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Pheromone Trapping in Controlling Key Insect Pests: Progress and Prospects

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ABSTRACT

In recent years, pheromone trapping has been employed in many pest management programmes worldwide. Pheromone trapping can assist decision making in integrated pest management (IPM) programmes. Considerable improvements have been made in the identification and formulation of blends of pheromones for the management of agricultural insect pests. The progress and prospects of using pheromone for monitoring, mass trapping and mating disruption are discussed, with emphasis on Lepidopteran and Coleopteran pests, as the main pests of oil palm in Malaysia fall within these two insect orders.

ABSTRAK

Kebelakangan ini, perangkap feromon kian banyak digunakan dalam program pengurusan perosak di seluruh dunia. Perangkap feromon boleh membantu dalam menyokong keputusan bagi program pengurusan perosak bersepadu (IPM). Terdapat kemajuan yang agak memberangsangkan dalam bidang pengenalpastian dan formulasi campuran feromon bagi penggunaan dalam pengurusan serangga perosak pertanian. Perkembangan dan prospek penggunaan feromon untuk pemantauan, penangkapan pukal, dan gangguan persenyawaan dibincangkan dalam artikel ini. Keutamaan diberikan kepada serangga perosak dari order Lepidoptera dan Coleoptera, memandangkan perosak utama bagi tanaman sawit di Malaysia tergolong dalam kedua-dua order tersebut.

Keywords: pheromone, monitoring, mass trapping, mating disruption, oil palm.

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INTRODUCTION

Agricultural insect pest management is largely dependent on the use of chemical insecticides. However, there are problems associated with insecticide usage such as environmental pollution, contamination of harvested agricultural yield and development of resistance in the pests. Pheromone trapping can provide tools for monitoring the activity and movement of target insects, providing information that will assist in insect pest management. Pheromones are efficient at low pest population densities, with no adverse affect on natural enemies, and their use leads to long-term reduction in insect pest populations that cannot be accomplished with conventional insecticides (Witzgall *et al.*, 2010).

Pheromones can contribute to integrated pest management (IPM) strategies by modifying insect behaviour, and mainly by capturing the adult stages of the pest. There are many different ways by which pheromones have been successfully deployed. The use of pheromones in pest control has developed along three main pathways: for the monitoring of insect populations with pheromone-baited traps, for control by mass trapping (using large numbers of traps to reduce pest population levels), and for control by mating disruption in which a synthetic pheromone is used to permeate the atmosphere so that an insect will be unsuccessful in finding a mate (Campion, 1983). Unlike other sampling methods that may be very time-consuming and require technical expertise, trapping-based monitoring is efficient and easy to use. In addition, the approach is effective over a range of pest densities and often provides the most practical means of monitoring adult pest activities. Among the attributes sought in a trapping system is low cost, sensitivity and specificity for the target pest species, and user convenience. Most studies conducted show farmers develop their own versatile traps that can be used in confined areas, remain out of view, and are as effective as other commercially available traps (Mullen and Dowdy, 2001).

The current interest in pheromone trapping associated with biological control led us to review the status of the progress and prospects of using pheromone trapping tactics. This review underlines the concepts deployed in pheromone trapping for insect pest management in agricultural crops. The successes, failures and future directions in using this method for controlling insect pests are deliberated upon. Focus is given to specific insect orders (Lepidoptera and Coleoptera) to which belong important pests of the oil palm.

CURRENT STATUS OF PHEROMONE TRAPPING

Pheromones are basically applied as monitoring tools worldwide, and pheromone-based control applications cover large areas (Ridgway *et al*., 1990; Howse *et al*., 1998; Baker and Heath, 2004). Pheromones as behaviour-modifying chemicals are elegant tools for insect management, and the prospect of a wide range of future applications specifically in agriculture continues to encourage research in insect olfactory physiology and chemical ecology (van der Goes van Naters and Carlson, 2006). The development of synthetic insect pheromones has given the agriculture sector a highly effective tool for the early detection of insect infestation. The use of pheromone-baited traps for the trapping of adult male Lepidoptera is now a well-established technique (Mullen and Dowdy, 2001).

Some of the important factors influencing trap catch are trap design (Jacquelyn *et al.,* 2008), alternative lures and release rates of substances (Anderbrant *et al.,* 1992; Walton *et al.,* 2004), position of the trap (Simandl and Anderbrant, 1995), weather (Walton *et al.,* 2004), wind conditions and intertrap spacing (Wilson and Morton, 1989; Wedding *et al.,* 1995).

The mode of action within certain insect families and the chemical structure of pheromones are rather complex. The pheromone of the main oil palm insect pest, *Metisa plana* (Lepidoptera: Psychidae), may have a chemical structure that does not normally coincide with the sex pheromone of other Lepidoptera. A better perceptive of the pheromone mechanisms would be valuable in advancing the basic understanding of the pheromone especially in Psychidae. Until recently, no sex pheromone of *M. plana* has been efficiently formulated. However, the use of live, virgin, receptive females has been successful in mass trapping studies (Norman *et al*., 2010). Effective pheromone trapping usually relies on a negative relationship between trap captures and the subsequent local population density (Howse *et al*., 1998; Norman and Basri, 2004; Norman *et al*., 2010).

Much useful information can be derived from trapping data, ranging from simple detection of a particular species in a locality, to the prediction of damage levels caused by the pest species, and the determination of appropriate control measures. Besides that, many pheromones have been registered for pest control, and there has been no evidence of adverse effects on public health, non-target organisms or the environment (Witzgall *et al*., 2010). The database of insect pheromones and related attractants contains hundreds of chemicals that have been developed in recent years (Arn *et al*., 1992; El-Sayed, 2008).

TRAP DESIGN AND PLACEMENT

Trap design, placement and density can affect the number of pests captured (Subchev *et al.,* 1994; Cork *et al.,* 2003; Jacquelyn *et al.,* 2008). The most common trap employs a sticky surface to retain the attracted insect. The suitability of sticky traps is dependent upon the population levels of the target species. Cardé and Elkinton (1984) mentioned that the most common sticky trap designs used are the delta trap, the tent trap and the wing trap. A sticky vane trap has been tested to be effective in capturing small moths of the oil palm bagworm, *Metisa plana* (Norman and Othman, 2006; Norman *et al.*, 2010).

A small trap has the advantage of being usable in areas where it might not be desirable to use the larger wing trap. The lower number of insects per cm^2 may be influenced by the smaller openings resulting from the trap being folded (Mullen and Dowdy, 2001). Usually sticky traps become ineffective when the sticky surfaces become covered with insects. This happens particularly when the pest population levels are high. These findings reveal that the area of the trapping surface has an influence on trap efficiency. As an alternative, water and cone traps have been made of sufficient volume to ensure that they are effectively non-overloading (Birch and Haynes, 1982). Cross *et al*. (2006a) developed various modifications of the sticky board trap, and compared them with the 'boll weevil', funnel, delta and sticky stake designs. They concluded that the development of an effective and practical trap design is critical to the commercial development of a pheromone for pest monitoring and control.

With the pine beauty moth, *Panolis flammea* (Denis & Schiffermuller) (Lepidoptera: Noctuidae), Bradshaw *et al*. (1983) showed that the most important features of a trap design is a heavy surface coating of sticky retentive material, together with a large catching area. These are important to maximize captures and reduce the frequency of replacing the traps.

Optimum trap design and pheromone dose levels are highly interrelated. Once the trap design and pheromone dose have been selected, trap placement has to be decided. Trap height does not appear to be critical over the limited range tested, but it should be standardized at a user-convenient height (Hand *et al*., 1987; Norman and Othman, 2006). In terms of placement, it has been shown that there are no significant differences in captures between traps hung on 4-m or 2-m poles (Norman *et al*., 2010). These results support earlier findings by Bradshaw *et al.* (1983), Hand *et al*. (1987) and Boo and Jung (1998) which state that trap height does not influence the numbers of moths caught. The optimum monitoring system should be positioned so that it catches a representative sample of the local population, has low maintenance costs, is easy to assess, preferably in the field, remains constantly effective throughout the flight season of the pest.

Dendy *et al.* (1989) tested several types of traps for catching the adult *Prostephanus truncatus* (Horn) (Coleoptera: Histeridae) in maize fields, and concluded that the adult beetles fly directly to a source of pheromone. The most effective trap design is the one that catches the flying beetle, and not a trap that requires the beetle to walk into it. In surveying invasive wood-boring and bark beetles, Brockerhoff *et al*. (2006) used traps baited with pheromones and kairomones. The study tested the efficacy of different lures for established or newly established exotic species, and the effects of trap placement and proximity of host trees on trap catch in order to improve trap efficiency. The lure type used had highly significant effects on trap catch. The results of this study confirm that odorant-baited traps can be used effectively for a nationwide surveillance programme to monitor populations of exotic beetles, as well as native species that infest the wood and bark of trees.

More recently, Tinzaara *et al*. (2005) evaluated the importance of distance, environmental factors, trap location and trap type on catches of *Cosmopolis sordidus* (Germar) (Coleoptera: Curculionidae) in pheromone-baited traps.

Besides design and placement, trap colour may also influence the captures. Wang *et al*. (2005) evaluated trap placement, trap diameter and trap colour on the captures of the tea tussock moth, *Euproctis pseudoconspersa*, in a tea plantation. Cardé and Elkinton (1984) showed that yellow traps caught more moths as well as bumble bees (*Bombus* spp.) compared to green traps. Herman *et al.* (1994) later evaluated the effect of pheromone trap position and colour on the tomato fruitworm moth, *Helicoverpa armigera*, Hubner. These studies show the trap colour might be important to maximize trap captures, depending on its high or low reflectance in the infested fields.

PHEROMONE DOSAGE

In both laboratory and field trials, Kawazu *et al*. (2004) revealed that there are no significant effects due to a change in the synthetic pheromone ratio in monitoring *Cnaphalocrocis medinalis* (Lepidoptera: Crambidae). Kawazu *et al.* (2000) suggested that there are remarkable geographical variations in female sex pheromones of the rice leaf folder moth, *C. medinalis*, or that several distinct species use different sex pheromone blends. Trapping experiments were also set up in brassica crops to test the potential for improving the lures in pheromone traps (Suckling *et al.*, 2002).

The right dosage of pheromone is also a crucial part in trapping the moths. Hand *et al*. (1987) found that increasing the dose of pheromone lures increased moth captures. Similarly, for the apple leafminer moth, *Phyllonorycter ringoniella* (Lepidoptera: Gracillariidae), Boo and Jung (1998) revealed that the attractivity of the lures increased with higher amounts of the pheromones, both in wind tunnel experiments and in the field. However, internal trapping, using one-tenth of the standard dose of the pheromone, was found to be a better indicator of leaf roller damage in orchards than in the normal boundary pheromone trapping (Alway, 1997; 1998). For the diamondback moth, *Plutella xylostella* (Lepidoptera: Yponomeutidae), a wide range of pheromone blends has been reported to be attractive to the male moths (Macaulay *et al.*, 1986; Zilahi-Balogh *et al*., 1995; Walker *et al*., 2003).

PHEROMONE TRAPPING AS A MONITORING TOOL

The monitoring of pest populations is essential for a successful IPM programme. According to Broza *et al*. (1991) and Mullen and Dowdy (2001), the use of pheromone-baited traps in monitoring insect populations offers several advantages over visual inspections and in locating where high pest population outbreaks are occurring. It is less labour-intensive and less costly. To maintain low pest densities, it is important that the pest populations be detected at an early stage of infestation and before serious outbreaks develop.

Monitoring systems are required to identify areas at risk and to minimize the use of insecticide treatments. There have been several approaches to improve the usefulness of pheromone-baited traps as monitoring tools in pheromone-treated plots.

The use of pheromone trapping in monitoring insect populations as an aid in decision making is the popular application of sex pheromones. However, estimating the population density over a specific area on the basis of the level of captures is not straightforward. Various factors such as pheromone dosage (Gross *et al.*, 2001; Branco *et al*., 2004), pheromone release rate (Khoo *et al.*, 2000), sampling area (Östrand and Anderbrandt, 2003), competition between females and traps (Unnithan and Saxena, 1991), and meteorological factors (Rajaram *et al.*, 1999) may constrain the ability to relate capture rate to the population density of the pest.

For Lepidopteran insects, several studies have shown that species like leaf rollers and the codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae) (Suckling and Burnip, 1993), can be monitored by pheromone traps. Armstrong *et al*. (1997) reported that male moths of several orchard leafrollers (Lepidoptera: Tortricidae): *Epiphyas postvittana* (Walker), *Planotortrix octo* (Dugdale), *P. excessana* (Walker), *Cnephasia jactatana*, *Ctenopseustis obliquana* (Walker) and *C. herana* (Felder and Rogenhofer), were captured using pheromone traps in order to determine the field populations of the species. More recently, Jamieson *et al.* (2004) did a distribution survey of the guava moth, *Coscinoptycha improbana* Meyrick (Lepidoptera: Carposinidae), and the diamondback moth, *P. xylostella,* in cruciferous vegetables (Walker *et al.,* 2003). Cameron *et al.* (2002) studied the effects of distance on the pheromone trap captures, showing a significant relationship in the movement of the potato moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae), by the mark-recapture method. Jactel *et al.* (2006) revealed that plate sticky traps always showed the highest trapping efficiency for monitoring of pine processionary moth *Thaumetopoea pityocampa* (Lepidoptera: Notodontidae) populations.

The effectiveness of pheromone trapping in detecting the presence of *Cydia succedana* (Denis & Schiffermüller) (Lepidoptera: Olethreutidae) in gorse plants (*Ulex europaeus* L.) has been studied (Sixtus *et al*., 2007). Previous attempts at using pheromone-baited traps for monitoring purposes had yielded mixed results. Some studies established a significant correlation between trap catches and forthcoming densities and/or defoliation (Thorpe *et al*., 1993; Evenden *et al*., 1995; Norman and Basri, 2004), whereas other studies failed to substantiate such a correlation (Sweeney *et al*., 1990; Carter *et al.*, 1992).

For Coleoptera, sex pheromones have been used for population monitoring and management of epidemic pest levels (Schlyter, 1992; Howse *et al*., 1998). There are relationships between pheromone trap catches, pest populations and crop damage in assessing the applicability of the male-produced, aggregation pheromone of the strawberry blossom weevil, *Anthonomus rubi*, for commercial monitoring and control (Cross *et al*., 2006b). Even weak attraction to generic blends may be sufficient for monitoring distribution and phenology (Witzgall *et al.,* 2010). However, some pheromones even attract females, and many of these species have long life cycles with short adult stages, which should support the use of pheromones for control (Maier, 2008; Ray *et al.,* 2009; Rodstein *et al*., 2009).

In Malaysia, pheromone traps are commonly used for monitoring and controlling the rhinoceros beetle, *Oryctes rhinoceros* (L.), a major pest of oil palm. The density as recommended by Chung (1997) for trapping is one trap per 2 ha. Additionally, pheromone traps have also been useful in studying the immigration and activity pattern of the rhinoceros beetle (Norman and Basri, 2004). A relationship in monitoring the fluctuation in population density of *O. rhinoceros* in relation to trapping the adult beetles has been established by Norman *et al*. (2007). In addition, pheromone traps have been deployed in measuring virus incidence in the beetles (Ramle *et al*., 2005).

TRANSFORMATION OF MONITORING TOOLS INTO PREDICTIVE TOOLS

Cardé and Elkinton (1984) reported that pheromone trapping experiments are commonly used to compare the behavioural activity due to synthetic compounds to that due to the natural pheromone, typically that emitted by caged insects. Norman and Othman (2006) developed the trapping strategies for the bagworm, *M. plana*, using live, receptive female adults as bait, which was shown to have potential for monitoring and the mass trapping of the pest. Pheromones have also been used to survey insect species distributions such as the click beetles (Coleoptera: Elateridae) *Agriotes proximus, A. lineatus* and *A. obscures*, and for field monitoring (Vernon and Toth, 2007; Toth *et al.,* 2008). The field monitoring was designed to evaluate the similarity of new sex attractants for the click beetle within the same genus, which would be useful as prognostic tool in controlling insect pests.

A relationship between trap catch and damage was studied by Bradley *et al*. (1998) for developing action thresholds for leaf rollers in apple orchards, based on the number of male moths caught in the pheromone traps. Qureshi *et al*. (1993) monitored and established the economic injury level of the pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), by developing a correlation between moth catches in the traps and larval infestation, using pheromone-baited traps as a sampling tool. In addition, Nyambo (1989) assessed the potential of pheromone traps in improving the timing of spray applications for monitoring and early warning of *Heliothis armigera* Hubner (Lepidoptera: Noctuidae) infestation in cotton fields in Tanzania. In trapping *O. rhinoceros*, there was a significant relationship between the number of adult females trapped and the number of second instar larvae found in the breeding sites at about 40-60 days after trapping (Norman and Basri, 2004). Therefore, trap catch data may be useful indicators of emerging larval infestations in the next trapping round, and may help plan appropriate control measures. These studies indicate that good predictions of the pests can be made to aid decisions on when to adopt plant protection measures, such as scheduled insecticidal sprays, as well as introducing natural enemies and beneficial plants for the control of the pest.

More recently, Cano *et al*. (2008) found that there was a linear relationship between temperature accumulations and trap catches of the male grapevine moth, *Lobesia botrana* (Lepidoptera: Tortricidae). Synthetic sex pheromone-baited delta traps were used as monitoring tools. The equations obtained were shown to be acceptable as useful tools in the management and prediction of outbreaks in the study area. This finding suggests that pheromone trap catches can predict the risk of pest damage.

MASS TRAPPING

Control of insect pests can be achieved by mass trapping using pheromone-baited traps that lure insects to their death. The possibility of direct control through mass trapping with pheromones has been studied worldwide (Smit *et al.,* 2001; Alpizar *et al.,* 2002; Norman and Othman, 2006; Norman *et al*., 2010). Besides *M. plana*, some of the insect pests controlled by mass trapping include *Dacus dorsalis* (Diptera: Tephiritidae), *Heliothis armigera* (Lepidoptera: Noctuidae), *Ostrinia nubilalis* (Lepidoptera: Pyralidae), *Cylas formicarius* (Coleoptera: Curculionidae), and *Scolytus multistriatus* (Coleoptera: Scolytidae) (Nguyen *et al*., 1996).

A number of significant factors may influence the effectiveness of pheromone traps in capturing insects, including the distance of the insects from the traps (Byers, 1999), the trap design (Valles *et al.,* 1991) and pheromone plume characteristics (AliNiazee, 1983). Besides these, other factors such as trap maintenance, cropping system, residue management and environmental conditions have been postulated to have an effect on pheromone efficacy. In general, mass trapping is cost-effective compared to mating disruption, because smaller amounts of pheromones are needed and crop contamination during application is much reduced (Witzgall *et al.,* 2010).

Mass trapping of male adults for the control of the bagworm, *M. plana*, in oil palm has been attempted by using live virgin females (Norman and Othman, 2006; Norman *et al.,* 2008; 2010). The results indicate that there is good potential to develop synthetic female sex pheromone for mass trapping the free-flying male moths. There is less of an occurrence of female bags with eggs in the trapping plots, hence lowering the number of live larvae per frond and reducing the frond damage levels. All this eventually contributed to relatively higher fruit bunch weights (Norman *et al*., 2010).

Mass trapping with pheromone-baited traps offers promising perspectives with beetles, where aggregation pheromones are frequently found (Francke and Dettner, 2005). In cotton crops, mass trapping with traps baited with an aggregation pheromone successfully reduced small overwintering populations of the boll weevil *Anthonomus grandis* Boheman (Coleoptera: Curculionidae) (Hardee, 1982). The population density of sweet potato weevils, *Cylas formicarius* Fabr. (Coleoptera: Brentidae), was also notably decreased in a field using pheromone-baited trap approaches (Yasuda, 1995).

Several studies in mass trapping of Coleoptera have been successfully deployed (Hardee, 1982; Yasuda, 1995; Francke and Dettner, 2005). Oehlschlager (2008) indicated that mass trapping was also used on a wide scale to manage *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), the banana corm weevil, as well as *Oryctes rhinoceros*, a pest of newly planted oil palm in Southeast Asia. For the control of *C. sordidus,* Tinzaara *et al.* (2002; 2008) demonstrated the use of aggregation pheromone in mass trapping, plus enhancement of the pheromone with host plant volatiles (kairomones), and integration of the pheromone with predators and entomopathogenic fungus.

At the farm level in Indonesia, Braun and van de Fliert (1999) studied the impact and effectiveness of the sex pheromone of the sweet potato weevil (*C. formicarius*). The use of the sex pheromone for mass trapping led to damage reduction, even when weevil pressure and damage levels were low. This finding suggests that there is potential for traps to play a significant role in reducing weevil damage in situations of higher weevil pressure.

The red palm weevil, *Rhynchophorus ferrugineus* (Olivier), is known as the most destructive insect pest of palms in the West Asia. It was observed that there were synergistic effects of temperature and humidity with pheromone traps in capturing the red palm weevils (Salem *et al*., 2008). In another palm weevil species, *R. palmarum* L. (Coleoptera: Curculionidae), a pheromone-based mass trapping system changed the distribution of the weevils in the plantation, and eventually decreased the incidence of red ring disease caused by the nematode *Bursaphelenchus cocophilus* Cobb., which is transmitted through the weevils (Oehlschlager *et al*., 1995). Clearly, the use of pheromone trapping was successful in reducing the weevil population as well as nematode infestations. Tomasev *et al*. (2007) also showed the potential of traps baited with a synthetic aggregation attractant which were successful in decreasing the population of the sugar-beet weevil, *Bothynoderes* (*Cleonus*) *punctiventris* (Coleoptera: Curculionidae), via mass trapping.

Innocenzi *et al*. (2001) conducted field trapping trials using components of a male aggregation pheromone of the strawberry blossom weevil, *Anthonomus rubi* Herbst (Coleoptera: Curculionidae), while Zada and Harel (2004) studied the components of the aggregation pheromone on the same species for mass trapping purposes.

A study in an oil palm plantation indicated that without any control measures, the population of the rhinoceros beetle can sustain its population in the oil palm trunk heaps, up to a period of about two years. The early placement of pheromone traps at the onset of replanting reduces the chances of breeding by removing adult beetles through mass trapping. The beetle population density in the trunk heaps is also reduced and therefore prevents the population from building up. For a medium-sized population, trapping can reduce the population density to below 10 individuals m^{-2} in the breeding grounds, in less than a year after replanting (Norman *et al*., 2007).

The ratio of the pheromone components in a pheromone blend is well-known to have a strong effect on its attractiveness in Lepidoptera (Roelofs, 1980: Linn and Roelofs, 1989), and in Coleoptera such as bark beetles (Wood, 1982). Blend ratios in *Prostephanus truncatus* (Coleoptera: Histeridae) pheromone lures have received some attention (Hodges *et al*., 2004); mixtures are better than the components alone but the results are otherwise statistically inconclusive (Dendy *et al.,* 1989; 1991). Hence, a 1:1 ratio has been adopted for the standard commercial lure (Hodges *et al.,* 2004). Mass trapping has also been used in an attempt to suppress the populations of the smaller European elm bark beetle, *Scolytus multistriatus* (Coleoptera: Scolytidae) (Birch and Haynes, 1982). Application of the traps shows good potential as a control method, especially at population densities of 30 000 insects ha^{-1} or below, and may be capable of decreasing the population pressure of immigrating beetles (Tomasev *et al*., 2007).

MATING DISRUPTION

Pheromone-mediated mating disruption is an alternative strategy which is compatible with biological control programmes and which has minimal effect on human health and the environment (Kirsch, 1988). Therefore, research should be expanded into pheromone delivery methods for mating disruption of multiple pest species to ensure that farmers do not need to apply pesticides to control other pests. The mating disruption technique has become the most commonly utilized application of semiochemicals for population control of, for example, the codling moth *Cydia pomonella* (Lepidoptera: Tortricidae) and the carob moth *Ectomyelois ceratoniae***,** (Lepidoptera: Pyralidae) **(**Baker and Heath, 2004; Vetter *et al*., 2006; Norin, 2007). In contrast to mass trapping, the natural pheromone is not required for mating disruption to be effective. Both attractive and non-attractive pheromone blends have been used, because off-blends can result in considerable cost savings (Stelinski *et al*., 2008).

A number of developments has to occur in order to make mating disruption an effective and economically viable control tactic. Continual advances in the understanding of the many biological characteristics, behavioural and otherwise, that influence the outcome of a mating-disruption programme are certainly instrumental in paving the way. Some advances are more technical in nature, such as the development of new techniques for the identification and synthesis of the pheromone over an extended period of time.

Cardé and Elkinton (1984) suggested that the most useful approach to monitor the efficacy of disruption with traps is to duplicate the natural emission rate, which is the rate of pheromone emission from the calling insects. A different approach can also be optimized, such as opting to use lures with very high release rates as a means to permeate the area with the pheromone, and later to monitor the changes in adult population densities. To do this, a proper combination of traps and pheromone baits must be used. In this case, the trap catch was expressed in terms of percent of total capture.

The mating disruption method has been successfully developed for many lepidopteran species such as the pink bollworm *Pectinophora gossypiella* (Lepidoptera: Gelechiidae), the oriental fruit moth

Grapholita molesta (Lepidoptera: Tortricidae), and the tomato pinworm *Keiferia lycopersicella* (Lepidoptera: Gelechiidae) (Deland *et al*., 1994; Cardé and Minks, 1995). Mating disruption using funnel traps was effective in controlling the olive pest, *Palpita unionalis* (Hubner) (Lepidoptera: Pyralidae), in commercial olive groves where damage can reach up to 90% of the leaf area (Hegazi *et al.,* 2007).

Albajes *et al.* (2002) conducted several field trials which employed traps in treated fields for monitoring the Mediterranean corn borer *Sesamia nonagrioides* Lefebvre (Lepidoptera: Noctuidae) population, and for mating disruption using funnel traps to evaluate the efficacy of sprayable formulations of a binary pheromone blend of the pest. Lykouressis *et al*. (2005) also evaluated the efficacy of mating disruption of the pink bollworm *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) by monitoring its population with pheromone-baited traps as well as by sampling flowers and bolls to record the damage levels. Mating disruption was found to be effective in preventing damage when applied early in the season, but damage levels were not proportionally reduced in relation to the reduction of trap catches. The efficacy of mating disruption in reducing moth catches depended on the orientation of the rows of crop in relation to the direction of the prevailing wind in the area. The effectiveness of pheromone disruption is a matter of disrupting communication between the males and females which leads mostly to mating disruption, as expressed by a reduction in insect pest catches in traps and a lowering of the damage levels.

Hand-applied mating disruption dispensers were used in Australian orchards to treat individual orchard blocks infested by the oriental fruit moth and the codling moth. It was found that there was an increased incidence of pest damage on the borders of the mating disruption treated blocks adjacent to blocks without the mating disruption treatment (Il'ichev, 2008). As for mating disruption application techniques, two pheromone dispensers were required to control three leafroller species, (Lepidoptera: Tortricidae): *Epiphyas postvittana*, *Ctenopseustis obliquana* and *Planotortrix octo*, in New Zealand. A single dispenser was then developed, which provided simultaneous and efficient mating disruption of the three leafroller species (El-Sayed *et al*., 2008). In an Australian study on codling moth population suppression, a new 'meso' dispenser was developed with release rates ranging between 10 and 30 mg a.i. codlemone per dispenser per day. At higher release rates per dispenser, the number of point sources was effectively reduced by >90% without any measurable loss of programme performance (Welter and Cave, 2008).

Mating disruption was successfully used in controlling the mountain pine beetle, *Dendroctonus ponderosae* (Coleoptera: Scolytidae), using a combination of aerial permeation with anti-aggregation pheromones or repellent non-host volatiles with attractant pheromones (Gillette *et al*., 2009). Previously, Oehlschlager (2008) reported that mating disruption has emerged as a strategy applicable specifically to Coleoptera.

FUTURE DIRECTIONS

From the initial pheromone identification of an insect pest to the commercial availability of the pheromone system, there are numerous time-consuming and costly stages. One of these stages is the development of an efficacious and cost-effective pheromone formulation (Weatherston, 1990).

By monitoring the number of insects captured in traps throughout the season, the phenology of populations can be determined. This is also a useful tool for determining necessary control actions. The advantage of pheromones for monitoring purposes is their sensitivity in detecting pest occurrence at very low densities. Accordingly, they are also being used for monitoring the movement of migratory pests. The success of pheromone trapping in capturing insect pests suggests that trapping strategies can be used to control population levels. Such strategies include mass trapping that will decrease the adult population, leading to a reduction in the pest population in the following generation. Knowledge of the emergence and migration of adult pests by using traps enables farmers to make more timely management decisions. Some improvements in mass trapping programmes such as treatment efficacy, economic feasibility, and performance of traps in survey and detection can be maximized. This can be aided by the use of geographical information systems (GIS) which makes it possible to capture, organize and evaluate insect population data and to visualize spatial and temporal fluctuations on a regional scale. Geo-referenced insect monitoring data can be correlated with relevant parameters such as the distribution of the crop and other vegetation, geography, climate, and insect control programmes.

Based on information gathered from pheromone trapping tactics worldwide, strategies can be developed for controlling agricultural insect pests, specifically oil palm insect pests such as the rhinoceros beetle, *Oryctes rhinoceros*, and bagworms (*Metisa plana, Pteroma pendula, Mahasena corbetti*), as well as other leaf-eating caterpillars in oil palm plantations. Several studies on pheromone trapping were successfully conducted for controlling

M. plana (Norman and Othman, 2006; Norman *et al*., 2008; 2010) and *O. rhinoceros* populations (Norman and Basri, 2004; Ramle *et al*., 2005). Knowledge of pheromone components and antagonists is also essential for the development of the mating disruption technique (Witzgall *et al.,* 2000). Useful information on pest populations in infected areas can be gathered to formulate strategies for further action in developing trapping methods against the pests. Despite the growing concern for biodiversity and conservation, rare and threatened insects can also be monitored by pheromone trapping. The use of pheromone traps in controlling pests which are selective and species-specific ensures that the biodiversity of other non-target species is not threatened.

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