FORUM

Potential of Mass Trapping for Long-Term Pest Management and Eradication of Invasive Species

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ABSTRACT Semiochemical-based pest management programs comprise three major approaches that are being used to provide environmentally friendly control methods of insect pests: mass trapping, "lure and kill," and mating disruption. In this article, we review the potential of mass trapping in long-term pest management as well as in the eradication of invasive species. We discuss similarities and differences between mass trapping and other two main approaches of semiochemical-based pest management programs. We highlight several study cases where mass trapping has been used either in long-term pest management [e.g., codling moth, *Cydia pomonella* (L.); pink bollworm, *Pectinophora gossypiella* (Saunders); bark beetles, palm weevils, corn rootworms (*Diabrotica* spp.); and fruit flies] or in eradication of invasive species [e.g., gypsy moth, *Lymantria dispar* (L.); and boll weevil, *Anthonomus grandis grandis* Boheman). We list the critical issues that affect the efficacy of mass trapping and compare these with previously published models developed to investigate mass trapping efficacy in pest control. We conclude that mass trapping has good potential to suppress or eradicate low-density, isolated pest populations; however, its full potential in pest management has not been adequately realized and therefore encourages further research and development of this technology.

KEY WORDS mass trapping, semiochemicals, integrated pest management, eradication

Semiochemicals are compounds produced naturally by insects that govern all aspects of their behavior, including mating, aggregation, defense, host recognition, and resource location. In recent years, semiochemical-based pest management programs have been increasingly used to provide environmentally friendly approaches to control major insect pests, including mating disruption, mass trapping, "lure and kill," and to a lesser extent "lure and infect" (Klein and Lacey 1999). Mating disruption that seeks to disorient or misdirect insects searching for mates has been the most successful direct control tactic, principally targeting moths (Cardé and Minks 1995, Suckling 2000). Mass trapping and lure and kill are similar technologies that have been used to control a wide range of insect pests, typically species in Lepidoptera, Coleoptera, and Diptera. These two technologies may be able to contribute to the eradication of new incursions of invasive species, because like other inversely density-dependent approaches, they have the greatest probability of success against pests at very low density, which is initially the case after an incursion.

The concept of mass trapping uses species-specific synthetic chemical lures, such as sex and aggregation pheromones and food/host attractants, to attract insects to a trap where they would be confined and die. Mass trapping using odor-baited traps is one of the older approaches to direct control of insects for population suppression and eradication (Steiner 1952). The density and efficiency of traps as well as the strength of lures need to be sufficient to catch enough insects to reduce economic damage. In bark beetles (Scolytidae: Coleoptera), most species that kill trees to reproduce have aggregation pheromones that attract both sexes about equally; in Lepidoptera, the female typically releases a species-specific sex pheromone that only attracts males. Therefore, the mechanisms of population reduction via trapping differ depending on the semiochemicals used.

In Coleoptera, mass trapping with synthetic pheromone-baited traps was undertaken shortly after the discovery and identification of bark beetle aggregation pheromones (Silverstein et al. 1968). Bedard and Wood (1974) used sticky-screen vane traps to catch Western pine beetles, *Dendroctonus brevicomis* LeConte, attracted to male- and female-produced aggregation pheromone components synergized weakly by myrcene, a host pine monoterpene. In moths, traps baited with synthetic sex pheromone are used to capture male moths and reduce mating of females. This approach requires the removal before mating of a large portion of the males in a given generation. Because female moths are not attracted to their sex pheromone, they are available to mate with any males that have escaped being caught. In addition to pheromones, volatiles from food and host-plant sources have

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been used to attract male and female insects searching for food, and females searching for oviposition sites. Attractants for Diptera may be food-based or have other effects, such as methyl eugenol, which is a powerful male attractant for some species, but it is not a sex pheromone (Steiner 1952, Asquith and Kido 1994, Raghu et al. 2002).

The public demand for environmentally benign alternatives to broad-spectrum insecticides has never been greater, and mass trapping can help satisfy this desire because the quantity of semiochemicals released into the environment is in relatively minute amounts. In addition, many if not most semiochemicals are relatively nontoxic to vertebrates as well as beneficial insects. Another advantage of this method is its high selectivity to the target pest species. Progress in developing these new technologies will be enhanced if researchers can integrate knowledge gained across production ecosystems, trapping, and diverse biologies (e.g., from fruit flies to beetles and moths). In this article, we review the recent developments in the application of semiochemicals in pest management with emphasis on the mass trapping approach. We provide an overview of the application of mass trapping in pest management and eradication for invasive species, followed by case studies. We summarize the knowledge that is needed for successful mass trapping programs. We discuss different methodologies used to measure the efficacy and risks associated with this approach, and we highlight the critical issues affecting mass trapping efficacy based on published models.

Relationship between Mass Trapping, Lure and Kill, and Mating Disruption. Mass trapping and lure and kill use similar approaches, and mass trapping can be considered a subset of the concept of lure and kill. However, the method of killing differs, and this results in an operational difference. For example, lure and kill systems that use gel droplets require the insect to approach and contact a point source (Brockerhoff and Suckling 1999), whereas traps with a larger killing surface do not usually need to elicit the same extent of close-range behavior.

Mating disruption relies on the principle of preventing pheromone communication between sexes by saturating the area with a high concentration of pheromone (e.g., Gaston et al. 1967). In this system, the responding sex is unable to find the emitting sex. Insects remain alive but disoriented during mating disruption, whereas they are removed from the population by mass trapping or lure and kill systems. In mass trapping and lure and kill, insects must find and contact the pheromone sources, which is affected by the density of pheromone sources both natural and synthetic. Both mass trapping and lure and kill require a good understanding of attractant release and response behaviors, and the requirements for attractant quality may be higher than that needed for disruption. Lure and kill systems for field control typically use insecticides, which may be a real or perceived potential hazard to consumers and the environment. Among the three approaches, mating disruption is the most widely used in pest management followed by mass trapping and lure and kill (Fig. 1). These three direct control approaches have been used mainly against lepidopteran pests. However, mass trapping has been used more against coleopteran, dipteran, and homopteran species, whereas lure and kill approaches have been evaluated more often against dipteran and coleopteran species (Fig. 2).

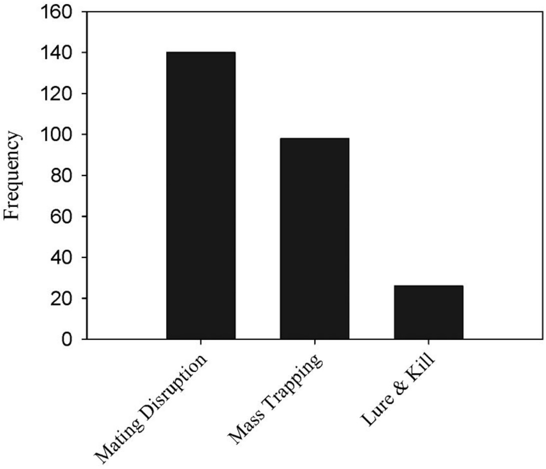

Fig. 1. Number of articles published from 1970 to 2005 (CABI abstracts) on the application of mating disruption, mass trapping, and lure and kill in pest management sorted by approach.

Application of Mass Trapping in Long-Term Pest Management. Mass trapping has been attempted for a variety of agricultural, orchard, and forest pests on scales ranging from a few to thousands of hectares. There are >200 reports of mass trapping from 1970 to 2005 to manage pest populations, mainly for Lepidoptera, Coleoptera, Diptera, and Homoptera (Fig. 2, El-Sayed 2006). The majority of mass trapping programs have been used for pest management rather than eradication programs. Mass trapping has been tested both as a stand-alone control method, and in combination with insecticides and other treatments (e.g., Huber et al. 1979, Jones 1998). The key objective of mass trapping in pest management or eradication is to capture enough insects in the treated area before they reproduce or damage crops, which requires the following: 1) deployed traps release pheromone/attractant that is perceived by a high proportion of the target insects in the specified area; 2) lures are able to attract insects more effectively than natural sources of attraction such as calling virgin females, mating aggregations, or food sources; 3) traps are efficient in catching and retaining attracted insects before they mate or oviposit; 4) lures and traps are effective during the entire period of adult emergence and mating; and 5) costs of trapping materials and labor are less than economic benefits from alternative treatments potentially increasing crop yield/quality.

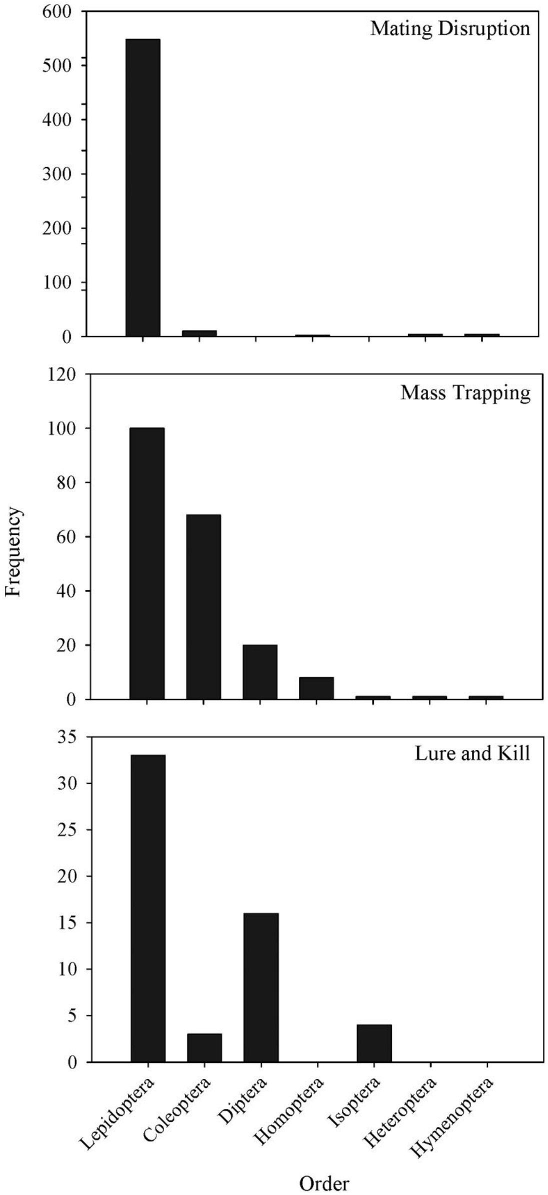

Fig. 2. Number of articles published from 1970 to 2005 (CABI abstracts) on the application of mating disruption, mass trapping, and lure and kill in pest management sorted by insect order.

Mass Trapping as a Stand-Alone Control Method. Stand-alone mass trapping has been tested for control of a wide range of insect pests, and the overall results of these programs can be classified into three categories based on success rate: 1) In some programs, mass trapping showed potential for pest management with a significant reduction in target pest population density or in pest damage (e.g., Madsen and Carty 1979, Faccioli et al. 1993, Mafra Neto and Habib 1996, Zhang et al. 2002). 2) Several mass trapping programs that resulted in small-to-moderate reductions of pest numbers or damage were considered unlikely to provide adequate control, instead indicating methods or situations to avoid with this technology (e.g., Huber et al. 1979, Willson and Trammel 1980, Pasqualini et al. 1997). 3) Mass trapping programs that provided no evidence of population or damage reduction were considered most likely to provide information on the conditions under which mass trapping should not be attempted, and this was also the case where the authors concluded that mass trapping was not suitable for control of the pest (e.g., Hagley 1978, Willson and Trammel 1980, Haniotakis et al. 1999, Yamanaka et al. 2001a) or could not be recommended (Youm et al. 1997), although later improvements in technologies might alter this view. In a few programs, the authors concluded that mass trapping was too expensive, but expense was not considered justification per se for rejection of the technology (e.g., Moraal et al. 1993).

Mass Trapping in Combination with Other Approaches. Compared with mass trapping as a stand-alone method, there have been a smaller number of programs in which mass trapping was combined with insecticides. Sometimes, this combined approach resulted in substantial reduction of the pest population, its damage, or both (e.g., Teich et al. 1979), whereas other combined approaches achieved only a lesser pest reduction (e.g., Huber et al. 1979, Yamanaka et al. 2001a); in these latter situations, the use of mass trapping may have achieved other stated objectives, such as a delay and reduction in insecticide use (Huber et al. 1979, Teich et al. 1979). This led some researchers to recommend the use of mass trapping in combination with insecticides (Huber et al. 1979, Teich et al. 1979, Ahmad and Attique 1993). As with mass trapping alone, there were also cases in which mass trapping in conjunction with chemical control failed to achieve any improvement (Hagley 1978), although this sometimes varied with the experimental conditions such as plot size (Yamanaka et al. 2001a). In some cases, insecticides were used to reduce the target pest population density before the use of mass trapping (Beroza and Knipling 1972, Emel'yanov and Bulyginskaya 1999).

Comparison of Mass Trapping with Other Control Methods. Several studies compared mass trapping with other methods of pest management. In several of these studies, mating disruption was considered to be more effective than mass trapping against the target pests, e.g., pink bollworm, *Pectinophora gossypiella* (Saunders) (e.g., Ahmad and Attique 1993). Trematerra (1993) considered mass trapping better than mating disruption on small, hilly sites, whereas others found mating disruption too expensive (e.g., Sternlicht et al. 1990, Mafra Neto and Habib 1996), particularly because of the cost of pheromone. Similarly, comparisons with the use of insecticides were equally varied. Önucar and Ulu (1999) found insecticides much more effective than mass trapping, whereas Huber et al. (1979) designed a mass trapping program for pink bollworm that was effective in delaying insecticide use and was equivalent in cost to only one insecticide spray. Other studies reported that insecticides were more expensive than mass trapping (e.g., Sternlicht et al. 1990). There could be cases where a combination of mass trapping and mating disruption would be effective, such as mass trapping female moths by using kairomones, while using sex pheromone to disrupt male orientation to females, although there are few female insect attractants reported (El-Sayed 2006).

Case Studies

Codling Moth. Codling moth, *Cydia pomonella* (L.), is a key pest of pome fruits worldwide (Beers et al. 2003). Mass trapping has been investigated as a possible control option against codling moth in North America and Europe (e.g., Hagley 1978, Willson and Trammel 1980, , Emel'yanov and Bulyginskaya 1999). In these trials, traps were baited with 1 mg of codlemone at densities ranging from 5 to 36 traps per hectare (Madsen and Carty 1979, Howell 1980, Willson and Trammel 1980) or used in combination with other approaches (Hagley 1978, Emel'yanov and Bulyginskaya 1999). The outcome of these trials varied greatly. Although some trials clearly indicated that mass trapping of male codling moth with sex pheromone can result in population suppression and hence significant reduction in damage (e.g., Madsen and Carty 1979, Emel'yanov and Bulyginskaya 1999), other trials have shown that mass trapping did not provide any economical control of this pest (e.g., Hagley 1978). The critical difference between the trials is that in the successful examples, mass trapping was targeting isolated and low-density populations compared with the unsuccessful trials that were targeting moderate-to-high population densities over more extensive areas. There was also evidence that mass trapping could be feasible against codling moth in conjunction with other control methods such as insecticides (e.g., Hagley 1978).

There are several factors that might have contributed to the failures of mass trapping against codling moth. First, competitiveness with calling females. It is known that female codling moths produce other minor compounds in addition to the single-component codlemone (El-Sayed et al. 1999), so females may be more attractive to males than pheromone traps. Second, the number of pheromone traps per hectare used in these unsuccessful trials was probably too low considering the high number of calling females in the orchards. And third, male codling moths are polygamous; therefore, if mass trapping did not achieve a high percentage of male removal, the remaining males could still mate with several females. Based on the above-named factors, it is premature at this stage to judge the efficacy of mass trapping to control codling moth, because fundamental experiments are still required to investigate the effect of different blends (i.e., competitiveness of synthetic pheromone with calling females), optimum trap density in relation to pest density, lure longevity, costs and efficiency of traps, risks of immigration, and integration with other control methods. It has been recognized that mass trapping could be improved if female attractants could be found (e.g., Phelan and Baker 1987), because this would greatly enhance efficacy by removing virgin and mated females, particularly if this could be added to male removal (Jones 1998). Kairomones, which are the odors of hosts or prey of insects, may be attractive to both males and females. Recent research has identified kairomones of codling moth (Light et al. 2001), which are being investigated for use in mass trapping, including modeling the impact of the combined use of kairomone and pheromone (Knight et al. 2001).

Pink Bollworm. Sex pheromone has been extensively used for control of the pink bollworm with mating disruption, attract and kill, and mass trapping (Baker et al. 1990, and references therein). Investigation on the efficacy of mass trapping to control pink bollworm was conducted in Arizona as early as the mid-1960s by using female gland extracts (e.g., Graham et al. 1966), but results of these initial trials were not promising, probably because they used a low concentration of pheromones at a low trap density. However, as soon as the sex pheromone of pink bollworm was identified (Hummel et al. 1973) and a synthetic copy of the sex pheromone was available, mass trapping was the first pheromone-based technique conceived as a potential approach to control pink bollworm. Flint et al. (1974, 1976) conducted several trials to investigate the efficacy of mass trapping for control of pink bollworm, and the results of these experiments showed promise. Huber and Hoffmann (1979) and Huber et al. (1979) conducted 3 yr of trials to investigate the possible application of mass trapping techniques to control pink bollworm. Their results showed an early season reduction in mating did occur and that subsequent pink bollworm population buildup was delayed compared with previous years. In these experiments, sticky or oil traps baited with 1 mg of gossyplure at a density of 5–20 traps per hectare were deployed in cotton fields with lure replacement every 2–3 wk. They concluded that mass trapping has the potential of being an effective pest management tool against pink bollworm. They reported three requirements for the success of large-scale mass trapping against pink bollworm: 1) low population present early in the cotton growing season, 2) cotton growing area should be isolated, and 3) other cotton pests did not cause severe problems. In the initial trials of mass trapping against pink bollworm, delta traps were used. However, these traps lost efficiency early in the season because of the buildup of dust, debris, and insect parts on the catch surface. These problems led to the development of an oil trap as a more efficient killing system for mass trapping of pink bollworm (Huber and Hoffmann 1979, Huber et al. 1979).

Although several of these trials with mass trapping against pink bollworm in the United States showed promising results, no further work was conducted to optimize the methodology, probably because 1) mating disruption began to show better results than mass trapping to control pink bollworm, and 2) there was a high cost and dependence on manual labor to install and maintain the traps. Mass trapping also has been investigated as a stand-alone approach, or in combination with insecticides, as a control option for pink bollworm in Pakistan, India, Brazil, and Egypt (Ahmad and Attique 1993, Nandihalli et al. 1993, Mafra Neto and Habib 1996; Nassef et al. 1999). In these trials, delta sticky traps or oil traps baited with 39 or 1 mg of gossyplure at densities of 10–20 traps per hectare were used. Results from these trials showed that mass trapping was an effective viable technique for control of pink bollworm either alone or in combinations with insecticides. Manual labor is readily available and relatively inexpensive in these regions, allowing for the application of mass trapping for control of PBW.

Bark Beetles. "Trap trees" are deliberately felled trees that become attractive to bark beetles and cause the concentration of the population so it can be removed when the trees are harvested. This practice has been used in Europe for >200 yr (Bakke and Riege 1982) and was suggested for use in North America by Hopkins (1909). Reduction of bark beetle populations by using trap trees seemed impractical to early workers unless the chemicals responsible for the attraction to trap trees and other attacked trees could be used as baits in a "mechanical trap" (summarized in Miller and Keen 1960). This became possible after the identification of the aggregation pheromone of the western pine beetle (Silverstein et al. 1968), which led to large-scale mass trapping of the bark beetles by baiting sticky traps with synthetic pheromone components (e.g., Bedard and Wood 1974).

Two experiments were done. The first test in 1970 was conducted in a 65-km^2 area surrounding Bass Lake in central California that was monitored with 104 survey traps on 0.8-km spacing (Bedard and Wood 1974). Two suppression areas, each of 1.3 km^2 with 66 traps on 161-m spacing were used on either side of the lake. Traps were a cross-vane design, each vane 0.76 by 2 m of sticky mesh raised so the top was 2.3 m above ground, and baited to release 2 mg of each of the pheromone components. It was concluded that mass trapping substantially reduced tree mortality caused by bark beetles throughout the test area (from 227 ± 24 trees killed before treatment to 73 ± 8 trees killed during the suppression period and only ≈30 trees killed the year thereafter). Suppression traps caught an estimated 405,000 *D. brevicomis,* whereas the survey traps caught 189,000 additional beetles during May and June 1970. An even larger test was conducted in northern California at McCloud Flats (Siskiyou Co., CA) from 1971 to 1974 (Wood et al. 1985). This study was similar in design as Bass Lake, but no significant trends in beetle attacks and emergence were related to treatment time or place (Wood et al. 1985). In 1973, Pitman et al. (1978) trapped *Dendroctonus ponderosae* (Hopkins) in large numbers by using synthetic aggregation baits with no apparent affect on numbers of trees killed, although there was a significant reduction in loss of tree volume as a result of a shift of attacks to smaller diameter trees near the baited traps.

The largest mass-trapping program for bark beetles was initiated in Norway and Sweden for *Ips typographus* (L.) beginning in 1979. The effects of trap models, pheromone composition, dispenser type, trap arrangements, and management options (removal of decaying beetles) on catches of each sex were investigated to optimize a mass trapping program (e.g., Bakke and Riege 1982). The success of the program has been debated, but Bakke (1982) reported that ≈600,000 pheromone-baited traps were deployed in regions of Norway where trees had been killed the previous year but in areas preferably with minor infestations. Traps were placed at 20-m spacing (≈20–30 traps per hectare) in clear-cut areas at least 10 m from living trees (later recommendations were at least 30 m). The traps caught an average of 4850 beetles per trap or 2.9 billion beetles in total, with ≈11,000 traps each capturing >21,000 beetles. During the trapping program sanitation and salvage logging was intensive. After a few years, the outbreak subsided but it is not known what effects the trapping program had on the decline in tree mortality as there were no untreated control regions due to political factors.

Sticky traps baited with sulcatol in only five locations at a commercial sawmill caught 43,000 ambrosia beetles, *Gnathotrichus sulcatus* (LeConte) (McLean and Borden 1979) that led to development of successful programs to reduce damage to wood at sawmills. Mass trapping programs by using aggregation pheromone of the smaller European elm bark beetle, *Scolytus multistriatus* (Marsham) (Pearce et al. 1975) were conducted in Detroit, MI, in 1974 (Lanier et al. 1976). Approximately 420 pheromone-baited sticky traps were placed on healthy American elms in each of two 1-km^2 plots. Over a million beetles were captured (estimated to be 20% of the emerging population), but there seemed to be no significant impact on the spread of Dutch elm disease vectored by the beetle (Cuthbert et al. 1977). Lanier et al. (1976) found that the number of beetles caught increased directly with trap surface area. Beetles also preferred black rather than white traps against the sky, and white traps set against trees, indicating that contrast was the significant factor. Trap height was optimal at 3 m (catching 25–60 times as many beetles as other levels). In 1975, mass trapping was undertaken again in Detroit where ≈4 million beetles were caught on 1,100 traps during the two flight periods. Significantly more beetles were caught in the trapping periphery indicating immigration of beetles from outside the treatment area. Unfortunately, the incidence of the disease increased in the treatment area due to the influx of beetles attracted to pheromone traps. In Ft Collins, CO, the entire city containing planted elms was gridded with 2,200 traps that caught 1.5 million beetles, and infection rates within the city dropped from 3.5% in 1974 to 2.8% in 1975. In Syracuse, NY, traps caught 816,000 beetles that were 63% of the brood emergence from eight infested trees and the infection rate dropped from 22 to 7%, but this may have been due to natural ebbing of the epidemic. Traps also were used to surround isolated stands of elms and intercept beetle vectors, in two cases there were no new infections but this could have occurred in spite of trapping. On the Capitol grounds in Washington, D.C., traps may have lowered populations enough to account for the declines in Dutch elm disease (Lanier et al. 1976).

Schlyter et al. (2001) deployed 80 traps baited with *Ips duplicatus* (Sahlberg) pheromone (Byers et al. 1990) for 3 yr in a 2000-ha "island" of Mongolian spruce surrounded by grassland. Catches in traps ranged from 0.5 to 1.7 million beetles each year. More than 20 yr of data were collected before the test showed that ≈555 trees were killed each year (fluctuating between 200 and 800 trees killed per year). The mass trapping was considered a success, because tree mortality dropped each of three successive treatment years (118, 100, and 88 per year).

Palm Weevils. Several species of palm weevils (Coleoptera: Rhynchophoridae) that are usually at relatively low population densities have been considered successfully controlled by mass trapping. *Rhynchophorus ferrugineus* (Oliver) is a pest of palms and causes serious damage to coconut and date plantations in several South Asian and Middle Eastern countries. Management was first attempted with food attractants in traps, but more recently greater success has been achieved with a synergistic combination of food and aggregation pheromone (4-methylnonan-5-ol) (Hallett et al. 1993, Abraham et al. 2001, Faleiro and Satarkar 2005). Soroker et al. (2005) reported that invasive *R. ferrugineus* infestations beginning in the 1980s in date plantations in Israel were controlled by a mass trapping program initiated in 1999 and ongoing through 2002. The program had 5000 baited (food + pheromone) traps (10/ha) covering >450 ha of date palms (≈70,000 trees of which 60 were infested). After 2002, no new infestations were reported.

The weevil *Rhynchophorus palmarum* (L.) is an important pest of palm species in tropical America and vectors the red ring nematode, *Bursaphelenchus cocophilus* (Cobb), disease (Oehlschlager et al. 2002). A trapping program over 30 ha from 1991 to 1993 used 243 traps baited with the aggregation pheromone 2-methyl-5(*E*)-hepten-4-ol and kairomone-releasing sugarcane (*Saccharum officinalis* L.) drenched in insecticide that killed >62,500 weevils (Oehlschlager et al. 1995). Mean catch per trap declined from 32.4 in the first 7 mo of trapping to 6.4 per trap in the latter 9 mo of trapping. The incidence of red ring nematode disease declined by ≈50% after 5 mo of trapping. In a similar program on a 8,700-ha plantation of oil palm near Quepos, Costa Rica, weevil-infested palms were removed from 1989 through 1992 in increasing numbers until the initiation of a mass trapping program that coincided with a dramatic decline in infested trees that approached very low densities in 2001 (Oehlschlager et al. 2002). In a 3,300-ha oil palm plantation in Honduras, mass trapping reduced weevil infested trees by 50% in 2 yr, 80% after 3 yr, and 94% after 5 yr. The current strategy for management of weevils in oil palm in tropical America is based on detecting and eliminating damaged kairomone-producing palms or weevil-infested palms and keeping weevil populations low by trapping with combined aggregation pheromone and food baits (Oehlschlager et al. 2002). These traps and baits also have been successful in reducing populations of both *R. palmarum* and the West Indian cane weevil, *Metamasius hemipterus hemipterus* (L.) (Alpizar et al. 2002).

Corn Rootworms. Several species of corn rootworms (Coleoptera: Chrysomelidae), especially the western corn rootworm, *Diabrotica virgifera virgifera* (LeConte), and northern corn rootworm, *Diabrotica barberi* (Smith & Lawrence), are serious pests of corn, *Zea mays* L., whereas the southern corn rootworm, *Diabrotica undecimpunctata howardi* (Barber), is the primary insect pest of peanut, *Arachis hypogaea* L. These and other *Diabrotica* spp. are attracted to several cucurbit flower and corn volatiles (Lampman and Metcalf 1988, Herbert et al. 1996, Hammack 2001). The female sex pheromone of western and northern corn rootworms, 8*R*-methyl-2*R*-decyl propanoate, also has been useful for monitoring (Ladd et al. 1985). A bait composed of powdered cucurbit containing feeding stimulants such as cucurbitacin and plant volatiles in a bran base infused with carbaryl insecticide was applied at 7–14 kg/ha in three 1–3-ha plots (Lance and Sutter 1992). The results showed that the numbers of *D. v. virgifera* and *D. barberi* on corn plants relative to untreated plots were reduced 77–85 and 55–92%, respectively, 48 h after applications. A large areawide treatment program covering 41.4 km^2 was undertaken in 1997 in Kansas by using a curcubit food bait and carbaryl insecticide (SLAM) compared with a control area of 10.3 km^2 (Wilde et al. 1998). Monitoring with Pherocon AM yellow sticky traps indicated areas with ≥35 rootworm adults per trap that required control treatments with SLAM (1177 ha required treatment in 1997). The SLAM applications resulted in ≥95% control (Wilde et al. 1998). The knowledge of *Diabrotica* semiochemicals and IPM developed in the USA was rapidly applied to the introduction of invasive *D. v. virgifera* into Serbia and surrounding countries (Edwards et al. 1999). The limited containment and control programs, however, did not seem to slow the spread of the western corn rootworm in Europe.

Fruit Flies. Control programs have been directed at three important fruit fly species (Diptera: Tephritidae) by using high numbers of semiochemical-baited traps. Steiner (1952) found that methyl eugenol is strongly attractive to male oriental fruit flies, *Bactrocera dorsalis* (Hendel), because the compound apparently serves as a precursor to the male's sex pheromone (Raghu et al. 2002). Traps, but usually pesticides, were combined with this lure to attract and kill a number of fruit fly species (Asquith and Kido 1994). The oriental fruit fly was eradicated from the Mariana Islands, the Amami Islands, the Okinawa Islands, and California with a combination of the lure and pesticides (Asquith and Kido 1994). Another program with the olive fruit fly, *Bactrocera* (*Dacus*) *oleae* (Gmelin), in southern Europe used sex pheromone components and food baits in traps to suppress populations so that on average four insecticide sprays were eliminated per season, and pesticide use per treatment was reduced by 99% (Haniotakis et al. 1986, Broumas and Haniotakis 1994). Large numbers of food/sex pheromone-baited traps have been used to monitor populations of Mediterranean fruit flies, *Ceratitis capitata* (Wiedemann), primarily to determine where the flies occurred, enabling better targeting of sterile male releases for control (Katsoyannos 1994, Enkerlin and Mumford 1997).

Application of Mass Trapping in Eradication of Invasive Species. Eradication can be defined as "the elimination of every single individual of a species from a geographical area that is sufficiently isolated to prevent recolonization" (Myers et al. 1998). Although the majority of mass trapping programs reported in the literature have been used for pest management, mass trapping has been integrated with other approaches in several eradication programs targeting lepidopteran, coleopteran, and dipteran species. Perhaps the most documented cases are the gypsy moth, the boll weevil, and fruit flies (Knipling 1983, Koyama et al. 1984, Douce et al. 1994).

Case Studies

Gypsy Moth. The gypsy moth, *Lymantria dispar* (L.), has been the target of an eradication campaign in the United States for many years. At a national level, and using the above-mentioned definition, the overall eradication of gypsy moth has not been achieved (Myers et al. 1998, Sharov et al. 1998). There have been "local eradications" only. This has led to changes in the objectives of the campaign, toward a "slow-the-spread" philosophy (Sharov et al. 1998). Human transport of gypsy moths (females and egg masses) is recognized as a major method of dispersal, and this probably interferes with the effectiveness of mass trapping on nonisolated sites. Moreover, male catch could be indicating population fronts of males only, rather than breeding populations, because females are flightless. In the analysis of the application of mass trapping in the gypsy moth, it must be acknowledged that, because it is impossible to have untreated "controls" in eradication programs, it cannot be stated scientifically that mass trapping is the cause of a population's disappearance (Dreistadt and Dahlsten 1989). Interpretation leading to such a conclusion has to be based on an accumulation of data from many repeated experiences whose combined circumstantial evidence is at least convincing, or better still, overwhelming. In practice, rather than absolute eradication, the gypsy moth "local" eradication criteria are typically "three years of no additional captures" (Horn 2003) of males in traps after treatment, or "one negative survey when using chemical insecticides or two negative surveys when using other technology (not including the season of treatment)" (Dreistadt and Dahlsten 1989). According to Dreistadt and Dahlsten (1989), these latter criteria were met in 30 locations where gypsy moth was sprayed with *Bacillus thuringiensis* (Bt) (some followed by mass trapping) at that time, notably in Oregon. Reports from the southeastern United States on mass trapping in Georgia and North Carolina (Douce et al. 1994) indicate that mass trapping has long been an acknowledged component of gypsy moth eradication or management (Dreistadt and Dahlsten 1989, Douce et al. 1994). The mass trapping was always used in combination with other treatments such as the bacterial insecticide, Bt. The use of Bt replaced the insecticide carbaryl, and Dreistadt and Dahlsten (1989) suggested that mass trapping was added to Bt to compensate for its lower efficacy in killing larvae compared with carbaryl. Mass trapping was recommended as part of the eradication of incipient (low) and isolated gypsy moth populations (Beroza and Knipling 1972, Dreistadt and Dahlsten 1989, Douce et al. 1994). In this role, mass trapping made a useful and sometimes major contribution with other control methods such as Bt to the eradication of small isolated gypsy moth populations (Appelt 1985). However, mass trapping was not part of a successful gypsy moth management program in Washington, D.C., which included an alternative pheromone treatment, namely, mating disruption (Favre et al. 1993). In California, the role of mass trapping has sometimes been unclear because the sprays of carbaryl and Bt seem to have been effective against such populations before mass trapping was initiated (Brown et al. 1984, Dreistadt and Dahlsten 1989). The preferred technology now is the use of mating disruption (Reardon et al. 1998).

Boll Weevil. The boll weevil, *Anthonomus grandis grandis* (Boheman), entered the United States from Mexico in 1892 and soon afterward caused serious economic damage to cotton, *Gossypium hirsutum* L. (Ridgway et al. 1990, Smith 1998). Insecticides such as DDT became prevalent after 1945 and controlled the boll weevil until it became resistant to all chlorinated hydrocarbon insecticides by 1960. Eradication of the boll weevil from the U.S. southwest was accomplished by a combination of cultural control, pheromone trapping, and insecticide application indicated by the pheromone trap catches. Cultural control was important in Arizona by eliminating "stubb" perennial cotton and plowing under the annual crop so there were few places in the surrounding desert that weevils could overwinter. In the south, cotton is grown year-round, and there are numerous areas to overwinter.

As early as 1902, unsuccessful attempts were made to trap boll weevils with cottonseed meal and molasses (Hardee 1982). Sticky traps were used to intercept flying weevils for 45 yr to study dispersal; and cotton extract, attractive in the laboratory, was shown to be unattractive in the field (Hardee 1982). Mass trapping boll weevils began in 1968 and indicated that low-density populations could be reduced further, but the probability of successes declined as population density increased (Hardee 1982, Ridgway et al. 1990). At the highest density of traps (14 traps per ha), it was estimated that 92% of the nonoutbreak population of emerging weevils could be trapped. Mitchell et al. (1976) determined that baited pheromone traps at 10 traps per acre captured 76% of the overwintering weevils and ≈96% of the late-emerging population. Lloyd et al. (1981) reported that three to four traps per acre captured 80–90% of the females. Knipling (1979), using population models with expected capture rates, suggested that populations could be suppressed to very low levels with as few as 10 traps per hectare. In eradication efforts throughout the cotton regions, pheromone traps were used to reduce populations, but more importantly to monitor levels and locations that then would be treated with organophosphate insecticides. This approach has proven effective in eradicating the boll weevil from most of its former domain, but complete eradication has been achieved only in the southwest (Smith 1998). It is clear that pheromone-baited trapping was complementary and necessary for reducing insecticide treatments.

Essential Knowledge for Successful Mass Trapping

Attractant Trap Competitiveness with Wild Females. Success with mass trapping is dependent on the use of lures that are competitive with natural sources of attraction (Mottus et al. 1996, Jones 1998). Care is needed in assessing the relative attractiveness of virgin females and pheromone blends in traps, because female calling is restricted to discrete daily periods, whereas synthetic pheromone is constantly released; thus, mean relative trap catches over longer periods may underestimate female attractiveness during calling. Synthetic components of the natural pheromone blend can be highly competitive with a calling female, but baits with less than all components are usually inadequate (El-Sayed and Trimble 2002a, El-Sayed 2006). For example, Yamanaka et al. (2001a) found a three-component pheromone blend to be as effective as using five components for the fall webworm, *Hyphantria cunea* (Drury). Senft (1991) reported how an unnatural blend of two pheromone components provided a more attractive blend than the natural pheromone for adult male pink bollworms. This may have been due to the races of the target insect that have different pheromone component blends and in these circumstances, mass trapping may fail unless research is done to ensure competitiveness with the local population.

Byers (1987) found that western pine bark beetles were less attracted to synergistic pheromone components when these components became separated in space and developed a model to explain the phenomenon. Byers (1987) suggested release of the individual components from a mosaic mixture of sources could be more disruptive of olfactory communication than use of full blends. However, few if any studies have tested this hypothesis of sensory imbalance; rather, the most complete blend available has usually been used in traps or other point sources for disruption.

Dose (release rate) also needs to be investigated, along with blend components, both as a means of improving relative attractiveness and to ensure that the target insects move into the trap where they are caught. Lower than optimal dosages will form shorter plumes of active space resulting in fewer attracted insects, whereas a higher than optimal dose may cause arrestment at a concentration corresponding to the natural dose at the source but at a distance too far from the trap. High lure loadings or point source densities could even cause some orientation disruption (Suckling and Brockerhoff 1999), although the total suppression effect may not be reduced.

The effective attraction radius (EAR) is a method for assessing the relative catching ability of various lure dosages and blends as well as trap efficiency (Byers et al. 1989). The EAR essentially determines the ratio of catch of a trap with lure to a passive trap without lure at the same insect population density (traps are close to each other but do not interact appreciably). Once an EAR is measured for a particular blend/dosage/trap, the value serves as a comparative index of attraction to other such trap–blend combinations regardless of different population densities existing during measurements. Another method for optimizing pheromone blends, dosages, and trap designs is the direct observation of the responding insect's behavior (Mottus et al. 1996) at various distances from the traps. An understanding of the longevity of the competitiveness of the pheromone dispenser in the field is also essential to determine when it should be replaced. This depends on dispenser technology regarding compound release rate and stability, but it is sometimes as infrequent as annually (e.g., Faccioli et al. 1993). Traps baited with virgin insects or natural extracts releasing pheromone have been used for research purposes, such as determining the relative attractiveness of synthetic pheromone traps (Howell 1980), but they have not been used for mass trapping.

One of the major advantages of pheromone-baited traps is that they release pheromone continuously, whereas females do so only during restricted periods as synchronized by circadian rhythms (e.g., El-Sayed and Trimble 2002b). Male moths are often active before females, both on a daily and seasonal basis (e.g., Hagley 1978), thus enabling traps to intercept males before female calling begins. The importance of visual cues for improving the attraction to traps and catch (e.g., Moraal et al. 1993) has been demonstrated for several species, e.g., *Ephestia cautella* (Walker) (Jones 1998) and currant borer, *Synanthedon tipuliformis* (Clerck) (Suckling et al. 2005), and should be considered when planning mass trapping trials.

Trap Designs and Density. Whereas some trap designs are useful for monitoring a wide range of lepidopteran pests, such as delta sticky traps and funnel traps, specific research is needed to optimize the trap design for mass trapping of a particular target species. Mass trapping for pest management has at times been tested against insect populations at high densities (Jones 1998), in which case the trap must have the capacity to catch large numbers of insects before becoming saturated (Huber et al. 1979, Reddy and Urs 1996). The literature indicates that mass trapping is most effective and useful at low pest density, particularly for eradication when only low trap catches would be expected and trap saturation is unlikely. Trap design must concentrate on ensuring that a large proportion of attracted insects are caught (Mottus et al. 1996). The benefits of this approach are well illustrated by the gypsy moth milk carton trap, by simple funnel traps placed over plastic bags (Teich et al. 1979, Patel et al. 1985), and by the Huber oil trap for pink bollworm (Huber and Hoffmann 1979, Huber et al. 1979). In regions with adequate rain, water traps can be effective and inexpensive (Byers 1993a).

Appropriate trap density and placement are also vitally important for effective mass trapping, e.g., dispenser placement in the trap and replacement, frequency of trap replacement, trap density and placement in the field, and trap color (especially for day-flying insects). Although highly effective lures and traps are important, success has been achieved only where the ratio of traps (in female equivalents) to wild females is sufficiently high. However, the high densities of traps required at high pest densities usually render the technique uneconomic (e.g., Roelofs et al. 1970). Trap densities that have achieved successful mass trapping of low density pests generally fall in the range of 10–40 traps per hectare. However, higher densities have sometimes been required (e.g., Sternlicht et al. 1990) and lower trap densities have been tested and sometimes seemed adequate (Pasqualini et al. 1997). It is important to know that the trap density selected for use is not causing partial and ineffective disruption instead of moth capture. This has happened in some programs (Yamanaka et al. 2001b, 2003), possibly because of using too high a trap density, and has been attributed to the males engaging in false trail following (i.e., repeatedly orienting upwind in different pheromone plumes without usually being captured) (Yamanaka et al. 2001b). Land use and topography could have an impact on plume structure and active space, especially with forest insects. Placement of traps in a few aggregations spaced widely over the treatment area would leave many areas unaffected and allow insects to find mates. A uniform distribution of traps seems intuitively the most effective use of resources. However, simulation models have shown that even placement of traps in a random distribution would catch about the same numbers as placement of the traps in a uniform grid (Byers 1993b).

Population Density of Target Pest. The literature shows that the population density of the target pest plays a key role in the success of mass trapping (Huber and Hoffmann 1979, Madsen and Carty 1979, Sternlicht et al. 1990, Emel'yanov and Bulyginskaya 1999). There are examples of research programs that have tested the technology against both high and low densities of the same pest [e.g., codling moth and redbanded leafroller, *Argyrotaenia velutinana* (Walker)], and this has confirmed earlier recognition (e.g., Roelofs et al. 1970) that mass trapping was likely to be effective only against low-density pest populations. This is attributed to the declining effects of competition for male moths between traps and wild females as pest density falls, rendering trapping inversely density dependent. Although aggregated distributions could play a role in mating even low-density populations are difficult to control. Although mass trapping of high-density pests has had some success (e.g., Mafra Neto and Habib 1996), there have more often been failures (e.g., Roelofs et al. 1970, Hagley 1978, Willson and Trammel 1980, Yamanaka et al. 2001a). In the context of eradication, an even higher level of trap efficacy is required than is necessary for satisfying pest managers content with reducing pest populations.

Isolation and Risk of Immigration. A recurrent theme in the literature on mass trapping is the importance of targeting isolated populations (e.g., Huber et al. 1979, Faccioli et al. 1993, Yamanaka et al. 2001a, Zhang et al. 2002). The pheromone traps of moths catch only males and the immigration of mated females is a constant threat if they are within flight range of the trapped area (e.g., Teich et al. 1979, Moraal et al. 1993). Immigration of males also often leads to high trap catches on the edges of the trial plots and may reduce the efficacy of mass trapping.

Biology and Ecology of Target Species. The literature has identified a number of features of the biology and ecology of pests that benefit or hinder mass trapping. Univoltinism is an advantage because only one generation of males has to be trapped per year (Sternlicht et al. 1990, Mottus et al. 1996, Emel'yanov and Bulyginskaya 1999, Zhang et al. 2002). This is linked to the potential rate of population increase (Madsen and Carty 1979); higher rates would reduce the effectiveness of mass trapping, and for some nondiapausing pests it is important to trap throughout the year (Teich et al. 1979, Sternlicht et al. 1990). At the other extreme are pests with long life cycles (Haniotakis et al. 1999) that may require long-duration monitoring and/or trapping to realize control or eradication; trapping may need to address extended diapause (Backhaus et al. 2002) with delayed adult emergence. Host range is another important pest characteristic that affects mass trapping. Monophagy is a major advantage (e.g., Sternlicht et al. 1990) that could limit trapping efforts to a particular plant species or crop; this also reduces the risk of immigration of mated females, because the host plant distribution is delineated in space. However, a wide host range presents difficulties in determining the pest distribution and may greatly increase the risk of immigration. This is also influenced by the mobility of the target pest as both adults (e.g., Moraal et al. 1993) and larvae (Beroza and Knipling 1972, Douce et al. 1994), with limited mobility (especially of mated females) being considered a significant advantage for successful mass trapping (Sternlicht et al. 1990). Protandry (emergence of males before females) is a common feature in the Lepidoptera (e.g., Hagley 1978) and in other insects, and this can be exploited by ensuring that traps are deployed before the onset of spring emergence. At this time, females will not have emerged, and pheromone traps will not incur any competition. Mating frequency of target males (e.g., Hagley 1978) and females (Howell 1980) is another factor influencing the success of mass trapping; a one-time mating by both sexes is the most advantageous.

Measuring Efficacy of Control

When instituting a mass trapping program, it is important to measure its efficacy and interpret the evidence of changes in population data. Mark–release–

recapture of males (Charmillot 1977, Baronio et al. 1992, Trematerra 1993, Reddy and Urs 1996) has often been used to measure the effectiveness of trapping, and recapture may vary from 10% (e.g., Baronio et al. 1992) to 100% (e.g., Reddy and Urs 1996), depending on such factors as trap density and the distance of releases from traps. Charmillot (1979) found that decreasing trap density resulted in a longer time to catch rather than a lower percentage of recapture, and this time increase could be critical for traps to compete with wild females; recapture rates are also temperature- and weather-dependent. These are some of the reasons why population data on the target pest or its damage also must be obtained to correctly determine the efficacy of mass trapping.

The most common method of measuring control efficacy is to monitor trap catches to determine whether they decline over time, thereby providing an indirect measure of insect removal (Faccioli et al. 1993, Moraal et al. 1993, Trematerra 1993, Mottus et al. 1996). This is sometimes accompanied by measurement of changes in the population sex ratio (e.g., Howell 1980), because mass trapping of male moths should cause a dramatic shift in favor of females. A more direct method of measuring efficacy would assess the mated status of trapped males but this has not been used in practice, as mating status of male moths is difficult to determine. Slightly less direct is measurement of the mating of tethered or caged females (Hagley 1978, Meng et al. 1985, Yamanaka et al. 2001a, Zhang et al. 2002), which assumes that the females used are equivalent in attractiveness to wild females. This method may be modified by determining the proportion of virgin females that attract males into traps (Yamanaka et al. 2001b) or by recording the level of infertility/fertility in wild egg masses within the trap zone (Patel et al. 1985).

Modeling of Mass Trapping

Pheromone-based technology has attracted considerable interest in modeling of its pest control potential. Modeling has provided insight into understanding the critical issues affecting efficacy of mass trapping, which can be compared with the practical experience of field practitioners. Many of the issues identified in this review as important for the success or failure of these control methods are suggested or confirmed by models. Modeling indicates that the efficiency of mass trapping increases as target population density decreases (i.e., inverse density dependence) (Beroza and Knipling 1972, Nakasuji and Fujita 1980, Barclay 1984, Barclay and Li 1991), making it an effective method in an integrated program of eradication. This is supported by models that show that low-density populations are much easier to annihilate (Barclay 1984, Byers 1993b), and some modelers recommend that high-density populations should be reduced to low density by some other means before using mass trapping (Beroza and Knipling 1972, Barclay 1984, Barclay and Li 1991). Simulation of mass trapping in confined areas indicates that the time required to catch all the insects in an area increases logarithmically with increases in initial target density (Byers 1993b). The catch rate decreases exponentially with time, but the time to catch the last remaining insects increases exponentially. Compared with mating disruption, low target density is shown to be even more important for successful mass trapping (Nakasuji and Fujita 1980). These models indicate that to achieve major population suppression, mass trapping must remove a very high proportion of males where the population is high, but this drops to a much lower proportion where the population is low (Nakasuji and Fujita 1980).

The ratio of traps/lures to wild females seems critical (Beroza and Knipling 1972, Nakamura and Oyama 1978), and trap–female competition has been shown in models to be a major factor contributing to the ineffectiveness of mass trapping in reducing high-density populations (Beroza and Knipling 1972, Nakasuji and Fujita 1980). It also must be remembered that, during trapping, the accumulation of unmated females means that the trap–virgin female ratio declines over time (Beroza and Knipling 1972) whereas the females remain sexually active. Similarly, a high relative attractancy of lures (versus females) has been shown to be important (Nakamura and Oyama 1978, Nakamura 1982).

Isolation of the treatment area, which fieldworkers consider so important for mass trapping, is also identified as a critical issue by modelers. Isolated populations are much easier to annihilate (Beroza and Knipling 1972, Barclay 1984), whereas immigration is a severe threat to eradication (Barclay and Li 1991) and the success of control treatments in general (Byers and Castle 2005). With respect to pheromone, trap design and placement, catch rate has been shown in models to improve with increasing range of the lures/traps and insect flight speed, and as mentioned above, a uniform or random trap distribution has little apparent effect on rate of catch (Byers 1993b).

The biological characteristics of the target species of mass trapping have not been modeled extensively. However, models indicate that the ease of control or eradication varies inversely with birth rate and survivorship (Beroza and Knipling 1972, Barclay 1984). Also, target species whose populations are density-dependent are easier to control (Barclay 1984, Fisher et al. 1985) than density-independent populations. Species whose males do not mate very frequently are more easily reduced (Barclay 1984) by mass trapping, and this is assisted if trapping also delays mating (Barclay 1984). Models confirm the practical experience that capture rates of males, or mating of tethered females, are not wholly reliable methods for assessing the effectiveness of mass trapping; this requires population assessment in the following generation, such as egg counts (Nakasuji and Fujita 1980). Nakasuji and Fujita (1980) considered the overall importance of the various factors affecting the efficiency of mass trapping. The most important was the need for low population density of the target pest, followed by trap design and related issues (i.e., blend, dosage, and trap

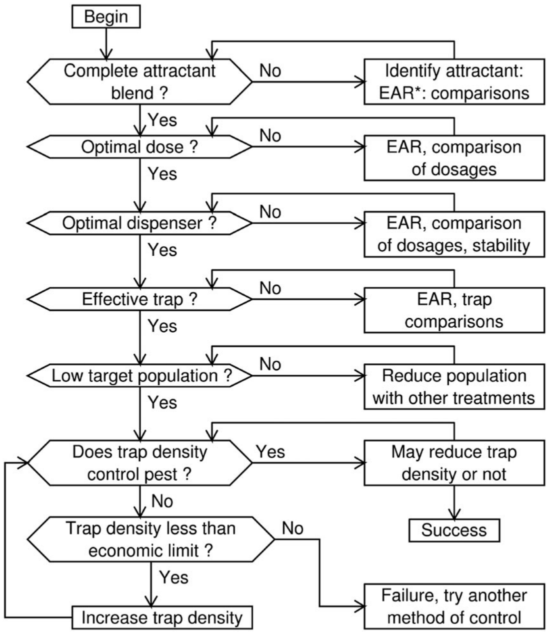

Fig. 3. Flow diagram of steps considered important in the development of a successful mass trapping program. The EAR* is key to many of the steps as the method can be used to optimize trap and lure parameters, such as pheromone components (full blend), dosage (release rate), dispenser design (longevity), and trap design (efficiency).

density). Fisher et al. (1985) introduced the concept of a critical minimum pheromone release rate required for eradication of a given species, below which only population reduction but not eradication could be achieved and above which mating disruption might occur.

Based on research and modeling with the fall webworm, Yamanaka et al. (2003) concluded that the reduction of mating through mass trapping of this species was possibly due to false trail following, with higher pheromone dose in the traps increasing male "clustering" around them but not increasing trap catch (i.e., increasing false trail following or adaptation). It is unclear how widely these conclusions can be applied to mass trapping of species that form aggregations, such as bark beetles, but it shows that merely attracting the insects into an area is insufficient, unless additional measures such as patch treatment with insecticides also are used (e.g., James et al. 2000).

Barclay and Li (1991) examined optimization of the cost of pest control where different methods were being combined. The optimum combination was found to change as population density changes. To minimize cost at high density, pest control methods that are positively density-dependent or density-independent, such as insecticides, should be used; at low density, the lowest costs would be achieved by using inversely density dependent methods, such as sterile insect release or mass trapping (also, lure and kill and mating disruption). Their models indicate that the combination of a density-independent insecticide, such as Bt, and inversely density-dependent mass trapping should be synergistic, and that it should be most cost-effective to switch from the insecticide to mass trapping at low population density.

Conclusions

This review of mass trapping has revealed that most studies encountered problems that detracted from the potential of mass trapping for control of insect pests. We have identified key factors that can contribute to success or failure of mass trapping. A flow diagram (Fig. 3) should aid in the development of mass trapping programs, because many studies lacked one or more critical components in the sequence of research toward final system delivery. Competitiveness of synthetic lures with wild females is a crucial factor in the success of mass trapping, and it is essential to optimize both blend composition and dose. Traps should have the capacity to capture large numbers and a high proportion of attracted insects, whereas trap density should be optimized to avoid any partial mating disruption or false trail following that might hinder trapping. Isolation and low population density of the target pest are other key factors for success of mass trapping. Biology of the target pest can be very important, because mass trapping is likely to be more efficient against univoltine, monophagous, and monogamous species compared with multivoltine, polyphagous, and polygamous species. Unfortunately, although mass trapping was the first approach to be conceived in semiochemicals-based pest management, the numbers of studies dealing with mass trapping are declining. We hope that our review will reverse this trend, increase awareness of its potential, and encourage further research into exploring and refining mass trapping for efficient and environmentally friendly pest control.

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