FORUM

Potential of "Lure and Kill" in Long-Term Pest Management and Eradication of Invasive Species

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ABSTRACT "Lure and kill" technology has been used for several decades in pest management and eradication of invasive species. In lure and kill, the insect pest attracted by a semiochemical lure is not "entrapped" at the source of the attractant as in mass trapping, but instead the insect is subjected to a killing agent, which eliminates affected individuals from the population after a short period. In past decades, a growing scientific literature has been published on this concept. This article provides the first review on the potential of lure and kill in long-term pest management and eradication of invasive species. We present a summary of lure and kill, either when used as a stand-alone control method or in combination with other methods. We discuss its efficacy in comparison with other control methods. Several case studies in which lure and kill has been used with the aims of long-term pest management (e.g., pink bollworm, Egyptian cotton leafworm, codling moth, apple maggot, biting flies, and bark beetles) or the eradication of invasive species (e.g., tephritid fruit flies and boll weevils) are provided. Subsequently, we identify essential knowledge required for successful lure and kill programs that include lure competitiveness with natural odor source; lure density; lure formulation and release rate; pest population density and risk of immigration; and biology and ecology of the target species. The risks associated with lure and kill, especially when used in the eradication programs, are highlighted. We comment on the cost-effectiveness of this technology and its strengths and weaknesses, and list key reasons for success and failure. We conclude that lure and kill can be highly effective in controlling small, low-density, isolated populations, and thus it has the potential to add value to long-term pest management. In the eradication of invasive species, lure and kill offers a major advantage in effectiveness by its being inverse density dependent and it provides some improvements in efficacy over related control methods. However, the inclusion of insecticides or sterilants in lure and kill formulations presents a major obstacle to public acceptance.

KEY WORDS lure and kill, attract and kill, attracticides, semiochemicals, pheromones

Reducing the quantity of insecticide applied in the environment is a major objective that drives research for the discovery of new behavior-modifying chemicals (semiochemicals) and for investigation of their potential in pest management and eradication of invasive species. Semiochemicals are being used in pest management either alone as in mass trapping or mating disruption (Cardé and Minks 1995, Suckling 2000, El-Sayed et al. 2006, Byers 2007) or in combination with insecticides, sterilants or insect pathogens termed "lure and kill" (or "lure and sterilize" and "lure and infect"). Lure and kill typically uses semiochemicals and insecticides in a concentrated area at the lure source to provide pest control. The insect responding to the semiochemical lure is not "entrapped" at the source of the attractant by adhesive, water, or other physical device as in mass trapping, but instead the insect is subjected to a killing or sterilizing agent, which effectively eliminates it from the population after a short time (Jones 1998). This tactic has been described in the literature with different nomenclatures, for example, lure and kill, attract and kill, male annihilation, bait sprays, and attracticide. In some cases, the boundaries between mass trapping and lure and kill are further blurred, such as when traps are insecticide treated. Success of the lure and kill approach in pest management depends on 1) insects contacting the insecticide either mixed with semiochemical or applied adjacent to the lure, 2) adequate dosing with the insecticide before leaving the lure, and 3) the level of mortality or adverse behavior-modifying effects that are eventually detrimental to the insect population. Usually, insects can be attracted to a point source either by chemical signals, visual cues, acoustic cues, or combination of any of these signals and cues.

Attractants used in lure and kill can be either crude baits or synthetic semiochemicals. Crude baits have been used extensively with crawling insects (e.g., ants

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and cockroaches), whereas semiochemicals-based lure and kill has been used mainly with flying insects (e.g., Lepidoptera, Diptera, and Coleoptera). This article focuses only on lure and kill that use semiochemicals, which include pheromones (e.g., sex pheromones), kairomones (e.g., host volatiles), attractants with a known behavioral function (e.g., host plant or oviposition odors), and attractants identified through the screening of candidate chemicals with poorly known behavioral functions (Beroza and Green 1963). Semiochemicals used in lure and kill should have several key attributes to be suitable: 1) the deployed lures releasing the odor plumes are perceived by nearly all adult males or females or both in the treated area, 2) the odor plumes are able to attract males or females or both more effectively than natural odor sources (e.g., virgin or mated females in the case of sex pheromone) within the treated area, 3) the lures entice these adult insects to make direct contact with an insecticidal (or sterilant) component where all or a very high percentage are subsequently killed (or sterilized), and 4) treatment is done from the time of first adult emergence to the time of last adult emergence in the treated area (this may be seasonal or continuous). As part of a pest management program, the effectiveness of lure and kill may not need to be optimal, provided the benefits of male and/or female removal result in damage reduction or crop yield increases that are greater than the cost of the treatment. In pest management, residual populations that remain after treatment can be tolerable if populations are kept under an "economic" threshold, but this is not the aim in pest eradication. Therefore, the key objective for success of this technology in an eradication program of invasive species is to lure and kill all adult insects in a specified area before they mate, disperse, and reproduce.

Considerable data have been accumulated in the scientific literature on the application of semiochemicals in pest management (El-Sayed 2008). In a recently published article, El-Sayed et al. (2006) provided a review on the potential of mass trapping in long-term pest management and eradication of invasive species. In the present article, we provide a complementary review on the potential of lure and kill approaches that use semiochemicals for these purposes. Reviewing the literature on lure and kill indicates this approach has been mainly used against agriculturally and medically important pests, and too a lesser extent against forestry pests. We provide an overview on the application of lure and kill in pest management, and eradication of invasive species supported by case studies, and we summarize the knowledge that is needed for successful lure and kill programs. We discuss different methodologies used to measure the efficacy and risks associated with this approach and highlight the critical issues affecting lure and kill efficacy based on published data.

Lure and Kill Formulation. Lure and kill technology is patentable, and this has resulted in commercial development (Antilla et al. 1996, Charmillot et al. 2000) accompanied by commercial trials, and marketing of a variety of formulations. Those products using droplets of paste or gel, applied by hand, are variously named Attract and Kill, Sirene, Appeal, and most recently GF-120 and SPLAT. The pheromone/semiochemical and insecticide are incorporated in a paste, gel, or wax at known concentrations during manufacture, and the user applies specified numbers of droplets per hectare directly from the commercial hand-held applicator. These formulations dominate the literature. There are also microencapsulated formulations (pheromone/semiochemical and insecticide) that are applied with a hand-held sprayer to provide a known number of lures per hectare. This method also can accommodate other formulations of the insecticide (e.g., emulsifiable concentrate). A third hand-applied lure and kill formulation uses plastic sheets containing the pheromone that are cut into individual lures; these are stapled to the substrate and then hand-sprayed with insecticide. The Ecogen No-mate hollow fibers (also called Attract and Kill) can be applied by air; the hollow fibers, containing the pheromone, are premixed with an adhesive containing the insecticide before application.

Lure and Kill as a Stand-Alone Control Method. In evaluating the results of various lure and kill programs, several were initially considered to cause substantial reductions in the target pest population or damage. These included some testing paste/gel products as stand-alone treatments against pests at low pest density (Suckling and Brockerhoff 1999, Charmillot et al. 2000, Ebbinghaus et al. 2001, Ioriatti and Angeli 2002), although more detailed analysis was needed to confirm the conclusions (see below). Lure and kill tests that resulted in much less reduction of pest numbers or damage (Charmillot et al. 1996, Trematerra et al. 1999, Angeli et al. 2000) were considered unlikely to be promising and may indicate methods or situations to avoid. Lure and kill programs that gave no evidence of population or damage reduction (Moraal et al. 1993, Downham et al. 1995) were considered most likely to provide information on the conditions under which lure and kill should not be attempted; in these cases, the authors themselves concluded that lure and kill was not suitable for control of the target pest (Moraal et al. 1993, Downham et al. 1995), although later technology improvements may change this view. In one case, the authors also concluded that lure and kill was too expensive (Moraal et al. 1993); however, in regard to invasive species with high potential economic impact, the cost–benefit equation may be quite different. Programs in which lure and kill alone was able to substantially reduce the target pest population were considered of particular interest for assisting in eradication of invasive species; they also provided a better indication of the effectiveness of the lure and kill technology without complex interactions with other control methods. A prime example is the application of "male annihilation" for tephritid fruit flies (Cunningham 1989) that are considered quarantine pests in many countries.

Lure and Kill in Combination with Other Approaches. There are few cases in which lure and kill technology has been used in combination with general application of insecticides (Hofer and Angst 1995, Antilla et al. 1996, Ioriatti and Angeli 2002). In two cases (Hofer and Angst 1995, Antilla et al. 1996), there were major benefits from the inclusion of lure and kill due to major damage reduction and/or reduced levels of insecticide sprays. In the third case, the use of insecticides was a confounding influence that complicated the interpretation of trial results (Ioriatti and Angeli 2002).

Comparison of Lure and Kill with Other Control Methods. Some authors compared lure and kill directly in their trials with other control methods, or they discussed such comparisons. For example, Charmillot et al. (2000) evaluated the efficacy of both mass trapping and lure and kill against codling moth and concluded that lure and kill was more effective, a view also held for other pests based on likely efficiency of male removal compared with traps (Suckling and Brockerhoff 1999). Lure and kill also was considered as effective as conventional applications of insecticides, or better, against cotton bollworm (Hofer and Angst 1995) and codling moth (Olszak and Pluciennik 1999). However, most comments were reserved for comparing lure and kill with mating disruption. It was especially noted that lure and kill was more effective than mating disruption on small, hilly sites (Hofer and Angst 1995, Ioriatti and Angeli 2002, Charmillot et al. 2000) and was less sensitive than mating disruption to problems caused by the shape and size of treated areas, by higher population densities, by the need for isolation, and by environmental factors such as wind (Charmillot et al. 2000). Some concluded simply that lure and kill was more effective, especially on high-density populations (Hofer and Angst 1995), and mating disruption was phased out of some trials (Antilla et al. 1996) in favor of lure and kill. The high cost of pheromone for mating disruption was also a concern (Ioriatti and Angeli 2002). All these factors are important in deciding the potential added value that lure and kill could bring to pest management and eradication of invasive species, compared with mating disruption or other approaches using semiochemicals.

Use of Lure and Kill in Long-Term Pest Management

Most of the lure and kill publications in the literature refer to the use of this technology as part of pest management programs. Although there were a few cases of lure and kill being used in combination with other treatments, notably insecticides, it was normally a stand-alone treatment. Both situations are of interest for determining its potential for long-term management. The use of lure and kill has become an integral part of an areawide integrated pest management (IPM) approach to long-term management of fruit flies by using semiochemical-based "bait sprays" and male annihilation (Vargas et al. 2003a,b; also see Tephritid Fruit Flies). Many of the examples in the case studies that follow are summarized in Table 1.

Case Studies. *Pink Bollworm.* The pink bollworm, *Pectinophora gossypiella* (Saunders), is a major economic pest of cotton, *Gossypium hirsutum* L., in all cotton-growing regions around the world. *P. gossypiella* was the first species of Lepidoptera to be investigated for the suitability of lure and kill to manage these pests (Hummel et al. 1973). Gossyplure [1:1 mixture of (Z,Z)-7,11-hexadecadienyl acetate and (Z,E)-7,11-hexadecadienyl acetate] is the pink bollworm sex pheromone that has been commercially used to control this moth since 1977 by mating disruption (Gaston et al. 1977). The success of mating disruption against pink bollworm encouraged researchers to investigate the addition of small amount of insecticides to kill male pink bollworm moths attracted to and contacting the pheromone sources (Butler and Las 1983, Beasley and Henneberry 1984). The first trials investigating the potential of lure and kill approach against pink bollworm were conducted in California and Arizona in the early 1980s (Butler and Las 1983, Beasley and Henneberry 1984). In these trials, gossyplure was applied aerially either as NoMate fibers or disruptant flakes at a rate of 1.85–2.77 g/ha with and without permethrin added. Assessment was carried out by monitoring male moth trap catch, and by crop damage (counting pink bollworm-infested flowers and infested bolls). Both NoMate fibers and disruptant flakes without the insecticide were highly effective in reducing male moth catches. However, the addition of permethrin to the disruptant flakes significantly improved the effectiveness of control. The results of these trials indicated that a lure and kill approach was feasible with pink bollworm. In 1987, the first patent that describes a device for lure and kill (Ecogen hollow fiber) was approved in the United States for management of pink bollworm (Conlee and Staten 1986). Subsequently, an areawide trial for control of pink bollworm program was conducted in Parker Valley, AZ, over 6 yr by using the Ecogen NoMate fibers combined with permethrin. Lure and kill densities varied, and the gossyplure dose ranged from 25 to 35 g/ha, with two to four applications per year. Assessment was achieved by larval counts in bolls. The authors concluded that the program provided excellent control of pink bollworm, which greatly reduced the damage and the need for sprays, and with very low residual populations (Beasley and Henneberry 1984).

Another trial investigating the potential of lure and kill approach for management of pink bollworm was conducted in Egypt in 1990 for two consecutive years (Hofer and Angst 1995). An isolated cotton field of 14 ha was treated with 7,000–8,000 lure and kill droplets of 50 μl each (i.e., 0.6 g of gossyplure and 25.5 g of cypermethrin per ha) that was applied four times per season. Assessment was achieved by larval counts in the bolls and crop yields. They concluded that the program resulted in reducing larval infestation and improving yields.

Table 1. Lure and kill: analysis of field trials

Target	Reference	Lure	Lure density	Lure dosage; insecticide dosage	Trial period	Result and conclusion
C. pomonella	Hofer and Brassel (1992)	Attract and Kill	6–8 × 100 μl drops per tree	0.8 g/ha; 33 g furathiocarb/ha/application	1 yr	Damage very low but significance unknown; "control" was a single highly infested tree nearby
	Ioriatti and Angeli (2002)	Sirene CM	1,100–2,000 × 57 mg drops per ha	0.10–0.18 g/ha; 4−7 g permethrin	2 yr	Control seemed similar to conventional insecticides but trials confounded by immigration, pseudoreplication, and spray interventions
	Ebbinghaus et al. (2001)	Appeal	2, 4, 6,000 × 100 μl drops per ha	Not stated	2 yr	Control at 4–6000 drops per ha equivalent to IGR spraying; very low residual pop
	Angeli et al. (2000)	Sirene CM	1,200–2,000 × 50 μl drops per ha	0.08–0.20 g/ha; 3–7.5 g permethrin/ha	3 yr	Control equivalent to conventional insecticide on isolated orchard with low density; less effective at higher density; residual pop remained
	Charmillot et al. (1996, 2000)	Sirene CM	1040–4140 × 50 or 100 μl drops per ha	0.08–0.43 g/ha 3–16.2 g permethrin/ha	3 yr	Good control where low initial pest density—at end, very low residual pop; poor control where high initial pest density
	Losel et al. (2000)	Castor oil based (Appeal?)	7,500 × 100 μl drops per ha	0.75 g 30 g cyβuthrin/ha	1 yr	Control equivalent to IGR insecticides and very low residual pop; used low density CM sites; lure drop density = 5 per tree
	Olszak and Pluciennik (1999)	Appeal	1–3 drops per tree	Not stated	1 yr	Control equal to or better than triflumuron; target CM density (untreated) caused damage of 5–6%
Paranthrene tabaniformis	Moraal et al. (1993)	Sticky ribbed tube + model female	30 ribbed tubes per ha	Cypermethrin	1 yr	Failed to reduce damage; probably due to immigration of mated females onto small plots from old heavily infested trees

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Table 1. Continued

Target	Reference	Lure	Lure density	Lure dosage; insecticide dosage	Trial period	Result and conclusion
P. gossypiella	Antilla et al. (1996)	NoMate fiber + permethrin	Various	25–37 g/ha	6 yr	Insecticides oversprayed; excellent control with greatly reduced sprays and damage, and very low residual pop
	Hofer and Brassel (1992)	Attract and Kill	5–600? × 50 µl drops per ha	0.6 g 25.5 g cypermethrin	1 yr	Damage one third of "control" plot (conventionally grown cotton)
	Hofer and Angst (1995)	Sirene	5,000 × 50 µl drops per ha	0.4 g 15.8 g cypermethrin	2 yr	Reduced larval infestation allowed delayed and reduced insecticide; commercialized 1994; better than insecticide programme (including yield)
S. littoralis	Downham et al. (1995)	MC (Micro-encapsulated) or PVC	500 spray points or PVC lures per ha	MC 0.5–2.5 g 0.95–1.9 g λ-cyhalothrin PVC 0.5 g 1.45 g λ-cyhalothrin	3 yr	Brief suppression of mating but no reduction of egg masses; not a viable control technique in these trials; high density target pest; partial mating disruption achieved rather than "lure and kill"
E. kuehniella	Trematerra (1995)	Laminar dispenser plus sign stimulus	One dispenser every 220–280 m^3	2 mg of sex pheromone plus 5 mg of cypermethrin	2–3 yr	Number of moths captured in treated mill was significantly lower than control mill; it was not possible to eliminate all infestation
Rhyacionia buoliana	Sukovata et al. (2004)	Rhvkil (ricinoleic acid plus petroleum oil)	1,000–2,000 droplets per ha	Each droplets is 0.05 g, contains 0.25% sex pheromone and 2% permethrin	3 yr	No significance difference in trap catch between treated and control plots; however, shoot damage was reduced significantly in treated plot
Rhagoletis pomonella	Bostanian and Racette (2001)	Red spheres, yellow boards with butyl hexanoate	Every 2–3 m along orchard periphery	6–12% cypermethrin or 1.3–1.7% deltamethrin	5 yr	Apple maggot activity less in Quebec so lure and kill a successful alternative to conventional insecticide use

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Table 1. Continued

Target	Reference	Lure	Lure density	Lure dosage; insecticide dosage	Trial period	Result and conclusion
Glossina spp.	Esterhuizen et al. (2006)	Blue and black cloth with acetone, 1-octen-3-ol, and 4-methylphenol	8–12 per km^2	Each station released 350 mg/h acetone, 5.7 mg/h 1-oceten-3-ol, 15.5 mg/h 4-methylphenol; cloth dipped in 0.8% deltamethrin	1–2 yr	99% reduction in females of *G. austeni* but only 85% reduction in *G. brevipalpis* due to its higher mobility
S. calcitrans	Meifert et al. (1978)	Williams traps placed between poultry manure and feeding cattle	1 station per 5 cattle (5 stations 10 m apart)	Live cattle odors; 2.5 g permethrin/m^2	8 d	Up to 90% reduction in stable fly pop after 8 d of treatments, about 30% of pop per day removed by stations
M. domestica	Chapman et al. (1998b)	White board with (Z)-9-tricosene mixed with sugar		2.5 g of 40% (Z)-9-tricosene/bait; organophosphate alfacron (10% azamethiphos)	Not stated	Pop not estimated but concluded that lure and kill with female fly pheromone is promising
D. frontalis	Coulson et al. (1973)	Frontalure induced natural pheromone and pine tree odors	6 per tree	2 mg frontalure in plastic vial caps; cacodylic acid (systemic arsenate)	4 mo	Insecticide-treated trees had significantly less brood
Dendroctonus brevicomis	Hall et al. (1982)	*exo*-Brevicomin, frontalin and myrcene (EFM)	420 baited and insecticide treated trees	2 mg/d each compound per tree; 1–4% chlorpyriphos and 1–4% carbaryl to point of runoff	1 yr	4% Chlorpyriphos and 4% carbaryl were effective in killing bark beetle and protecting ponderosa pines
Dendroctonus valens	Hall (1984)	Synthetic EFM induced attacks (pitch) of *D. brevicomis* attractive to *D. valens*	795 attractive trees treated with insecticides	2 mg/d EFM (as above); 1–4% chlorpyriphos and carbaryl as above, 1–4% fenitrothion, 0.1–0.4% permethrin	3 yr	Only 4% carbaryl or 4% fenitrothion caused significant reduction in attacks, applications in July more effective than in Sept.; treatments that protected pines from *D. brevicomis* did not work against *D. valens*
Ips typographus	Dedek et al. (1988)	Synthetic aggregation pheromone (*cis*-verbenol and methylbutenol)	2 per group of 4–6 trees, 15 groups	≈1 mg/d *cis*-verbenol and 50 mg/d methylbutenol); 2-mm-thick by 20-cm-wide ring of paste (15% methamidophos) on trunk (1 g/cm trunk diam)	3 mo	Bark beetle attacked treated trees equally to controls, indicating no repellent action of insecticide; no brood production in insecticide-treated trees; treatment of trees after windfalls also effective

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Table 1. Continued

Target	Reference	Lure	Lure density	Lure dosage; insecticide dosage	Trial period	Result and conclusion
	Drumont et al. (1992)	Pheroprax lure (*cis*-verbenol and methylbutenol)	1 per tree, 80 trees among 16 sites	About as above; 25 g of cyhalothrin/liter (12 ml/liter water/m^2 bark)	3 mo	Trap trees caught 4,600–16,800 beetles or 2.3–12.7 times a trap, equivalent to brood from 1 colonized tree
S. multistriatus	Lanier and Jones (1985)	Multilure (daily: 25 μg of 4-methyl-3-heptanol, 6 μg of α-multistritin, 50 μg of α-cubebene)	14 baited trees, 2 control	1 Multilure per tree; 27.4% cacodylic acid to runoff in axe frill on trunk, some cacodylic-treated sprayed with 0.5% chlorpyrifos	5 mo	Lure attracted beetles to treated and untreated trees but more attracted to treated; no. of beetles killed greatly increased by cacodylic-treated and insecticide sprayed with chlorpyrifos
P. scarabaeoides	Gonzales and Campos (1995)	2-(Chloroethyl)phosphonic acid treatment producing attractive ethylene	4–7 baited barrier trees next to insecticide-treated trees	12% Ethrel; 2.5% (wt:vol) lambda cyalothrine-A at 5.7 liters per tree	3 mo	Insect density in treated plots was 11–13% that of control plots after treatment but increased to 40–60% at end of exp 3 mo later
Bactrocera spp.	Cunningham and Suda (1986)	Methyleugenol	6 stations (1 station per 10 ha)	Unspecified amt of methyleugenol + 5% naled; 25 g of 25% malathion per station	4 mo	≥99% reduction of male flies, but only 48% reduction in fruit infestation, probably due to immigration of males that mated with females who were not caught
B. dorsalis	Steiner et al. (1965)	Methyl eugenol	125 sq miles over 33 sq miles	3% Naled	6 mo	Eradication of oriental fruit fly from Rota, Mariana islands
Bactrocera oleae	Broumas et al. (2002)	Ammonium bicarbonate Plus synthetic pheromone (1,7-dioxaspiro [5,5] undecane)	15,000–20,000 traps per 300 ha	Deltamethrin 15 mg (AI)/trap	4 yr	Lower trap captures and fruit infestation levels compared with standard bait sprays only in the field
B. cucurbitae	Cunningham and Steiner (1972)	Methyl eugenol plus naled	1,171 stations per 2 mile^2	0.9 oz 5% (wt:wt) solution of naled in cue-lure	77 d	99% reduction in male fly pop, long residual life of lure-poison
Ceratits capitata	Navarro-Lopis et al. (2008)	Biolure, EPAlure, Biolure 100, TMA Susbin, SEDQ, Trypack	6 traps per plot 4 plot = 24 traps	DSVP strip	90 d	Lures have similar efficacy over the 90-d test period; all lures were food-based attractants with varying formulations

Egyptian Cotton Leafworm. The Egyptian cotton leafworm, *Spodoptera littoralis* (Boisduval), is considered a key pest of cotton in the Nile delta of Egypt. Trials examining the potential of lure and kill approach to control *S. littoralis* were investigated over 3 yr in the late 1980s in upper Egypt (McVeigh and Bettany 1986, Downham et al. 1995). In these trials, 1 mg per lure of a binary mixture of the two pheromone compounds, (*Z,E*)-9,11-tetradecadienyl acetate and (*E,E*)-10,12-tetradecadienyl acetate, in a ratio 99:1, respectively, was used to lure male *S. littoralis.* Lure and kill was applied using two different formulations: sprayable microencapsulated formulation containing a mixture of sex pheromone and λ-cyhalothrin, or polyvinylchloride pheromone formulation stapled to the underside of cotton leaves with λ-cyhalothrin applied over it. Both formulations were distributed to give a density of 500 point sources per ha. Assessments of the effectiveness of lure and kill approach were made using tethered females, male catch, and egg mass counts. Although lure and kill caused a significant reduction in mating of the tethered females and trap catch, this was not corroborated with a reduction in egg masses compared with control plots. The results of these trials indicate that the efficacy of lure and kill seemed to be poor and short-lived for controlling Egyptian cotton leafworm. In the same trial, lure and kill was compared with mating disruption (also 500 point sources per ha), and similar degrees of mating suppression were obtained with both methods. Therefore, it was concluded that the mating suppression observed with lure and kill was due to disruption of mating communication rather than lethal contacts with insecticide incorporated into the pheromone sources. The failure of these preliminary lure and kill trials to provide adequate control of *S. littoralis* could be attributed to many factors, including a suboptimal pheromone blend used to attract males because females produce other minor compounds (Campion et al. 1980) that were not included in the lure. The release rate of the pheromone from the point sources was not measured in these trials, and it is known that optimum release rate can be very important to achieve false trail following to the point of contact with the source (i.e., effective attracticide). Also, the density of the attracticide sources employed in these trials could have been below that needed to provide adequate contacts with lure and kill formulations. Other factors that might have contributed to the failure of these trials could be the high density of the target pest and/or the partial but incomplete mating disruption achieved by pheromone sources rather than lure and kill. Since these preliminary trials, no attempts have been made to improve the efficacy of lure and kill approaches to control *S. littoralis.* In spite of these disappointing results, the potential of the lure and kill approach against this important pest has not been fully explored as yet, because much basic information including blend composition, optimum release rate, optimum lure density, formulation persistence, mortality from insecticide, and sublethal effects on behavior and reproduction, is still lacking.

Codling Moth. The success of lure and kill against several lepidopterous pests encouraged researchers to try this approach against the codling moth, *Cydia pomonella* (L.) (Charmillot et al. 2000, Ebbinghaus et al. 2001). In general, most of the lure and kill trials gave control that was similar to/or better than treatment with insecticides or insect growth regulators (IGRs) (Olszak and Pluciennik 1999, Angeli et al. 2000, Losel et al. 2000), whereas in a few trials lure and kill did not provided an acceptable control level (Hofer and Brassel 1992). In all these trials, only the primary sex pheromone compound of codling moth [(*E,E*)-8,10-dodecadienol] was combined with various insecticides (i.e., furathiocarb, permethrin, cypermethrin, and cyfluthrin) in various formulations (Charmillot et al. 2000, Ebbinghaus et al. 2001).

In a 3-yr trial conducted in an apple (*Malus* spp.) orchard in Switzerland between 1995 and 1997 (Charmillot et al. 1996, 2000), a gel formulation that contained 0.16% codlemone and 6% permethrin was applied at densities of 1,000–4,000 droplets per ha, which corresponded to 0.08–0.43 g of codlemone and 3–16.2 g of permethrin per ha. The droplets were applied two times per season with 5–7-wk intervals, and success was assessed by female mating and counting fruit damage caused by codling moth. This trial achieved good control in areas where low initial pest density was recorded, and poor control in a plot with high initial pest density. A small lure and kill trial using a similar formulation was conducted in the southern Okanagan valley, British Columbia, to investigate the response of male codling moth to lure and kill formulations (Krupke et al. 2002). The number of droplets per hectare is an important factor that determined the success of this technology against codling moth in these trials because a higher droplet density resulted in a higher frequency of males contacting the lure and kill formulation. However, another important factor is a high ratio of the lure and kill droplets to calling females so that males are more likely to contact the droplets than females. It was found that male codling moth exhibited autotomy of thoracic legs when exposed to sublethal doses of insecticides which impaired their ability to mate. However, some male codling moths were caught in traps baited with calling females, indicating that these males were able to locate and fly toward calling females in the treated plot. This might be due to either males locating a calling female due to suboptimal attractiveness of the droplets under field conditions, or that males flew to the lure and kill droplets but they did not actually contact the droplets.

Another trial that used a caster oil-based formulation containing 0.1% codlemone and 4% cyfluthrin was conducted in apple orchards in Poland between 1998 and 1999 (Ebbinghaus et al. 2001). The lure and kill droplets were applied as 100-μl droplets at densities of 2,000, 4,000, and 6000 droplets per ha. The droplets were applied two times per season with 6-wk intervals, and the success of the trial was assessed by counting fruit damage caused by codling moth larvae. It was concluded that the lure and kill approach provided a good control at densities of 4,000–6,000 droplets per ha, which was equivalent to control by spraying with IGRs (Ebbinghaus et al. 2001). In a subsequent study by the same group, it was determined that the spatial distribution of the lure and kill formulation was an important factor for effective control, and the vertical position of the droplets was more important than the horizontal position because male codling moths are predominately active in upper parts of the tree crowns. Environmental degradation of the formulation also can lead to reduction of the attractiveness of the pheromone and the knockdown effect of insecticides. The population density of codling moth also is an important factor in determining the success of the lure and kill against codling moth, and the approach is more effective at low population density than at high population density. The population density interacts with the density of the droplets per ha in determining the efficacy of lure and kill against codling moth, with more than three droplets/tree required for efficient control.

Stored-Product Moths. Lure and kill approaches have been tested for control of stored-products pests, mainly the Mediterranean flour moth, *Ephestia kuehniella* (Zeller), and the Indianmeal moth, *Plodia interpunctella* (Hübner), in flour mills and warehouses. Trematerra and Capizzi (1991) investigated the potential of the lure and kill approach against *E. kuehniella.* They used laminar pheromone dispensers baited with 2 mg of the sex pheromone [(*Z,E*)-9,12-tetradecadienyl acetate and (*Z,E*)-9,12-tetradecadienol in 6:1 ratio] and 5 mg of cypermethrin at a density of one dispenser every 220–280 m^3. Under these circumstances lure and kill was effective in maintaining the population level of *E. kuehniella* in the flour mill below the economic threshold. Trematerra and Capizzi (1991) demonstrated the importance of visual stimuli in increasing the efficacy of the lure and kill formulation against *E. kuehniella* when higher numbers of males were attracted to silhouette subtriangular forms resembling the female of this species. Another trial investigating the potential of lure and kill to control *E. kuehniella* was conducted in Italy for two consecutive years (1992–1993) in a 16,000-m^3 flour mill. In this trial, 5 mg of cypermethrin was applied to laminated dispensers containing 2 mg of the sex pheromone that released 13 μg of sex pheromone per day. Assessment was achieved by recording number of adult males caught in pheromone baited funnel traps. The lure and kill formulations were combined with a visual stimulus to form a "sign stimulus." A similar flour mill in the same area was used as control. The presence of lure and kill formulations led to a significant reduction in the number of males caught in pheromone-baited traps throughout the mill and caused a significant decrease in the *E. kuehniella* population. The authors highlighted the need to control outdoor populations to manage the risk of immigration and thus reinfestation. A recent study aimed at investigating the potential of lure and kill to control a similar species, the Indianmeal moth, in small warehouse rooms indicates that this approach is effective only when the population level was low (Nansen and Phillips 2004).

Apple Maggot. Lure and kill is a promising method to control the apple maggot, *Rhagoletis pomonella* (Walsh), in eastern United States and Quebec, Canada. Fein et al. (1982) identified apple volatiles attractive to apple maggot flies (Reissig et al. 1982, 1985). Yellow colors mimic apple foliage that is attractive to immature flies, whereas red attracts sexually mature flies that mate and oviposit on mature apples (Bostanian and Racette 2001). Odor-baited red spheres (representing apples) coated with adhesive have been used for apple maggot control in IPM (Prokopy et al. 1990). Red spheres mimicking apples were coated with sucrose solutions or filled with sucrose and gelatinized corn flour and insecticide that killed any attracted flies (Hu et al. 2000). Yellow boards and red spheres were sprayed with cypermethrin and deltamethrin in kerosene with butyl hexanoate at 2–3-m intervals along the periphery of an apple orchard to reduce fly infestations (Bostanian and Racette 2001). For the treatment to be considered effective with a high percentage of uninjured fruit, no more than 13 flies should be caught per four traps baited as above on the plot periphery, which was 1.6 times the action threshold.

Biting Flies. The treatment of large tracts of land with insecticide to reduce insect vectors of disease has many potential problems. Among them are high costs, chemical resistance, nontarget insect mortality, and a lack of public acceptance of widespread sprayings (Day and Sjogren 1994). Dipteran vectors such as mosquitoes and biting flies are often attracted to carbon dioxide, lactic acid, and octenol, associated with vertebrate hosts, as well as various ovipositional stimulants (DeFoliart and Morris 1967, Acree et al. 1968, Gillies 1980, Adeyeye and Butler 1991, Kline et al. 1991).

The density of trapping stations is critical to successful control. Removal trapping of the tsetse fly, *Glossina* spp., populations that vector trypanosomiasis (sleeping sickness) was done in West Africa in the early 1940s (Morris and Morris 1949). It was observed that baited traps could reduce local populations by up to 70% but had little effect on overall populations in the region. Small numbers of baited traps (five to seven traps per acre) had little effect until the density reached ≈20 traps per acre when successful control was achieved. Biconical traps impregnated with 400 mg of deltamethrin and spaced at 300-m intervals over a large area caused a 96.6% reduction in *Glossina palpalis* (Robineau-Desvoidy) populations and interrupted their breeding cycle (Küpper et al. 1985). However, the baited traps with insecticide were ahead of their time and phased out in the 1950s, being replaced by larger scale insecticide treatments. In 1978, use of baited traps with insecticide was rediscovered (Vale et al. 1985, Laveissiere 1988, Day and Sjogren 1994). Recently, Esterhuizen et al. (2006) treated a 35-km^2 area in Zululand, South Africa, with eight to 12 lure and kill stations per km^2. Cloth targets were made of blue and black cloth dipped in 0.8% deltamethrin and baited with acetone (350 mg/ha), 1-octene-3-ol (5.7 mg/h), and 4-methylphenol (15.5 mg/h). They reported a 99% reduction in *G. austeni* Newstead females after 13 mo of treatment and up to 85% for *G. brevipalpis* Newstead. It was concluded that the *G. brevipalpis* were less affected by the program due to their higher flight mobility.

The stable fly, *Stomoxys calcitrans* (L.), is easily disturbed and flies often between vertebrate hosts while feeding, thus transmitting equine infections such as anemia, anthrax, and trypanosomes (Day and Sjogren 1994). The Williams trap (Williams 1973) was used by Rugg (1982) to reduce populations of *S. calcitrans* at the Taronga Zoo in Sydney, Australia, by 79% after only 7.5 d of trapping. When Williams traps contained a pyrethroid compound, permethrin (2.5 g/m^2), and they were placed between the fly source (poultry manure from a poultry house) and the "lure" of cattle feeding nearby, populations were reduced even more, by up to 90% in a week (Meifert et al. 1978). They calculated that 30% of the adults were removed each day when one station per five domestic animals was used.

The house fly, *Musca domestica* L., although it does not bite, has been involved in the spread of numerous diseases including salmonella, diphtheria, tuberculosis, hepatitis, and amoebic dysentery (Hanley et al. 2004). High populations of house fly are associated with livestock feeding lots and garbage landfill sites where up to 1,500 flies can be produced per m^2 of landfill waste. Commonly, synthetic insecticides are sprayed at the site to control house flies, but this can pose a health risk and is not very effective due to multiple insecticide resistance (Chapman et al. 1993). Target sites baited with house fly sex pheromone (Z)-9-tricosene mixed with sugar and insecticide were used to reduce house fly outbreaks at poultry units (Chapman et al. 1998a, 1998b). The advantages are reduced exposure of humans to insecticide and less potential for insecticide resistance due to ingestion compared with cuticular contact. In these studies, males are primarily attracted and killed, so improved baits for females would likely enhance the success of such programs.

Bark Beetles. "Trap trees" have been felled in European forests for several centuries to concentrate the attracted bark beetles in an attempt to lower their populations and spare desired standing trees from attack (Bakke and Riege 1982). In the wide sense, trap trees lure and kill beetles attracted to the natural odors of the dying trees and pheromones of attacking insects (Byers 2004), until the trees are removed by the forester. Thus, it was a logical step to treat these trap trees with insecticide or to bait a healthy tree with bark beetle pheromone to create a trap tree that also could be treated with insecticide. In United States, Coulson et al. (1973) used a synthetic aggregation pheromone mixture (Frontalure) to attract southern pine beetles, *Dendroctonus frontalis* Zimmermann, to cacodylic acid poisoned pines. Hall et al. (1982) sprayed 420 ponderosa pines, *Pinus ponderosa* Dougl., with the insecticides carbaryl or chloropyrifos and then baited with western pine beetle, *Dendroctonus brevicomis* LeConte, synthetic pheromone components. All but one tree received arriving beetles that bored through the bark, but most were eventually overcome by the insecticide and the trees survived. However, more predators, *Temnochila chlorodia* (Mannerheim), attracted to the lure were killed by the insecticides than in baited control trees. In a similar test, Hall (1984) first baited ponderosa pines with *D. brevicomis* pheromone components to induce resinous attacks that then caused attraction of the red turpentine beetle, *Dendroctonus valens* LeConte, but if these trees had been sprayed with several insecticides (carbaryl, chloropyriphos, fenitrothion, and permethrin), the trees were protected from colonization by *D. valens.* Lanier and Jones (1985) used trap trees of American elm baited with *Scolytus multistriatus* (Marsham) synthetic pheromone (Multilure) to attract these beetles that vector Dutch elm disease. Some of the trees were sprayed with chlorpyrifos that killed arriving beetles and prevented the elms from being colonized.

In Europe, Norway spruce trees baited with synthetic pheromone components of the bark beetle *Ips typographus* (L.) (*cis*-verbenol and 2-methyl-3-buten-2-ol) were treated with a band of ^{32}P-labelled methamidophos insecticide that penetrated the ascending sap as a systemic that did not prevent beetle entry of the tree but significantly inhibited brood production (Dedek and Pape 1988, Dedek et al. 1988). Trap trees baited with *I. typographus* pheromone and treated with pyrethroid insecticide (cyhalothrin) killed attacking beetles of *I. typographus* (Drumont et al. 1992). The pyrethroid insecticides also were recommended for control of the ambrosia beetle *Trypodendron lineatum* (Olivier) that enters the sapwood. They estimated that a lure on a trap tree attracts and kills up to 14 times more beetles than a lure in a trap alone, or almost as many beetles as is produced by a colonized tree (2,300–17,000 beetles). Olive trees when treated by 2-(chloroethyl)phosphonic acid release a primary attractant, ethylene, that attracts the olive beetle, *Phloeotribus scarabaeoides* (Bernard), and when combined with insecticide lambda cyalothrine-A sprays, caused a significant reduction in attack density and population level in the treated area (Gonzalez and Campos 1995). Pena et al. (1998) also released ethylene from dispensers placed on olive logs to attract *P. scarabaeoides* where they were killed by cypermethrin, resulting in no colonization.

Use of Lure and Kill in Eradication of Invasive Species

Despite the use of lure and kill in eradication efforts with orders such as Diptera and Coleoptera, no evidence could be found that lure and kill has been used for pest eradication or even as part of an eradication program for any lepidopterous pest. This is probably because the technology is relatively new against moth pests. However, it should not be assumed that lure and kill is unsuitable for use in moth eradication. The practice of lure and kill has been used for many years in eradication programs against other pests, the most important being for containment or eradication of fruit flies. This programs demonstrate the validity of the application principles potentially to eradicate lepidopteran pests.

Case Studies. *Tephritid Fruit Flies.* Case studies on the tephritid fruit flies are an interesting contrast to those reported for other species. Due to their stature as key regulatory pests and the inability to determine infestation easily (larvae are internal feeders), tephritid fruit flies have garnered the attention of agricultural states such as California, Florida, and Texas in the United States and countries such as New Zealand and Japan where the flies are not established. Efforts to eradicate fruit flies have largely overshadowed methods for their control and only recently has IPM been developed to replace insecticide cover sprays used for decades to control these pests. Successful eradication of fruit flies has followed the development of attractants for use in detection and delimitation, as well as the lure and kill concept discussed herein. Froggatt (1909) suggested that male fruit flies could be "annihilated" by attraction to kerosene, whereas in 1912 Howlett (1915) showed that citronella oil (which contains methyl eugenol), was attractive to tephritid flies, probably mainly *Bactrocera dorsalis* (Hendel), the oriental fruit fly (Bateman et al. 1966a). In 1931, traps baited with kerosene were used in a program to control fruit flies, and in 1935 terpinyl acetate was used to attempt control of another fruit fly, *Ceratitis* (=*Pterandrus*) *rosa* Karsch (Karsch), in South Africa. This was followed by the use of proteinaceous food baits (Gow 1954) in the United States and other parts of the world, which were the basis for the protein bait sprays developed 50 yr later with GF-120 (Prokopy et al. 2003, Mangan et al. 2006). Food odor attractants including proteinaceous "bait" have been used extensively for fruit fly control (Jang and Light 1996). Various members of the family Tephritidae, which includes the genera *Bactrocera, Anastrepha, Rhagoletis,* and *Ceratitis,* are attracted to odors from hyrolyzed protein baits. The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), was suppressed by hydrolyzed protein baits mixed with malathion, phloxine B, or spinosad (Peck and McQuate 2000; Vargas et al. 2003a, 2003b). Katsoyannos and Papadopoulos (2004) found that yellow plastic spheres baited with food attractants ammonium acetate, putrescine, and trimethylamine captured *C. capitata,* in this case more females were attracted. In Pakistan, simple wooden blocks soaked with insecticide and lure attracted and killed >4 times more male fruit flies (*B. dorsalis*) than any commercial traps, and which were also more expensive (Stonehouse et al. 2002).

A unique lure and kill technology termed male annihilation or MAT was developed for fruit flies in the genus *Bactrocera* by using a natural product methyl eugenol (4-allyl-1,2-diemethoxybenzenecarboxylate) (Cunningham and Suda 1986, Cunningham 1989). This chemical was so attractive to male fruit flies that it was used to eradicate new infestations in many parts of the world including Rota (oriental fruit fly; Steiner et al. 1965), Japan (melon fly; Kuba et al. 1996), Australia (papaya fruit fly, *Bactrocera papayae* Drew & Hancock; Cantrell et al. 2002) and on numerous occasions against oriental fruit fly in California. Another compound called cuelure [4-(*p*-acetoxyphenyl)-2-butanone)], developed by Beroza et al. (1960) was found to be attractive to males of the *Bactrocera* complex as well but is not able to eradicate fruit flies as a stand-alone technology. Beroza et al. (1960) tried analogs of a known male lure, anisylacetone, and found several para-substituted derivatives of 4-phenylbutanone were attractive to melon flies, *Bactrocera* (=*Dacus*) *cucurbitae* (Coquillett). Cunningham and Steiner (1972) used cue-lure soaked on fiberboard blocks and released 9,000 male *B. cucurbitae* that had been dyed different colors in the treated and untreated areas. They found that 96% fewer flies were recaptured in the treated plot despite its having more baited traps, whereas marked flies were recaptured up to 3 mo after being released in the check plot only. Cue-lure was the most active compound for *B. cucurbitae* and a range of other species in the genus and was used with an insecticide to destroy ≈50% of male Queensland fruit fly, *Bactrocera tryoni* (Frogatt), in a town in Australia (Bateman et al. 1966a). However, they concluded that although the insecticide killed all flies that came to the lure, a stronger lure was needed, or a higher density of trap stations. In a larger test, protein baits with insecticide, attractive to both male and female Queensland fruit fly, were compared with male lures with insecticide and the combination in several towns in Australia. Bateman et al. (1966b) found that sometimes the protein baits were effective but that combination baits (protein + insecticides) were the most effective in preventing fruit infestation.

Several attractants have been identified to attract male Mediterranean fruit flies, including trimedlure and ceralure (Jang and Light 1996; Jang et al. 2001, 2003, 2005). However, these have not been found to be attractive enough or tested sufficiently as a standalone control technology and currently must be used with other techniques such as the sterile insect technique. Navarro-Llopis et al. (2008) evaluated several trap–food–lure combinations for attract and kill of Mediterranean fruit fly and found specific traps and lures potentially useful for areawide control of this pest in Spain. California currently uses a combination of bait sprays, and sterile insects as the primary methods to eradicate introductions of Mediterranean fruit fly (CDFA 1999).

One concern is that nontarget and beneficial insects can be attracted to the baits and killed by insecticides. Michaud (2003) tested two fruit fly bait/insecticides, Nu-Lure/malathion and GF-120/spinosad for their toxicity to coccinellid, lacewing, and flower bug species. Coccinellids [*Olla v-nigrum* (Mulsant) and *Scymnus* spp.] and the insidious flower bug, *Orius insidiosus* (Say), did not succumb to Nu-Lure/malathion. However, Nu-Lure was attractive to some syrphid flies that were then killed. Both Nu-Lure and GF-120 caused mortality of two parasitoid wasps. In another study, Uchida et al. (2003, 2007) baited traps with cue-lure and methyl eugenol and found many insect species were attracted, although most of the attraction of nontarget insects may have been to odors of decaying insects in the traps.

Olive fruit flies, *Bactrocera oleae* (Gmelin), are of great economic importance in the Mediterranean regions of Europe, and as such, attempts to control olive fly have been well reported in the literature. Like other *Bactrocera,* early control measures used wide spectrum organophosphate insecticides as cover sprays, which in many cases resulted in serious effects on the nontarget fauna (Feron and D'Aquilar 1962). Later, attractive proteinaceous baits were developed with insecticides as early "attract and kill" formulations (Orphanidis et al. 1958). The identification of the olive fly pheromone led to tests of pheromone and food attractant combinations with various toxicants (Broumas et al. 1985, Haniotakis et al. 1986) Olive fly was controlled by Ecotraps (Rovesti 1997) that combine ammonia-releasing salts as food attractants with a sex pheromone (a spiroacetal) and deltamethrin insecticide at one trap per tree. Broumas et al. (1985) conducted a 4-yr study in which they compared the ammonium carbonate/pheromone lure with deltamethrin on a 300-ha orchard and found both trap capture and fruit infestation was lower compared with orchards in which a bait spray only was used. An areawide pest management system was constructed in Italy that predicts whether an area is suitable for lure and kill (or mass trapping) if its active infestation does not exceed 30% on 80% of farms by the third week of October (Petacchi et al. 2003).

Lure and kill methods have been tested on a number of other fruit fly species. The Mexican fruit fly, *Anastrepha ludens* (Loew), and the Caribbean fruit fly, *Anastrepha suspensa* (Loew), are serious pests of citrus and other fruits and may invade southern Texas and occasionally California and Florida (Nilakhe et al. 1991, Epsky et al. 1993). McPhail traps baited with torula yeast or other proteinaceous baits have been used for the last century (Robacker and Warfield 1993, Thomas et al. 2001). However, during the last decades, synthetic food-odor lures such as trimethyl amine, ammonium acetate and putrescine have become more prevalent because these components are more selectively attractive to the fruit flies (Heath et al. 2004). McPhail and Multi-Lure traps catch more than "Mitchell" killing stations with these lures, but the Mitchell station is less expensive per unit (Holler et al. 2006). The Mitchell station uses permethrin insecticide that kills flies ≈30 min after contact (Holler et al. 2006).

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 (Ridgway et al. 1990, Smith 1998). Insecticides such as DDT controlled the boll weevil from 1945 until it became resistant to all chlorinated hydrocarbon insecticides by 1960. Eradication of the boll weevil from the southwest was accomplished by a combination of cultural control, pheromone trapping, and insecticide application in response to pheromone trap catches. Mass trapping boll weevils began in 1968 and indicated that low-density populations could be reduced further, but the probability of success declined as population density increased (Hardee 1982, Ridgway et al. 1990). At the highest density of traps (14 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 four traps per acre. These studies merely trapped weevils but demonstrated the effectiveness of the lure. More recently, Villavaso et al. (1998) compared pheromone-baited traps to baited sticks with adhesive to determine the relative attractiveness. They found that three times more boll weevils contacted the bait sticks than the pheromone traps. All weevils that contacted the sticks that had insecticide were killed. Thus, bait sticks with insecticide (malathion) should be about three times more effective than baited traps.

Essential Knowledge for Successful Lure and Kill

Lure Competitiveness with Natural Odor Source (Including Insecticide–Lure Interactions). Different kinds of research and development have been undertaken to ensure that lure and kill formulations do indeed lure and kill the majority of adult insects of the target species (Brockerhoff and Suckling 1999, Losel et al. 2000, Poullot et al. 2001, Evenden and McLaughlin 2004). The addition of insecticide to the pheromone adds a new layer of complexity to the many factors influencing efficacy. Key among these factors are semiochemical blend, semiochemical dose (and associated field longevity, including possible blend changes), lure formulation, lure density, insecticide choice, and insecticide dose (and associated field longevity). Other factors that affect the success of lure and kill include lure/trap placement, lure/trap height, and lure/trap design/size. There are complex interactions between the pheromone/semiochemical, the insecticide, and insect behavior which need to be understood if high kill rates are to be achieved. The presence of the insecticide or other formulation components (such as gel, oil, or adhesive) must not compromise the ability of the semiochemicals to cause insects to land and contact the toxic substrate. For example, the ability of a sex pheromone lure to compete with wild females is fundamental to the success of lure and kill technology in Lepidoptera (e.g., Krupke et al. 2002). Lure and kill has been able to exploit existing knowledge of sex pheromone composition or other behaviorally active semiochemicals of the target insects. Nevertheless, the pheromone is being used to influence male behavior, and research is necessary in this context to confirm its greater attractiveness than virgin females and its ability to induce males to contact the lures. Research needs to directly compare lure attractiveness with virgin females to optimize pheromone blend, release rate, and dose (Downham et al. 1995, Brockerhoff and Suckling 1999, Poullot et al. 2001), all of which may need refinements, particularly to increase male-lure contact (Downham et al. 1995) and insecticidal efficacy (Brockerhoff and Suckling 1999, Losel et al. 2000). This kind of research also assists in determining the period of attractiveness and effectiveness of the lures and the required frequency of lure replacement, which may vary from a matter of days (Downham et al. 1995) to several months depending on the formulation, pheromone composition, and insecticide used (Brockerhoff and Suckling 1999, Suckling and Brockerhoff 1999). Both field and wind tunnel research has been valuable in this regard (Poullot et al. 2001). The constant release of pheromone by the lures gives them an advantage over virgin females which "call" during restricted periods of the day; this is particularly useful because many males are active earlier, both daily and seasonally, when the lures do not have to compete with wild females (Losel et al. 2000).

Lure Density. At a given pest population density, the efficacy of lure and kill increases as the number of point sources per ha increases (Downham et al. 1995, Suckling and Brockerhoff 1999, Krupke et al. 2002); however, this is up to some upper limit. For example with sex pheromone, lure density per ha must be sufficient to compete with the numbers of wild females calling in the field, and this is most readily achieved where population densities are low (see below). Compared with many traps in mass trapping, high densities of lure and kill point sources can be deployed more easily and with lower labor costs; trials of paste or gel formulations have been used at up to 7,500 droplets per ha (Losel et al. 2000) and the Ecogen Nomate hollow fibers (aerial applications) (Antilla et al. 1996) seem to have been used at even higher densities. However, care is required because higher densities of pheromone point sources may carry a greater risk of interference between them (Suckling and Brockerhoff 1999), causing some mating disruption of the target pest in the case of sex pheromone (Downham et al. 1995), and failure to obtain sufficient lure and kill (Downham et al. 1995). In this context, understanding the behavior of insects close to and contacting the lures is critical. It is possible that increasing the density of lure and kill dispensers can lead to an increase in pest immigration into the treated area. This will result in an increase in the population density of the target pests and can lead to failure of the lure and kill program. Therefore, understanding the correlation between density of applications and insect immigration is critical.

Lure Formulation. Lure formulation has been largely the preserve of commercial companies, but several programs have added their own design features, such as to improve contact between insect and lure/toxin (McVeigh and Bettany 1986), even to the point of adding visual female or flower models to induce landing behavior (Miller et al. 1990, Moraal et al. 1993). As with mass trapping, an understanding of optimum lure height and placement has contributed to efficacy of lure and kill. The insecticide used in lure and kill must be chosen carefully, particularly to avoid such problems as repellency that could prevent lure contact. The preferred compounds are mainly fast-acting pyrethroids (e.g., cyfluthrin, λ-cyhalothrin, cypermethrin, furathiocarb, and permethrin). Although pyrethroids are known to be repellent in some situations and to some insects, lure and kill research has been able to develop formulations without this problem (De Souza et al. 1992, Haynes et al. 1996, Brockerhoff and Suckling 1999). Recent research has focused on obtaining a better understanding of the way insects obtain and respond to both lethal and sublethal doses of insecticide because this is fundamental to the success of lure and kill. These studies include the effects of insecticides on insect behavior, required time of contact, rapidity of kill, sublethal effects on mating ability of insects, and the longevity of insecticide efficacy (De Souza et al. 1992, Haynes et al. 1996, Suckling and Brockerhoff 1999, Poullot et al. 2001). All these factors contribute to the selection of insecticide and semiochemical dose to determine the frequency of lure replacement (i.e., the number of applications required). Lure and kill formulations probably require longer periods of efficacy than would broadcast conventional insecticide spraying (in part because it prevents the next generation as the mechanism of control) and some pyrethroids, such as cypermethrin (Ioriatti and Angeli 2002), are sufficiently persistent to offer this benefit.

Unlike mass trapping, sublethal effects of lure and kill can be an important component of efficacy because the insecticidal contact may reduce the ability of males to respond to and mate with females, even if males are not killed outright (Suckling and Brockerhoff 1999). Insects that have acquired a sublethal dosage may be more vulnerable to natural enemies. Although lower, sublethal dosages may be worrisome due to risks of survivors developing resistance, if the dose is high enough to reduce the ability of the individual to protect itself against natural enemies, then the risk of developing resistance may actually be very low.

Careful experimentation has been able to separate the effects of lure competition and insecticidal components in lure and kill efficacy against some pests (Brockerhoff and Suckling 1999) and shown that against other pests, the insecticidal component is the key and not semiochemical disruption (Charmillot et al. 1996). Without this crucial insecticidal effect, lure and kill becomes less effective and no more than partial mating disruption (Downham et al. 1995). Suckling and Brockerhoff (1999) used exclusion cages placed over lure and kill droplets to show that 500 point sources of pheromone reduced trap catch in the plots by point source competition, but the catch was reduced about half as much when the droplets were exposed, thereby allowing mortality from contact with the droplets.

Population Density of Target Pest and Risk of Immigration. There are some indications that lure and kill is more effective than mass trapping or mating disruption when attempting control at higher population densities, for example, initial trials against some higher density pest species has shown promise (Suckling and Brockerhoff 1999). However, the majority of trials confirm the critical importance of population density (Downham et al. 1995, Angeli et al. 2000, Losel et al. 2000, Ebbinghaus et al. 2001, Krupke et al. 2002) and the inverse density dependence of lure and kill (Krupke et al. 2002). There are frequent examples of lure and kill failing to control pest populations at high density (e.g., Trematerra et al. 1999, Angeli et al. 2000, Charmillot et al. 2000). However, lure and kill is as susceptible as mass trapping and mating disruption to the negative influence of immigration, and the literature regularly identifies the need to use lure and kill for the control of isolated smaller populations (Moraal et al. 1993, Downham et al. 1995, Angeli et al. 2000, Charmillot et al. 2000). This will not necessarily overcome the problem of attempting to control at high pest density (Trematerra et al. 1999), although a higher density of lures may help compensate in controlling higher densities. The potential for lure and kill technology in the eradication of invasive species lies in treatment of "populations" that are initially at low density, in complete coverage of the population based on delimitation surveys, and when there is a low risk of immigration.

Biology and Ecology of Target Species. With fewer pest species having been targeted by lure and kill compared with mass trapping or mating disruption, there is less information in the literature on the influence of pest biology and ecology on efficacy. It is reasonable to assume that the influences will be similar for the three methods, and this is supported by limited evidence to date. For example, several authors stress the importance of initiating control early in the season (Hofer and Angst 1995) before the onset of male moth flight (Charmillot et al. 2000), and ensuring that lure and kill is maintained throughout each generation (Ebbinghaus et al. 2001). These recommendations are to exploit protandry and would benefit from univoltinism. The risk to effective lure and kill posed by immigration is aggravated by mobile adult males and females (Moraal et al. 1993). With tephritid fruit flies, early studies on melon fly ecology showed that melon flies preferred to "roost" on hedgerows and boarders outside of melon and cucurbit fields (Nishida and Bess 1957), and females moved into the field primarily to lay eggs on host fruit. As a result recent use of this information has been successfully implemented in an areawide melon fly pest management program in Hawaii where border foliage attractive to the flies are preferentially planted and bait sprays applied to the borders at regular interval resulting in population reduction in the fields (Vargas et al. 2003a).

Measuring Efficacy of Control. The efficacy of lure and kill against moths is routinely measured by monitoring the males of the target pest with pheromone traps to confirm population decline. This is usually supported by records of pest damage or infestation (Moraal et al. 1993, Downham et al. 1995, Trematerra et al. 1999), which is preferable to merely monitoring populations of males but much more time consuming. These methods provide an overall assessment that can be compared with untreated "control" plots but do not distinguish the effects of lure and kill from other mortality factors affecting the population. In particular, it is important to determine the impact of lure and kill on mating (Krupke et al. 2002). The proportion of tethered or caged virgin females which mate (McVeigh and Bettany 1986, Downham et al. 1995, Charmillot et al. 2000) has been used to provide a more direct measure of lure and kill efficacy, and to guide the choice of lure density (Charmillot et al. 1996). This method assumes that the females used are equal in attractiveness to wild virgin moths. Modifications of this approach include recording the proportion of monitoring traps (containing either caged females or pheromone) that fail to attract a male (Suckling and Brockerhoff 1999, Krupke et al. 2002), because these traps can be considered as equivalent to females that have not mated. The mated status of males, which can be determined in some species of Lepidoptera by dissection (Evenden et al. 2003), may be a useful technique for assessing the proportion of virgin males caught in the monitoring traps. Mark–recapture of males is another technique that has been used in field cages and in the field to measure the efficacy of lure and kill and to assist with determining an appropriate lure density (Krupke et al. 2002, Brockerhoff and Suckling 1999).

Lure and Kill: Risks. The insecticidal component of lure and kill could be perceived by the public as a risk if this technology were to be used in urban environments, such as in the eradication of invasive species. Concern over the use of the broad-spectrum organophosphate insecticide "naled" as the active ingredient in "minugel," a lure and kill formulation applied well above ground level to telephone poles, against *Bactrocera* fruit flies in urban California is a case in point. For years, a mixture of methyl eugenol and naled 5% mixed with the thickening agent minugel has been applied to urban infestations of oriental fruit fly. When applied at a rate of 600 spots per sq mile onto telephone poles, this technique has historically been used successfully for eradication of small outbreaks in California (CDFA 1993). However, increasing concern over organophosphate insecticides has spurned research into alternatives. These "perceived risks," however, must be weighed against the benefit, which in this case can be avoiding significant reductions in trade, increased use of other insecticides or permanent establishment of alien invasive species. The presence of numerous insecticidal point sources in an urban environment can be expected to elicit at least some public opposition, even though the candidate insecticides have low mammalian toxicity, are used in very low quantities per ha compared with conventional spraying (Suckling and Brockerhoff 1999, Trematera et al. 1999, Losel et al. 2000), and most formulations have a low risk of lethality to nontarget organisms. In some cases, natural enemies can be highly attracted to semiochemicals used in lure and kill formulations, and therefore the effect of lure and kill on nontarget species has to carefully be investigated to minimize this undesirable effect on nontarget species. The aerial application of the hollow fiber formulation of lure and kill (Antilla et al. 1996) would be totally unacceptable to the general public, particularly in an urban environment. Efficacy of all the lure and kill formulations is closely dependent on the number of point sources per ha, and, even with paste or gel formulations, optimal densities would likely be in 1,000 sources rather than 100 sources per ha. In addition, the concentration of insecticide in the lures could be expected to be ≈5–6%, and the droplets of some formulations are susceptible to rain splash that spreads them to some extent after application. If the droplets are not totally inaccessible, children or others contacting them, although at minimal risk, may have an allergic response, or a belief that this is happening, which could create severe negative public relations. Risk of lure and kill failure could come from various other aspects of methodology, such as an inadequate odor blend or insufficient lure density for the target population density. Many of these risks can be minimized by careful research and development. A model of mass trapping using knowledge of the lure's effective attraction radius can be used to investigate lure and kill efficacy in regard to lure density versus pest densities (Byers 2007).

Overall Evaluation of Lure and Kill

Lure and Kill: Success and Failure. Analysis of the main lure and kill programs and the associated research and development provide a guide to the key reasons for success and failure. There are several examples provided in the literature of the successful use of lure and kill in pest control, i.e., it provided a major reduction in pest population or damage. Examination of these cases shows that the key reasons for success can be summarized as follows: 1) low-density target population (Angeli et al. 2000, Charmillot et al. 2000, Losel et al. 2000, Ebbinghaus et al. 2001); 2) isolated target population (no or minimal immigration) (Downham et al. 1995, Angeli et al. 2000, Charmillot et al. 2000); 3) a lure competitive with wild females (Angeli et al. 2000, Charmillot et al. 2000, Ebbinghaus et al. 2001); 4) high lure density (relative to pest density) (Angeli et al. 2000, Charmillot et al. 2000, Losel et al. 2000); 5) optimal lure placement (Charmillot et al. 2000, Losel et al. 2000, Ebbinghaus et al. 2001); and 6) lure deployment before male emergence and throughout flight period (Charmillot et al. 2000, Ebbinghaus et al. 2001).

However, examination of the cases in which lure and kill failed to provide a major reduction in pest population or damage indicate key reasons for failure of lure and kill which can be summarized as follows: 1) too high density of target population (Downham et al. 1995, Trematerra et al. 1999, Angeli et al. 2000, Charmillot et al. 2000); 2) target population not isolated (high risk of immigration, high pest mobility) (Moraal et al. 1993, Trematerra et al. 1999); 3) inadequate pheromone lure that was not competitive with females (Downham et al. 1995); 4) insufficient density of point sources in relation to target pest density (Moraal et al. 1993, Downham et al. 1995, Trematerra et al. 1999); and 5) lure and kill formulations applied after damage done (Charmillot et al. 2000).

Lure and Kill: Strengths and Weaknesses. *Strengths.* The inverse density dependence of lure and kill (i.e., its efficacy improves as target density declines) confers major advantages on the use of this technology in eradication of invasive species. Cost-effectiveness improves as the pest density declines and this counters the usual problem of facing rising costs for removing increasingly rare individuals as eradication continues in the case of invasive species (Myers et al. 1998). Lure and kill is, therefore, highly effective against low-density populations (Suckling and Brockerhoff 1999, Charmillot et al. 2000, Ioriatti and Angeli 2002, Krupke et al. 2002), particularly if they are isolated from immigration. Today, toxic synthetic lures can be produced which are highly competitive with wild virgin females; this is due to the production of improved pheromone blends and dosages, and partly because the pheromone is constantly released from the lures, even when females are not calling (Krupke et al. 2002). The combination of lure and insecticide enables the use of very small amounts of insecticide per given area (Brockerhoff and Suckling 1999, Suckling and Brockerhoff 1999, Losel et al. 2000). Moreover, the major formulations are very durable (Losel et al. 2000) enabling the insecticide component to be twice as persistent as conventionally applied insecticide (Hofer and Angst 1995) and therefore requiring fewer applications. The target insects are killed by the briefest contact with the insecticide (Losel et al. 2000, Poullot et al. 2001), during which adequate uptake of the toxin can occur (Losel et al. 2000). Much less pheromone is used per ha than in mating disruption (Suckling and Brockerhoff 1999, Trematerra et al. 1999, Charmillot et al. 2000), and this should bring another major cost saving; this is because the primary mode of action is insecticidal. Unlike insecticide treatments and mating disruption which are sensitive to topography and environmental conditions, lure and kill technology can be used in a variety of conditions, including small, irregular, and hilly sites (Charmillot et al. 2000, Ioriatti and Angeli 2002). The pheromone is able to penetrate complex environments difficult to reach with spray coverage and this enables attraction and kill of males from remote, protected or cryptic habitats. In addition, lure and kill products do not cause spray drift (Suckling and Brockerhoff 1999), which occurs with conventional insecticides. Almost all formulations also can be applied in ways that avoid insecticide being deposited on crops that will be harvested as food (Suckling and Brockerhoff 1999, Ioriatti and Angeli 2002). The method of insecticide use provides for high selectivity (Suckling and Brockerhoff 1999, Charmillot et al. 2000, Losel et al. 2000, Ioriatti and Angeli 2002), with minimal impact on nontarget organisms. This includes a high level of safety to workers and the public. No expensive special equipment is required to apply most lure and kill formulations. They can be deployed by a minimally trained work force (Olszak and Pluciennik 1999, Losel et al. 2000).

Weaknesses. The major weaknesses of lure and kill are the reciprocal of its strengths. The method has decreased efficacy at high pest density (Downham et al. 1995, Charmillot et al. 2000, Ioriatti and Angeli 2002), due to competition from greater numbers of calling wild females (Losel et al. 2000) and because males in this situation use many other cues than pheromone to locate their mates. Just like mass trapping, lure and kill is susceptible to immigration of the target pest into the treated area (Moraal et al. 1993, Charmillot et al. 2000, Ioriatti and Angeli 2002), particularly by flying mated females. The extreme dependence of lure and kill on a highly competitive lure and rapid-acting insecticide can be seen as a major weakness because of the many factors which must be optimized for success—lure blend, dose, distribution, and placement, insecticide formulation, and dose. Research and development is essential to address these issues. It has been pointed out that there are cost savings from lure and kill due to the small quantities of pheromone and insecticide required per hectare. However, its ability to compete with wild females is dependent on the number of pheromone point sources per hectare. The labor involved in deployment of the lures is significant and becomes a trade-off between efficacy and cost (Losel et al. 2000), particularly at higher pest densities. This is a further reason to focus the potential use of this technology on low density, isolated populations.

Lure and Kill: Cost-Effectiveness. A full cost–benefit analysis of lure and kill is beyond the scope of this review and is recognized as fraught with difficulties in the context of eradication (Myers et al. 2000). Sharov and Liebhold (1998) have shown that there are sound economic reasons for eradicating small incipient populations ahead of the main front of spreading gypsy moth populations. The important issue for the cost-effectiveness of lure and kill is in its increasing efficacy as pest populations decline. This results in, first, ineffectiveness and too high cost to control high density targets (including intolerably high distribution/placement costs); and second, high and increasing effectiveness against low and falling populations. This makes the method suitable for the final stages of an eradication program and overcomes the usual major obstacle in eradication of rapidly rising costs for removal of rarer and rarer insects. Concentrating efforts on the eradication of low-density populations also assists in limiting trap costs because few moths will be caught and trap design is unlikely to need to cope with trap saturation problems. Mating disruption uses "large" quantities of pheromone per ha and this is a major cost. Lure and kill uses much less pheromone and this reduced cost has been identified as an important issue for the cost-effectiveness of the technology (see above), while deployment costs of lure and kill are reported to remain similar to mating disruption.

New Developments. The majority of lure and kill methods developed in the past 10 yr have used the female sex pheromones of the target pest species as attractants. However, it has been recognized that lure and kill could be improved if female attractants could be found, because this would greatly enhance efficacy by removing virgin and mated females, particularly if this could be added to male removal. Kairomones, which are the odors of the hosts or prey of insects, may also be attractive to both males and females. Recent research has identified kairomones of codling moth which are being investigated for lure and kill (Potting and Knight 2001). Also, floral volatiles that attract noctuid moths (e.g., El-Sayed et al. 2008) can enhance the efficacy of lure and kill for noctuid pests. Another new development for control of lepidopterous pests is "lure and sterilize" (Charmillot et al. 2002). In this trial, the target pest is codling moth, and in this technique the pheromone (codlemone at 0.12–0.35 g/ha per application) attracts males to contact a chemosterilant, fenoxycarb, at 5% (4.6–13.2 g fenoxycarb/ha per application). The result is autosterilization of the males that can then disperse and, in some cases, mate with virgin females which remain sterile. Five years of trials have been undertaken, using 1,540–4,400 by 50 μl drops/ha in two to three applications per season (i.e., 198–526 g formulated paste per ha per year), and placing one third of lures in the lower parts of apple and pear trees and two thirds in the upper parts. Good population reduction (overwintering larvae) was achieved in the first 2 yr, but lowering the paste amounts to ≈200 g/ha allowed population increase. Although autosterilization is predicted to approximately double the efficacy of lure and kill with insecticides (Potting and Knight 2001, Charmillot et al. 2002), this has still to be demonstrated because there was a high residual population at the end of these trials in 2000. Autosterilization could be considered for pest management and eradication of invasive species as an alternative to lure and kill. However, an effective chemosterilant would have to be found and chemosterilant chemicals would likely create the same public concerns as insecticides.

Conclusions

Lure and kill has the potential to add value in both long-term pest management of many economically important pests and in the eradication of invasive species by being instrumental in control or eradication of small, low-density, isolated populations either inside the main distribution area of a pest or during the final stages of eradication. We have identified key factors that can contribute to success of lure and kill as follows: low-density target population; isolated target population; a lure competitive with wild females; high lure density relative to pest density; optimal lure placement; and lure deployment before adult emergence and throughout flight period are conditions that favor a successful lure and kill program. The key steps in developing a successful lure and kill program under the constraints of population and economic conditions

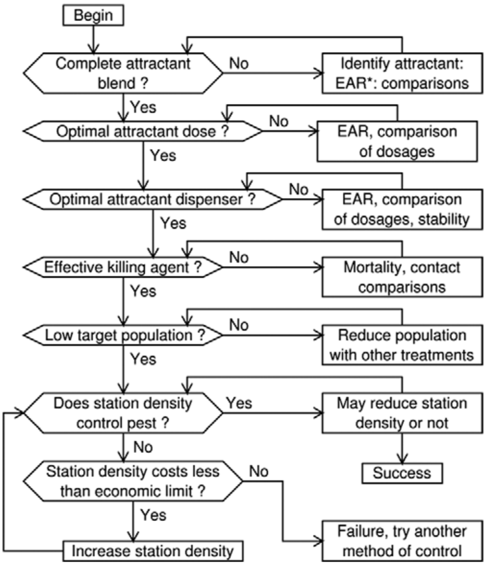

Fig. 1. Flow diagram of steps considered important in the development of a successful lure and kill program by using semiochemical attractants in contact-insecticide killing stations. The EAR* (effective attraction radius) is key to the initial steps as the method can be used to optimize trap and lure parameters such as pheromone components (full blend), dosage (release rate), dispenser design (longevity), and trap design (efficiency).

are illustrated in a flow diagram (Fig. 1). Lure and kill may offer some improvements in efficacy over other control methods using semiochemicals, but the inclusion of insecticides or sterilant in lure and kill formulations may present major obstacles to public acceptance in urban areas, where new incursions are often detected first. This could be the main reason that other control methods (i.e., mass trapping or mating disruption) have been preferred in eradication programs.

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