding populations such as the gypsy moth (*Lymantria dispar*) (Elkinton & Cardé, 1981) that it has become an essential part of our arsenal of tools for tracking and ameliorating pest-movement-related threats.

One example of a successful use of pheromone traps in detecting invasive species is the pink bollworm (*Pectinophora gossypiella*). Every summer

since the 1970s, the California Department of Food and Agriculture (CDFA) has monitored an extensive grid of pheromone traps to protect against the pink bollworm becoming established in the Central Valley of California. The grid density averages approximately one trap per 250 ha, but it extends at various densities throughout the Central Valley (Baker *et al.*, 1990). When a male moth is discovered in a trap, an airdrop of sterile moths, reared at the USDA-APHIS sterile pink bollworm moth-rearing facility in Phoenix, is implemented. The plane is guided to the exact field by GPS coordinates. Sterile moths are dyed pink by the diet they ingest at the rearing facility, and so the many sterile males captured in the pheromone traps are easily distinguished from non-dyed males that have been blown in on weather systems from southern desert valleys.

The presence of a non-dyed male in a trap is assumed to be indicative of fertile, wild females being present in the same area, and that the threat of an increasing endemic population of pink bollworms becoming established is real. Airdrops of sterile moths are aimed at creating a ratio of at least 60:1 pink:normal-colored (sterile:wild) male captures in the pheromone traps. When the 60:1 ratio cannot be attained, either by too many wild males present or too few sterile individuals being produced at a particular time by the sterile moth-rearing facility, the CDFA then applies pheromone mating disruption. Monitoring and sanitation of this exotic pest under this program has provided a significant savings to growers and to the environment, allowing cotton to continue to be grown in central California with minimal insecticide load and maximum profits.

21.3 | Mass trapping

The once-discounted technique of mass trapping using either male-produced or female-produced pheromones has become a newly appreciated, highly effective, environmentally friendly and relatively inexpensive means of suppressing populations of certain pest species whose pheromone communication systems and bionomical characteristics make them susceptible to this approach. In this technique after much experimentation,

Fig. 21.1 Incidence of American palm weevil-vectored red ring disease in oil palms in Costa Rica, before and after mass trapping of the weevils, as measured by the number of diseased trees that had to be removed each year from two plantations, A and B, from 1989 to 2001. Plantation A comprised 6514 ha and Plantation B totaled 8719 ha. From 1989 to 1992, before the implementation of mass trapping of the weevils, disease incidence steadily rose. During this period only normal sanitation and diseased palm tree removal were used to try to control the weevils. After 1992, when pheromone mass trapping was added to the program, the incidence of red ring disease declined dramatically (from Oehlschlager *et al.*, 2002).
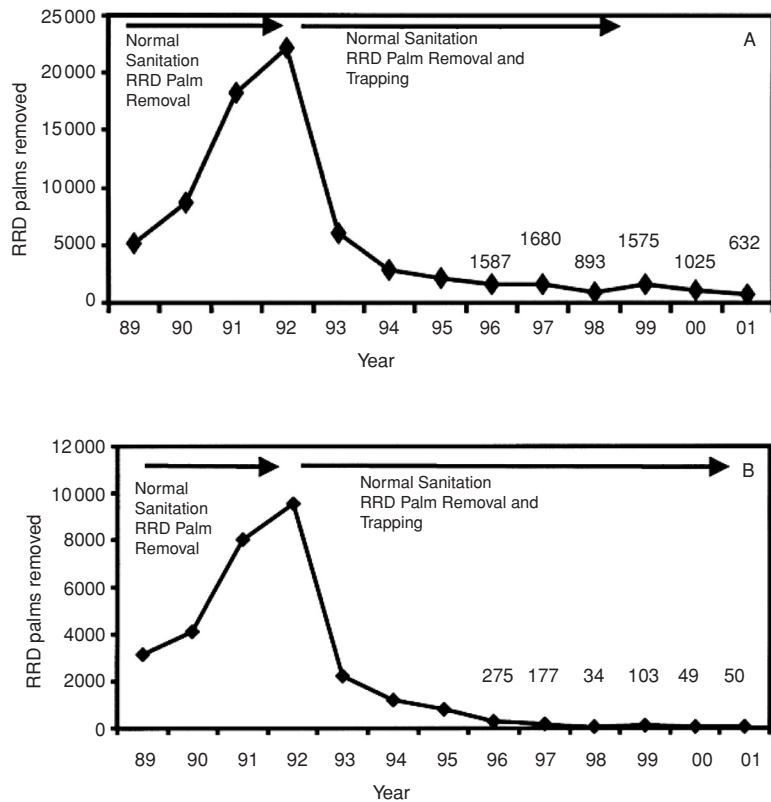
traps are deployed at densities on the crop plants that have proven to attract and capture sufficiently large numbers of insects such that reduced damage to the crop occurs.

One example of successful mass trapping using pheromone traps concerns the American palm weevil (*Rhynchophorus palmarum*). This species is a highly damaging pest of oil and coconut palms in Central and South America. A related species, *R. ferrugineus*, is a major pest of oil and other palms in the Middle East. Larvae of *R. palmarum* cause direct damage when they bore into the trunks of the trees, but they also are a vector of red ring disease, which is caused by a nematode, *Rhadinaphelenchus cocophilus*. In the early 1990s, losses of trees either due to the weevil itself or to red ring disease (which necessitates removal of the infected trees) often routinely reached 15%.

In 1991 following successful preliminary experiments, plantation-wide mass trapping of the American palm weevil was undertaken on two major oil palm plantations in Costa Rica, one comprising 6514 ha and the other comprising 8719 ha (Oehlschlager *et al.*, 2002). Four-

liter bucket traps baited with the male-produced sex pheromone plus insecticide-laced sugarcane (Chinchilla & Oehlschlager, 1992; Oehlschlager *et al.*, 1992, 1993) were deployed at chest level at a density of only one trap per 6.6 ha. The results in the two plantations were virtually identical (Fig. 21.1). Before the mass-trapping program was implemented, normal sanitation procedures involving removal of red ring disease-infected palms had failed to reduce the incidence of this disease. However, once mass trapping was added to the system, after one year the incidence of diseased trees needing to be removed dropped by nearly 80%, from about 10 000 diseased trees removed to 2000 (Oehlschlager *et al.*, 2002) (Fig. 21.1). During that first year (1992–1993) more than 200 000 weevils were trapped. In each successive year, the incidence of diseased trees declined until in 2001 only 50 diseased trees needed to be removed through sanitation (Oehlschlager *et al.*, 2002) (Fig. 21.1).

In subsequent commercial development of the *R. palmarum* mass-trapping system, approximately 25 000 ha of palm plantings were estimated to be

under mass-trapping control yearly at the start of this century in Central and South America (A. C. Oehlschlager, personal communication). The density of traps used has typically been only one trap per 7 ha. In addition to the ability of this male-based pheromone to attract females, the success of this mass-trapping system (Oehlschlager *et al.*, 2002) is due first to the fact that although the weevils are highly damaging and cause high levels of tree mortality on a per-weevil basis, they are present in relatively small numbers. Second, the weevils have a long adult life, and so the steady capture of moderate numbers of weevils throughout the year can remove a large proportion of a generation and have a significant impact on population growth. Third, the adults are strong flyers, which, in conjunction with the highly attractive pheromone blend, allows the pheromone traps to be widely spaced (Oehlschlager *et al.*, 2002).

These same characteristics have come into play in other highly successful and effective commercial mass-trapping systems against other tropical weevil pest species. For *R. ferrugineus*, more than 35 000 ha of palm plantings are treated with mass trapping every year in the Middle East. For another pest of palm, coconut rhinocerous beetle (*Oryctes rhinoceros*), more than 50 000 ha yearly are under a mass-trapping program in the Middle East (A. C. Oehlschlager, personal communication). An estimated 10 000 ha of commercially grown bananas in the American tropics is under mass-trapping programs every year against the banana weevil, *Cosmopolites sordidus* (Germar) (A. C. Oehlschlager, personal communication).

In the early 1980s a "boll weevil eradication" program was initiated in the southeastern USA that relied extensively on a boll weevil lure and trap system developed over many years (Hardee *et al.*, 1967a, b; Tumlinson *et al.* 1968, 1969, 1970, 1971). In the early years, the traps served mainly as detection and monitoring tools and guided decision making on insecticide spraying. If trap captures exceeded an average of 0.1 weevils per trap, insecticides were applied. However, if capture levels were lower than this, mass trapping alone was considered adequate for population suppression. In the later years, the traps operated in a mass-trapping mode because populations had been reduced during the preceding years and weevil captures rarely exceeded 0.1 per trap. The scale of this effort was immense; in 1988 alone approximately 590 000 traps were deployed and more than 8.25 million pheromone dispensers were used in these southeastern states (Ridgway *et al.*, 1990).

The impact of the program was significant (Table 21.1), in terms of allowing cotton production to once again expand and flourish, in terms of the reduction in insecticides applied per hectare (savings of $US 69–74/ha in Virginia, North Carolina and South Carolina) and in terms of the increased yield value of the harvested cotton per hectare (increase of $US 85.25/ha) (Ridgway *et al.* 1990).

21.4 | Mating disruption

Mating disruption involves dispensing relatively large amounts of sex pheromone over crop hectarage and suppressing males' abilities to locate females for mating. It used to be assumed that most, if not all, females would need to remain unmated in order for mating disruption to be effective, but current thinking has shifted, with evidence showing that females' ability to mate merely needs to be impaired such that their first and second matings are delayed, not prevented. Since the introduction of the first commercial pheromone mating disruptant in the world in 1976 against the pink bollworm on cotton, use of the mating disruption technique has grown slowly but steadily. Worldwide, over the past several years nearly 400 000 ha of various agricultural crops and forests have been under commercial mating disruption targeting a wide variety of insect pests. Examples of two of many such successful mating disruption programs are given below. Many other examples exist worldwide, in addition to these from the USA.

21.4.1 Successful mating disruption in IPM using commercial dispensers

In the early 1990s, apple and pear growers in California and the Pacific Northwest adopted a Codling Moth Areawide Management Program (CAMP) that relied on mating disruption for controlling the codling moth (*Cydia pomonella*). One overall goal of this study was to achieve an 80% or greater reduction of the use of

Table 21.1 Boll weevil captures in successive years of the expanded boll weevil eradication zones in North Carolina and South Carolina, USA

| Year | Hectares | No. of fields | Percentage of fields capturing indicated numbers of weevils | | |
			0	1–5	>5
1983					
N.C.	6 600	800	0	1	99
S.C.	21 240	2 000	2	5	93
1984					
N.C.	9 200	1 000	21	35	44
S.C.	32 000	2 300	22	25	53
1985					
N.C.	9 400	1 000	90	7	3
S.C.	37 000	4 300	81	12	7
1986					
N.C.	8 600	1 000	>99.9	0	0
S.C.	34 400	4 200	97.3	2.3	0.4

Fig. 21.2 The number of hectares treated each year with codling moth commercial mating disruption products in Washington State, USA from 1990 to 2002 (Brunner *et al.*, 2001; years 2001 and 2002 provided by Brunner, personal communication). In 1995 the CAMP program (Codling Moth Areawide Management Project) began with subsidized mating disruption applications provided to growers. The three CAMP sites in Washington State comprised a constant 760 hectares during the five years of the program (1995–1999).
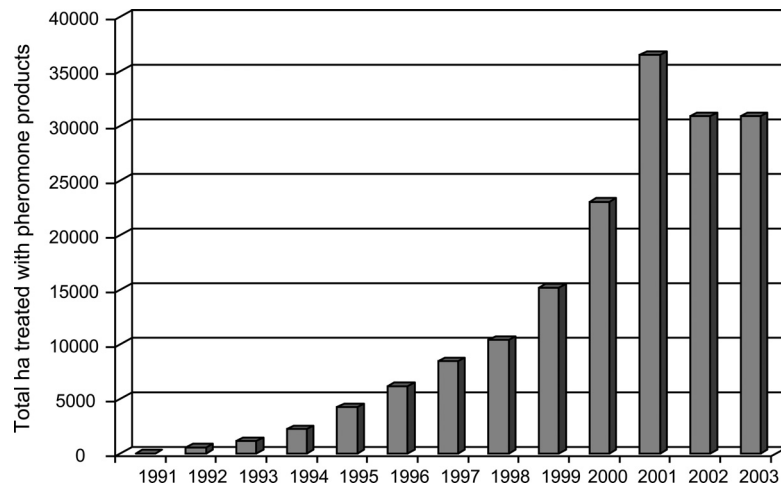
broad-spectrum conventional insecticides by the end of the five-year program. A subsidy was provided to all participating growers of $US 125/ha for the first three years of the project to help defray the cost ($US 275/ha) of the mating disruption treatments (Brunner *et al.*, 2001). For the final two years, growers had to pay the full cost of the treatments themselves. Standard high-dose codling moth monitoring traps were used to assess trap-capture reductions and damage assessments were made for all blocks within the CAMP

project and compared with fruit from non-CAMP-participating grower blocks.

The number of hectares of apples under mating disruption in Washington State increased steadily during this project as word of successful codling moth population suppression spread (Fig. 21.2). Growers statewide continued to use this technique for years after the subsidies had disappeared, indicating that they were satisfied with the population suppression and their economic balance sheets. Participants in the CAMP

Table 21.2 | Pink bollworm damage to cotton bolls during successive years of the Parker Valley Mating Disruption Project, Arizona, USA

	Larvae per 100 bolls				
	1989	1990	1991	1992	1993
9 July	–	0.3	–	0.19	0
16 July	–	0.6	0.6	0.09	–
23 July	3.6	1.4	0.03	0.95	–
30 July	7.7	2.7	0.09	0.61	0
6 Aug	17.9	1.5	0.03	0	0
13 Aug	25.9	5.9	0.03	2.45	0
27 Aug	36.4	20.6	1.6	1.19	0
3 Sept	34.5	10.9	1.9	1.6	0
10 Sept	21.6	10.4	3.7	1.78	0
17 Sept	28.4	33.3	6.6	–	0
Total bolls sampled/yr	23 847	31 630	21 675	25 603	22 852

program achieved a 75% reduction in insecticide applications while reducing damage to unprecedented levels (Brunner et al., 2001). Damage at harvest fell from 0.8% the year before the program started to 0.55% during year 1, 0.2% during year 2 and to between 0.01% and 0.03% during year 4. These levels were accomplished during 1998 with one-half the density of dispensers per hectare, because this was the first year without a cost subsidy from the program. Also, secondary pests did not arise with the reduced insecticide pressure, as had initially been feared would occur. On the contrary, comparison plots under conventional practice experienced higher levels of secondary pests and often lower levels of beneficial insects and mites than did the CAMP program plots (Brunner et al., 2001).

In the Parker Valley of Arizona with over 10 000 ha of cotton, growers in the late 1980s mandated an area wide mating disruption program due to this pest's high level of resistance to insecticides (Staten et al., 1997). As in the codling moth CAMP program, damage diminished year by year in the Parker Valley with continued area wide application of pheromone mating disruption formulations. Whereas the percentage of infested bolls out of the tens of thousands that were sampled each year was more than 25% during mid-August of year 1, during the same August period

in year 2 (1990) damage was only 5.9% (Staten et al., 1997) (Table 21.2). At the mid-August point of year 3 damage was only 0.03% and by 1993, out of more than 22 000 bolls sampled season-long, not a single infested boll was found (0% damage) (Table 21.2). In contrast, the central Arizona average infestation rate for conventionally insecticide-treated hectarage in 1993 was 9–10% by mid-August (Staten et al., 1997).

21.4.2 Behavioral mechanisms underlying mating disruption success

There is evidence from many studies that what has now been more aptly termed "competition" (Cardé, 1990; Cardé & Minks, 1995) but had previously been called "confusion" or "false trail-following," does in fact occur in mating-disruption-treated fields, especially those receiving discrete point sources of dispensers such as hollow fibers or ropes. It is unknown, but we regard it as unlikely, that male moths in fields treated with sprayable microcapsules, creating a nearly uniform fog of pheromone from the closely spaced, weak point source emitters, would be subject to the competition mechanism. The majority of species that have been tested for their responses to uniform clouds of pheromone quickly habituate when released in the pheromone fog, and cease upwind flight after only 1or 2 seconds, reverting

to cross-wind casting within the cloud (Kennedy *et al.*, 1981; Baker, 1985; Justus & Cardé, 2002).

Cardé & Minks (1995) and Cardé *et al.* (1997) hypothesized that combinations of mechanisms will likely be operating in concert to various degrees, depending on the type of pheromone emission by the dispensers of a particular mating disruption formulation, to reduce males' abilities to respond to pheromone plumes from their females. For dispensers acting in a competitive mode, when males are being "confused" and flying upwind in the plumes of synthetic pheromone emitted by hollow fibers (Haynes *et al.*, 1986; Miller *et al.*, 1990) or Shin-Etsu ropes (Cardé *et al*, 1997; Stelinski *et al.* 2004, 2005), they are receiving high-concentration contacts with the strands of pheromone in those plumes, and habituation of the olfactory pathways is occurring as a result of the male remaining in upwind flight and continuing to maintain contact with those strong pheromone strands (Baker *et al.*, 1998). Habituation that results in reduced upwind flight in response to Shin-Etsu ropes has been observed in pink bollworm males by Cardé *et al.* (1997), and Stelinski *et al.* (2003a, b) have found evidence of long-lasting adaptation of the peripheral pheromone receptors in tortricids. Stelinski *et al.* (2004, 2005) documented that males of four tortricid orchard pest species are attracted in various degrees to individual rope dispensers in the field but often do not proceed all the way to the dispenser.

Miller *et al.* (2006a, b) developed an intriguing new mathematical foundation for judging the degree to which competition (attraction) and non-competitive (habituation) mechanisms contribute to the efficacy of a particular mating disruptant formulation and dispenser deployment density. As formulations use increasingly widely spaced, high emission rate strategies for emitting pheromones, optimal attraction using the blends most closely approximating the natural female blend will become necessary to prolong the time a male spends locked onto the plume dosing himself with high amounts of pheromone in the plume strands to become habituated. At the other extreme, sprayable microcapsule formulations will likely depend very little, if at all, on the attraction–competition mecha-

nism, relying almost exclusively on habituation or plume camouflage (Cardé, 1990; Cardé & Minks, 1995). Regardless of the type of formulation, it is expected that all should be able to take advantage of the advanced period of sexual responsiveness that males exhibit before females begin to emit pheromone.

21.4.3 How mating disruption may suppress population growth

It had routinely been assumed that successful mating disruption can only occur if the majority of females in a population are prevented from mating after the application of a mating disruption formulation. In reality, the females' ability to obtain their first or second matings merely needs to be impaired and delayed. In all but a handful of the huge number of mating disruption field trials that have been conducted over the years, disruption of mating with freely flying females has not been directly assessed. The use of tethered females or clipped-wing females placed on "mating tables" or at stations deployed throughout the disruption plot and then dissected for the presence (mated) or absence (unmated) of spermatophores does not assess what is really happening to feral females that have the ability to fly freely throughout the area. The tethered female technique gives the illusion of being a robust, real-world assessment of mating disruption efficacy, and although it is one of many good indicators, it is especially deficient when the insects distribute themselves unevenly within the habitat due to environmental factors such as heat, humidity and wind. Unless the researcher knows ahead of time the locations where adults typically are most densely clumped and can tether the females there, the ability of the disruptant formulation to keep males from finding females will be overestimated.

Knight (1997) introduced the concept of delayed mating of females within mating disruption plots, based on the relatively high proportion of codling moth females that he found had mated in mating disruption orchards, yet the formulation successfully reduced damage. Earlier studies on the oriental fruit moth that monitored the mating success of freely flying females had suggested that something other than elimination of

mating was operating. For the highly successful and grower-accepted Shin-Etsu rope formulation, Rice & Kirsch (1990) found that in plot after plot treated with mating disruptant, females' abilities to mate at least once in disruption-treated plots was suppressed at most by 50% relative to check plots during a flight. The suppression of mating by the disruptant was often as little as 15–20%, despite the reduction of fruit damage in these plots to acceptable levels comparable to those using standard insecticide regimes (Rice & Kirsch, 1990). Thousands of females were captured in terpinyl acetate bait pails and analyzed for the presence or absence of spermatophores in their bursae copulatrices in both the disruptant-treated plots and the check plots. Vickers *et al.* (1985) and Vickers (1990) reported similar results for oriental fruit moth feral female mating success in Australian rope-treated mating disruption plots (23% mated females in mating disruption plots versus 90% in check plots).

Delayed mating was directly confirmed in studies on European corn borer (*Ostrinia nubilalis*) using very high-release-rate metered semiochemical timed release systems (MSTRS^{TM}: www.mstrs.com) mating disruption dispensers (Fadamiro *et al.*, 1999). Analyses were made of the bursae copulatrices of more than 2400 feral females that were captured by hand-netting during the daylight hours as they were flushed from their grassy aggregation areas. During each of the two summer flights, 100% of the females eventually became mated despite the application of high-release-rate, low-point-source density dispensers (Fadamiro *et al.*, 1999). During the first flight about 50% of the females were virgin for the first few days of the flight in the mating disruption plots, but the mating success of females in these plots eventually reached 100% during the ensuing weeks as the flight proceeded. However, females attained this 100%-mated status more slowly in the mating disruption plots than in the check plots, in which females were 100% mated beginning at day 1. Analysis of the number of matings by (number of spermatophores in) European corn borer females showed that throughout the entire flight females captured in the disruption plots were attaining first and second matings at a significantly lower rate than those from the check plots (Fadamiro

et al., 1999). The mating disruptant was impairing the ability of females to attract and mate with males on a constant, daily basis but it did not completely eliminate mating. The application of this MSTRS formulation has subsequently been shown to reduce damage to corn by an average of 50–70% in various trials (T. C. Baker, unpublished data). Thus, as demonstrated in the oriental fruit moth (Rice & Kirsch, 1990) and codling moth studies (Knight, 1997), mating disruption success does not require keeping the population of females virgin, but rather just needs to impede females' ability to attract males and retard the dates at which they achieve their first or even second matings. Retarding the dates at which first or second matings occur achieved significantly affects fecundity in the European corn borer and codling moth (Knight, 1997; Fadamiro and Baker, 1999).

21.4.4 Methods to assess the efficacy of mating disruption

Of primary importance to growers and to companies marketing mating disruption products is the ability of a formulation to reduce crop damage to acceptable levels. In this context, "successful" mating disruption means assessing crop damage in pheromone-treated plots versus untreated check plots and finding that damage in mating disruption plots is lower. This process is problematic, but considered by many to be a significant outcome. The assessment is relatively straightforward, but it is essential that plots be large enough to reduce the probability that significant numbers of gravid females can fly in from nearby untreated plots and confound the damage data in the pheromone-treated plots.

Being an indirect measure of actual mating disruption efficacy, damage assessment evaluates the end result of many processes that are of interest to those operating in commercial IPM and agronomic arenas. Conclusions that mating disruption was "successful" in the context of suppressing damage and being cost-effective can be arrived at without knowing exactly to what degree the formulation affected the behavior of males to reduce mating by freely flying feral females.

Considered over many years to be the ultimate test of mating disruption efficacy, tethering females either on a thread or by clipping their

wings and placing them on open arenas so that they cannot move from the location at which they are placed has been a good tool in assessing mating disruption efficacy (see Evendon et al., 1999a, b), but this is only one of several indirect measures.

If the adult moths in the natural population reside in a more clumped distribution in some preferred substructure of the vegetative habitat, placing females on artificial stations outside of each of these clumps will overestimate the efficacy of the disruption formulation with regard to preventing mating of feral females. The formulation in effect will only be assessed for its ability to prevent the tethered females from attracting males such that they leave their aggregation sites. This long-distance attraction will be easier to disrupt than will be the disruption of males within the same clumps that also contain females.

Another limitation to this technique is that once a female mates with the first male arriving at her station, she emits no more pheromone and the ability to assess disruption of communication using that female ends. The data are binomial, with no opportunity for a graded assessment from individual females as to how many males the female could have attracted had it been calling for the entire activity period that night and not been mated.

In another technique, a few virgin females are placed in small screen cages containing sugar water source to keep the females alive and hydrated (see Cardé et al., 1977). The cage is situated within a sticky trap, and so males that are attracted to the calling, virgin females become ensnared before reaching the females. Males that do manage to land on the cage containing the females without getting trapped will still not be able to mate with any female in the cage. We feel that this technique has many advantages over other indirect measurement techniques such as the use of tethered females.

First, as with tethered females, the caged females are emitting their natural blend at its natural emission rate. However, unlike tethered females, the caged females in traps provide a graded assessment of their ability to attract males. If males are able to get close enough to the calling females that they can be trapped, they certainly

will have mated if given that opportunity at such close range. The final step, mating, is an unnecessary one to examine because if the disruptant was not able to prevent a male's long-distance orientation to the female's plume, certainly it will not be sufficient to stop the male's orientation to the female over the last 10–20 cm or so.

The most widely used technique for assessing the disruption of mate-finding communication by disruptant formulations is the use of standard pheromone monitoring traps containing synthetic pheromone lures (see Rice & Kirsch, 1990; Knight, 1997; Staten et al., 1997; Baker et al., 1998; Fadamiro et al., 1999). This technique can be as informative as the use of caged calling females if the lure that is used has been shown previously in untreated check plots to be able to attract equivalent numbers of males as do caged calling females.

The advantage of assessing trap capture reduction is that it provides a robust, graded data set from these continuously emitting sources. The disruption formulation is challenged throughout the attraction period each night or evening for its ability to continuously suppress the ability of males to locate "females." Using monitoring traps baited with a good synthetic lure is also easier and less problematic than is the use of live, calling females.

21.4.5 Pheromone component blend composition in the disruptant formulation

Minks & Cardé (1988) and Cardé & Minks (1995) reviewed results from many key sex pheromone communication disruption experiments and concluded that for a given species, the synthetic blend compositions and ratios most closely mimicking the natural blend for that species should be the most effective mating disruptants at a given dose per hectare because they will be able to make use of more of the mechanisms (see above) that result in disruption than will suboptimal, partial blends or off-ratios. Although the majority of field experimental evidence supports this conclusion, this does not mean that one or more of the more minor components, due to their more subtle effects, might be able to be eliminated from the final formulated product and still retain sufficient efficacy. There are, however, a few apparent

exceptions to this general rule (see Evendon *et al.*, 1999a, b, c, 2000).

21.4.6 Some limitations to mating disruption

A primary obstacle to the use of pheromone mating disruption on any crop is that it must be applied no later than the start of the first adult flight period, that is, before a grower knows for sure that there is even going to be a pest problem that season. The requirement of this "up-front" investment in pheromone puts mating disruption at a disadvantage compared to curative pest management tools that provide a wait-and-see option (see also Chapter 4). For example, insecticide applications can be made after a preliminary assessment of the population density during the first flight of adults or even after oviposition when larval damage can be assessed. Pheromone mating disruption cannot be used curatively in that manner.

Charmillot (1990) summed up lessons he and his co-workers learned concerning when it is that mating disruption becomes less effective for codling moth population suppression. His lessons regarding codling moth are applicable to mating disruption efforts on other pests as well. First, mating disruption works best when applied on an areawide basis and is not advisable on very small areas (less than 1 ha). The crop borders represent vulnerable edges for immigration of mated females from adjoining untreated crop areas, and they also serve as a zone that concentrates females along the borders when there are no nearby planting of the same crop. Due to geometry, small hectarage accentuates the problem because the edge-to-area ratio becomes greater. Also, the use of more widely spaced dispensers requires that borders be given special attention to reduce the presence of pheromone-free clean-air "holes" along the borders. This can be accomplished either by decreasing the spacing between dispensers, or else through the use of different dispenser technology along borders, such as sprayable microcapsules.

Except for a few small groups or pairs of species, pheromones are extremely species-specific. The replacement of broad-spectrum insecticides in some IPM systems with mating disruption that targets only one species in a pest com-

plex, might lead to increases in the populations of species that had been only secondary pests before mating disruption was used (see Rice & Kirsch, 1990). No pheromone disruption formulation has been created thus far that functions effectively as a "broad-spectrum" formulation. Evendon *et al.* (1999b, c) experimented with single blend formulations targeting obliquebanded leafroller (*Choristoneura rosaceana*) and threelined leafroller (*Pandemis limitata*) with some success. Perhaps there are other situations where effective multi-species blend formulations can be developed, although there are still none that have attained commercial success.

Pheromone mating disruption formulations have to this point been expensive compared with curative applications of insecticides. Although growers of many crops are now well aware that mating disruption "works" as a pest management tool, pheromones' expense plus the up-front nature of the cost has put them at a disadvantage relative to curative pest management tools. The active ingredient, the pheromone itself, is the most expensive part of a formulation. Costs per gram of even the least expensive pheromone components are approximately \$US 1.00, and many other more expensive major pheromone components cost \$US 3 to 20 per gram. Formulating the active ingredient into specialized dispensers adds to the cost, but nevertheless, if cheaper organic synthetic routes to the active ingredients can be developed, costs of the final formulated products could be reduced substantially.

21.5 Conclusions

Insect pheromone-related technologies for monitoring endemic pest populations, detecting invasive species, mass trapping for population suppression and mating disruption have had a relatively recent history of development in IPM compared to biological control and insecticide technologies. New progress in the application of pheromones in IPM is being made in many areas, including the knowledge that mass trapping can be a highly effective and economically beneficial use of these behavior-modifying chemicals. Novel lure-and-trap technologies continue to

be developed developed for new pest species as they come on the scene in various regions of the world. New insights are also being made regarding ways to determine empirically the modes of action of mating disruption formulations, and the acceptance of the mating disruption technique by growers and government agencies has continued to grow in recent years. It remains to be seen whether other behavior-modifying chemicals such as host plant volatiles can become as widely used as pheromones for insect IPM in field situations, where pheromones have been an integral part of insect IPM programs for approximately 35 years.

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