PHEROMONE MATING DISRUPTION WITH REFERENCE TO ORIENTAL FRUIT MOTH *GRAPHOLITA MOLESTA* (Busck). (Lepidoptera: Tortricidae) LITERATURE REVIEW

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Summary

Mating disruption is recognized as a powerful tool for control of OFM and is used by the majority of peach growers in Australia in regions where this insect is a pest. In some situations, control has been less than perfect and reasons for this are examined. Commercial formulations appear to have acceptable performance. Migration of mated moths from untreated peaches and other hosts is likely to be the principal cause of breakdown of control under mating disruption. Flights of females have been measured and are typically 160 metres with distances of up to 3 kilometres recorded. Movement can be focussed onto attractive susceptible peach crops, further magnifying the effect. This problem has been overcome by area wide use of mating disruption both in South Africa and Australia. Resistance to mating disruption has not been recorded but the possibility exists. Potential mechanisms are discussed.

INTRODUCTION

Oriental Fruit Moth (OFM) (*Grapholita molesta* Busck, Lepidoptera: Tortricidae) is one of the most important pests of commercial peach orchards in the Goulburn-Murray Valley region of Victoria. However, it is also recognised that in other stone fruit growing areas, such as Swan Hill, OFM is a minor problem at present. Some factors that are not yet identified may be significant in determining OFM population. No natural enemies of OFM have been identified in Australia which are capable of reducing OFM populations to levels below an economic threshold.

Chemical communication is vital to members of the class Insecta. Pheromones are chemical substances secreted by insects that affect the behaviour of other insects of the same species. There are many different types of pheromone affecting behaviours such as sexual communication, aggregation, alarm, epideiticity (spacing), trail following, trophillaxis, grooming and digging. Pheromones may also be involved in physiological development such as maturation and caste determination

Of these, sex pheromones are probably the most widespread and certainly the most widely documented used in plant protection. Insect sex pheromones are used in Integrated Pest Management (IPM) systems for the following:

— discovering species of insects in biocenosis and agricultural environment for taxonomic and plant protection investigations (Il'ichev *et al.* 1981),

— monitoring pests for detection (early warning, survey, quarantine), for threshold determination (timing of treatments and other sampling methods, risk assessment) and for density estimation (population trends, dispersion, risk assessment, effects of control measures) (Jutsum and Gordon 1989);

— forecasting of population density, trends and dispersion (Bailey 1980; Il'ichev *et al.* 1989);

— mapping for discovering centres and areas of infestation (hot spot) and risk assessment (Il'ichev 1991);

— sex pheromone barriers for localisation of infestation's centres and fixation of pest's dispersion (Il'ichev 1991).

— mass trapping for decreasing the level of population by using pheromone-baited traps (Campion and Nesbitt 1981);

— mating disruption for control of pests by the widespread application of synthetic pheromone over the target crop (Vickers *et al.* 1985; Barnes and Blomefield 1996).

MATING DISRUPTION

Use of mating disruption for pest control. OFM —a case study

Prolonged release of large quantities of sex pheromones may disrupt communication between male and female insects and can serve as a highly selective means for control of certain pests. Use of pheromones in this way is called mating disruption (MD). Several developments have permitted the use of pheromones as a control agent for OFM. These are:

1) The experimental demonstration of the possibility of control of OFM by MD (Rothschild 1975; Carde *et al.* 1977).

2) Synthesis of the sex pheromone of OFM in bulk at relatively low prices.

3) Development of effective and economical controlled release formulations.

The possibility of the control of OFM by MD with synthetic female pheromone has been demonstrated (Rothschild 1975; Vickers *et al.* 1985) in peach orchards in Victoria and NSW. The results of these trials supported the previous conclusion (Rothschild 1975) that disruption treatments could be as effective as insecticides for controlling OFM. MD can be more effective than insecticide control (Vickers *et al.* 1985), particularly when all orchards in a district are treated with MD. This eliminates the possibility of mated females migrating from untreated orchards and thus confounding the effects of the treatment.

An area-wide MD program utilising Isomate-M, a controlled release formulation of OFM pheromone, was initiated during the 1991–92 season in 1200 hectares (ha) of peaches and nectarines in the Tulbagh Valley, in South Africa. The project was an outstanding success. By the end of the season, shoot strikes were reduced to isolated occurrences and not a single infested fruit was recorded from the treated area (Barnes and Blomefield 1996). OFM continued to be a problem in the nearby Ceres district where the area-wide approach was not adopted and a patchwork approach of conventional insecticides on some orchards and MD on others was used. After the original success of the area-wide program in the Tulbagh, fruitgrowers became complacent and OFM has now returned as a pest (Blomefield, pers. com.).

MD against OFM in Spain, France and Italy has been an unquestionable success and commercial products have been developed, registered and adopted commercially, as happened in Australia and more recently in the United States (Audemard 1992). Field trials in California and Virginia peach orchards during 1983–87 with synthetic components of the OFM pheromone, have shown that pheromone treatments can reduce OFM damage at harvest to levels competitive with standard insecticide spray programs and at comparable cost. Results also suggest that when OFM populations are reduced to very low levels with pheromone treatments, reinfestation occurs slowly. The area of peaches and nectarines treated with Isomate-M in California increased dramatically from approximately 750 ha in 1987 to 1600 ha in 1988 (Rice and Kirsch 1988). The total area of peaches in western USA treated with MD for OFM is in excess of 4000 ha. The area treated is limited because of the presence of another moth, peach twig borer—*Anarsia lineatella* Zell. (Lepidoptera: Gelechiidae) (Jenkins, pers. com.).

The application in Italy of MD for the control of OFM in peach orchards has greatly increased recently, on the basis of the good results obtained in experiments some years ago (Molinari and Cravedi 1992). The investigation of MD for control of OFM in Spain has shown that this method of control was very specific for OFM (Gonzalez 1990). MD was successfully included in IPM programs for OFM control in peach orchards in France (Gendrier 1993). The trials of OFM control by MD using Isomate-M pheromone dispensers on peaches in Greece were combined with insecticide treatments (Kyparissoudas 1989). An investigation of OFM MD was done in peach orchards in Canada from 1987 to 1990. The authors of this study suggested that pheromone-mediated MD may have potential for the control of OFM in Niagara peach orchards if moth populations are small or are reduced to low levels with insecticides before treatment with pheromone (Pree *et al.* 1994). MD in combination with insecticides was developed as a means for control of OFM populations in pome and stone fruits in the former USSR (Atanov 1993).

Mechanisms of mating disruption

Control of insect pests by the mating disruption technique is achieved by the widespread application of synthetic pheromone over the target crop. This prevents males from locating virgin females in orchards or significantly delays their meeting. Where mating is sufficiently delayed, fecundity is reduced or eliminated (Vickers 1992). In this way, the fecundity of the targeted pest population is drastically reduced. The mechanisms by which MD operates are still not fully understood and investigated. Bartell (1982) suggested the following mechanisms:

1) *False-trail-following:* males are repeatedly attracted to the artificial odour sources which compete with the calling females.

2) *Masking of female odour plumes:* males cannot distinguish between female odour plumes and the background created by artificial sources.

3) *Sensory overload:* stimulation by the synthetic pheromone causes a reduction of responsiveness at the level of the receptor system (adaptation) or the central nervous system (habituation) (Arn 1992).

Some authors also believe that females can perceive their own pheromone, and that in its presence the calling or mating behaviour could be affected (Jutsum and Gordon 1989). The females may have responded to a super-abundance of their own sex pheromone by moving outside of the MD area to mate and then return for oviposition in response to the food attractant from shoot tip or ripening peach fruit (Il'ichev *et al.* 1999). Although there is no direct evidence that OFM females can detect their own sex pheromone, such a response has been detected in the females of some Tortricidae (Den Otter *et al.* 1996; Palaniswamy and Seabrook 1978).

MD works best as a sole treatment against low pest population densities. Unfortunately, in most cases, it is not possible to estimate the population density of the pest insects, nor to measure the amount of pheromone present in the volume of air in which was carried out the disruption of the males (Cravedi 1992). Through the use of food traps, it has been shown that mated females, albeit in small numbers, can be present even in large peach orchards where MD was applied. This situation does not generally jeopardise control of OFM, but suggests that mechanisms other than sex pheromone calling may allow some mating (Molinari and Cravedi 1989). An alternative explanation might be that breeding is occurring in unanticipated hosts nearby or that migration is occurring over longer distances than expected. Recent observations (Il'ichev *et al.* 1998) indicated that migration of mated OFM females from pear blocks under traditional chemical spray program to adjacent peach MD blocks resulted in damage at the edge of these peach blocks. Peach shoot tips and fruit could attract mated females from pears, where they have developed a high population, to the adjacent peach block for oviposition. This explanation of edge effects and the occurrence of shoot tip and fruit damage mostly on borders of MD-treated peach blocks may also indicate a behavioural avoidance of unmated females to MD (Il'ichev *et al.* 1999).

Where false trail following is the operating mechanism, sources of pheromone compete for males with female moths. Large numbers of MD dispensers with emission rates equivalent to females would be required. Alternatively, smaller numbers of dispensers with emission rates far higher than females would be effective. In either case, the technique would be less effective against high pest populations. In contrast, the adaptation/habituation mechanism is potentially independent of the initial population density of the pest and, in theory, should lead to effective control of OFM even at high population levels (Valeur and Lofstedt 1996). It is possible that several mechanisms operate concurrently. The investigation of behaviour of OFM males in overlapping sex pheromone plumes in a wind tunnel has concluded that both 'false trail following' and 'habituation/adaptation' result in MD in OFM moths (Valeur and Lofstedt 1996). Wind tunnel and field studies have demonstrated that habituation/adaptation may be the mechanism operating when OFM is controlled by MD (Rumbo and Vickers 1997). However, the authors state that the field concentrations required to achieve habituation/adaptation are higher than those observed in the field. It is possible that powerful discrete dispensers could give localised concentrations of pheromone sufficiently high for habituation/adaptation while the overall field concentration is much lower.

REASONS OF IMPERFECT CONTROL OF OFM WITH MD

In general, MD has been an outstanding success in the major stone fruit growing districts of Australia and is the cornerstone of IPM in the canning and fresh peach orchards of the Goulburn Murray Valley. In recent years, the technique has proven more reliable than conventional organophosphate insecticides spray program leading to adoption in more than 90% of the total acreage in the important Cobram and Invergordon districts. However, shoot and fruit damage in certain peach blocks has continued to cause problems.

Performance of commercial formulations

The success of OFM MD depends on the method of dispensing synthetic sex pheromone (Rothschild 1979) as well as the chemical composition of sex pheromone, rates of release (Lacey and Sanders 1992; Rothschild and Minks 1974) and the place of the pheromone dispenser in canopy (Baker and Haynes 1996).

The blends of OFM pheromone for MD used in commercial formulations are identical to those used in earlier trials and have been repeatedly demonstrated to be efficacious (Rothschild and Vickers 1991). Outputs exceed the thresholds determined by early researchers by a factor of 3 to 4 for most of the field life (Sexton and Il'ichev, in press). The widespread success of the Isomate-M, Isomate OFM Plus, Isomate OFM Rosso and other commercial formulations used elsewhere in the world suggest that in general, the output is adequate. Questions have been raised about the efficacy of certain formulations toward the end of their claimed field lives (Rice, pers. comm.). Data now available suggests that the output of the commercially available formulations used in Australia remain above the threshold required for MD for a period of more than 180 days (Sexton and Il'ichev, in press). The reliability of the threshold when considered independently of population pressure remains a moot point. However, it appears that the performance of commercially available formulations used in Australia is adequate.

Migration

The degree to which control is obtained with MD of OFM is ultimately determined by the number and fecundity of mated female moths in the treated area. Migration of mated females from sources of OFM breeding outside the treated area appears to be important. The impact of migration of mated female moths is likely to be determined by a number of factors:

1. The size of the initial source population.
2. The distance between the source of OFM and the orchard treated with MD.
3. The proportion of the population with the ability and predisposition to move over that distance.

It is possible to obtain a rough estimate of the number of mated female moths capable of causing economic damage in a peach orchard with a number of simple assumptions and published data.

Assumptions

1. Economically significant infestation of 1% fruit loss or more.
2. 250,000 fruit per hectare.
3. One larva is capable of infesting one fruit.
4. Oviposition 79 eggs per female moth (3rd generation) (Phillips and Proctor 1969).
5. Survival of larvae from hatching to establishment is 50% (Rothschild and Vickers 1991).

If one accepts the above assumptions, in the order of 60 mated female OFM moths would be capable of causing 1% infestation in a hectare of peaches.

Populations of late instar OFM larvae may range up to an estimated 30,000 per ha (Rothschild and Vickers 1991). If 80% of these larvae emerge as adult moths, the male to female ratio is 1:1 and 100% of the females are mated, the source population of mated OFM female could range to as high as 12,000 per hectare. Movement of only 0.5% of populations of this size to orchards of equivalent size relying on MD could result in significant economic damage.

Distance of movement

The distance between a source population and a peach orchard treated with MD may be as little as one row (6 metres). In such circumstances, sources are usually obvious but may not be anticipated. Recent work in Cobram has shown that OFM can breed to large numbers in unexpected hosts (eg. pears sprayed with a conventional insecticide program) and can move into adjacent peaches under MD (Il'ichev *et al.* 1998). Concentration of even low populations of OFM from adjacent less attractive hosts onto small focuses of highly attractive ripening peaches would have the potential to cause high levels of infestation. This may account for the apparent high susceptibility of late harvested varieties.

The significance of large populations of OFM in the range of several hundred metres (m) to a kilometre (km) or more from the peach crop treated with pheromone mating disruption is of great interest.

Studies of movement of OFM have shown that most adults do not disperse over distances greater than 200 m, although a small proportion may cover distances exceeding 1 km (Rothschild and Vickers 1991). Migration of mated female OFM between peach blocks and from orchards containing other hosts of OFM adjacent to pheromone-treated peaches was recorded in USA. In California, almonds and plums, and occasionally prunes and apples can produce high populations of OFM (Rice and Kirsch 1988). De Montaigne (1984) used pheromone traps to trap marked male moths released in French peach orchards. Moths were shown to able to travel at least 500 m suggesting that dispersal of moths was more important than previously considered (De Montaigne 1984). Movement of male moths within mixed pome and stone orchards in Hungary was estimated using pheromone traps. The movement of male moths away from peach orchards into open areas was very limited (generally less than 200 m) (Sziraki 1979).

The most comprehensive study of movement of OFM to date was conducted in USA using a vast array of bait lure traps (Yetter and Steiner 1931). Results from the Indiana trials showed that dispersal was greater before harvest and that the average distance travelled for marked female moths was 160 m compared with 142 m for marked male moths. The longest flight recorded for marked moth was 1,989 m for a female and 1,288 m for a male. The trials in Georgia found that the average distance travelled for the marked moths was 335 m with the greatest distance recorded being 1,859 m. Unlike the Indiana trials, dispersal was greater after peaches had been harvested and twig growth had ceased. Additional trials in Georgia confirmed that significant movement of moths occurred before and after harvest of peaches. Seven flights of between 1.6 km and 3.0 km were recorded (Steiner and Yetter 1933). From the above studies, it is clear that movement of significant numbers of both male and female of OFM over several hundred metres is likely to be a commonplace occurrence and a small proportion of a population can move a kilometre or more.

The above studies generally describe random dispersal of marked OFM released within a host crop. No study directly addresses the possibility of non-random dispersal from an unattractive oviposition site (eg. peach trees after harvest, with hardening shoots) to an attractive site (eg. a later variety of ripening peaches). Under these circumstances, it is conceivable that movement of mated OFM females would be directed by host volatiles (eg. peach fruit aroma) toward more favourable oviposition sites. Dispersal would be non-random and a larger proportion of the population could be involved. Such movement would be focussed in a way that would maximise economic damage. Yetter and Steiner (1932) provided evidence of non-random long distance movement of OFM in their data on dispersal of marked moths from points of release. In the study in Vincennes, Indiana, data was presented on the distances and directions of the longest flights. During the period of the experiment, wind direction was from the southwest on ten of the eighteen days when releases were made. Wind direction was not recorded on the other days. 93% of the moths undertaking longest flights flew in a southerly (S, SW or SE) direction. This implies a directed upwind flight rather than passive downwind movement (Yetter and Steiner 1932).

POSSIBILITY OF SELECTION FOR RESISTANCE TO MD

It is very difficult to eliminate all individuals of a particular species from an insect population. Mechanisms for development of resistance to MD can be imagined. If a small proportion of the target population is capable of reproducing parthenogenically, this characteristic would be strongly favoured under MD. There is no evidence of this in OFM so far. It is conceivable some members of the population might be less susceptible to the sensory overload component of the MD and could continue to search for females in the MD environment. This behaviour seems to be the norm with the Codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae). In such circumstances, if population densities were sufficient, males could find females using visual or other non-pheromone cues. Alternatively, selection might favour moths that are repelled by a superabundance of their own pheromone. These insects could avoid the effect of MD by moving outside the treated area to seek mates. The females might then return to the treated crop for oviposition. Again, males that are more sensitive to a minor component of the natural sex pheromone not included in the artificial disruption blend might be able to discriminate between females and 'false trails' and avoid the effect of MD.

Against this, where area-wide programs have been implemented and all sources of OFM have been eliminated, the populations of OFM have crashed to undetectable levels (Vickers *et al.* 1985; Barnes and Blomefield 1996; Il'ichev *et al.* 1998). Under such circumstances, the gene pool from which resistant moths could be selected is eliminated. It could be argued that development of resistance is unlikely, particularly if the mechanism of MD is density dependent.

CONCLUSIONS AND AREAS WARRANTING INVESTIGATION

Overall, the evidence strongly shows that MD can effectively control OFM. Area-wide programs aimed at suppression of OFM populations over whole fruit growing districts have been demonstrated to be effective and may be a practical strategy for more widespread use.

Gaps in knowledge exist and investigation of the following is warranted with a view to improving the reliability and sustainability of MD technology for OFM:

1. Low cost maintenance level of MD regimens to prevent re-establishment of OFM in peaches and other hosts in the wake of area-wide population suppression programs.
2. Migration of OFM and flight behaviour of adults, particularly long distance non-random migration.
3. The population dynamics of OFM breeding in hosts other than stone fruit, particularly pome fruit.
4. Crop and varietal mixes that favour or mitigate against high populations of OFM.
5. Large orchards which have been maintained under MD for many years should be observed for any signs of re-establishment of the pest which could signal some form of adaptation or resistance to MD.

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