Insect Pheromones and Other Behaviour-Modifying Chemicals: Applications and Regulation

BCPC Monograph No. 51

Foreword

Crop protection today is one of the crucial issues in agriculture. On the one hand, there is the necessity to take measures to control diseases and pests in agricultural crops: the growth of more or less uniform plants in sizable plots is an invitation for pathogens and insects to develop in epidemiological proportions. On the other hand, there is the possibility of unfavourable side effects of these measures on non-target organisms and the environment. In view of the increasing concern about this, the government of the UK and other countries are in the process of developing legislation, aiming at a drastic reduction of the use of agricultural chemicals for crop protection. The public concern about this is also reflected by the theme of the Bawden lecture at the opening session tomorrow of the Brighton Conference: "The hazards of healthy living — the agricultural component". And finally there is, in view of the 1992 Single European Market, the important problem of harmonization of pesticide regulation. The British Crop Protection Council is active also in this field: last January it organized an international meeting on pesticide regulation.

Your pheromone regulatory symposium, which precedes the Brighton Conference, has a relation to all topics just mentioned. In view of the necessity to have sufficient control measures available and the desirability to reduce the hazards of one-sided use of pesticides, it stresses the need for alternative pest control methods. One of these methods is the use of naturally occurring behaviour-modifying chemicals (BMCs) in insect control. They differ from conventional pesticides by the fact that they do not kill the plague insect, but modify its behaviour. A great advantage is that they are very selective, interfering specifically with the behaviour of a particular insect. This implies less hazards for non-target organisms. Moreover, the increasing use of such compounds will help to reduce the selection pressure by pesticides. This in its turn will decrease the chance for development of pesticide resistance, and thus reduce the chance that valuable pesticides will be lost for plant protection.

A number of pheromones have already been shown to provide valuable control of insect pests, but there is clearly a problem: behaviour-modifying chemicals are, as already expressed in the name, also chemicals, and the admission of these into practice requires a very long and tedious regulatory procedure. This of course raises the question of whether it is necessary that BMCs follow the same procedure as conventional pesticides. Those who are familiar with the selective action of pheromones, and in general with BMCs, will argue that this should not be required, but regulatory agencies may have a different opinion, pointing at the fact that the BMCs may be applied at concentrations higher than those occurring naturally. Some may also question whether it is sure that these chemicals or their formulations are free of hazards to persons who handle them. This matter will be an important point of discussion during this symposium.

A second point of discussion will be the proposed EC Pesticide Registration Directive for regulating the use of naturally occurring chemicals for pest control, in other words, the harmonization of regulatory measures for BMCs in the European Community. It would be very confusing indeed and unfortunate that regulations concerning admission of BMCs, for no solid reasons, would differ from one country to another.

It seems timely and appropriate that the organizers have brought together experts from various countries to discuss these topics, and not only to discuss them, but also to come up with recommendations to policy makers. During this symposium you will have a task which is not easy, but which is important.

On behalf of the British Crop Protection Council, I wish you success with this symposium, for the benefit of efficient and acceptable crop protection in the future.

J. Dekker, President
British Crop Protection Council

Preface

A comprehensive review of the use of naturally occurring behaviour-modifying chemicals (BMCs) for insect management took place at an international symposium held in association with the National Conference of the Entomological Society of America (ESA) at Boston, MA, in December 1987. Information presented at that symposium provided solid evidence that BMCs have been demonstrated to provide effective insect control and that these specialty chemicals provide the potential for a substantial expansion in the use of biologically based methods of insect control. In the words of one symposium participant, we have reached "a watershed and...the glass is half-full", not half empty. However, the three presentations on regulatory affairs and related discussions indicated that considerable misunderstanding and probably some unnecessary regulatory barriers to the development of BMCs existed. A review of some events following the 1987 symposium may provide a useful perspective of the aims of the regulatory symposium held in Brighton.

A senior regulatory official from the United States Environmental Protection Agency (US EPA) who was present at the Boston symposium expressed a desire to improve both communications and procedures and indicated that the agency would assign a person to continue interactions with representatives of the pheromone community. Following discussions with experts in the field of BMCs, a suggestion emerged that the US EPA would prepare a "white paper" to review the data available on a selected group of lepidopteran pheromone components (straight-chain acetates, aldehydes and alcohols with between 10 and 20 carbons) and to propose some regulatory options for reducing the regulatory data requirements.

Concurrently with the discussions with regulatory officials, an ad hoc committee, with representatives from academia, government, and industry, was established to provide a mechanism to facilitate additional communication. Two informal follow-up conferences were organized under the auspices of ESA. The primary purpose of the first, in December 1988, was to provide researchers with information on the regulatory requirements for BMCs; presentations were made by regulatory specialists on toxicology, environmental effects, and procedures. This informal session contributed significantly to improving the understanding of the regulatory process with particular reference to the special provisions for biochemical pesticides. At the second informal conference, in December 1989, the focus was on the industrial perspective, with presentations by representatives from private companies followed by a response from a national regulatory agency. During this conference, some of the concerns of industry were discussed and some suggestions were made to facilitate the regulatory process.

In January 1990, European representatives that had been involved in one or more of the US conferences recommended to the program policy committee of the British Crop Protection Council (BCPC) that BCPC take the initiative to stimulate European and North American dialogue on the applications and regulation of BMCs. The BCPC program policy committee responded by inviting European and North American interests to organize a symposium on applications and regulation of BMCs to be held immediately preceding the 1990 Brighton Crop Protection Conference. The primary objective of this initiative was to improve the understanding within the European Community (EC) of the provisions in the US EPA regulations that provide for reduced data requirements for microbial and biochemical pesticides through a tier-testing approach. A secondary objective of the initiative was to broaden the appreciation for the potential uses of BMCs as environmentally desirable pest control alternatives and to facilitate the regulatory process. Such an effort was particularly timely, because the proposed EC Pesticide Registration Directive, which was reviewed in depth at a BCPC symposium in January 1990, did not contain any special provision for regulating naturally occurring biochemical pesticides such as BMCs, although the draft EC directive did contain a special provision for microbial pesticides.

A workshop with 35 participants was held on the day preceding the symposium; this workshop was designed to highlight issues for discussion among the over 200 participants at the symposium. The workshop participants also developed a list of principles to serve as a guide for follow-up discussion and possible action by various regulatory officials. The organizations represented and the active participation of the attendees at both the workshop and symposium provided substantial evidence that the goal of improving the understanding of the actual and potential importance of BMCs and of the regulations governing their use was accomplished.

This monograph, which documents the symposium and workshop, is divided into six major sections. The first section presents interpretive summary of the proceedings. The second section provides an overview of the opportunities for utilizing BMCs for insect control. The third section deals with the status of regulations in the United States and Europe. The fourth section documents data on non-target effects of BMCs. The fifth section deals with some opportunities for expediting the regulatory process. The final section includes a report on the workshop.

Because of the need for creditable scientific documentation for possible use in decision making, the editors and a number of the authors involved made the decision that the three chapters in Section 3 and the four chapters in Section 4 should be scientifically peer-reviewed to validate the data presented. Therefore, formal peer reviews were obtained from two or more scientists for each of the seven technically referenced chapters.

We wish to express our appreciation to the BCPC and its representatives (program policy committee, publications staff, special representative) for the foresight and commitment necessary to bring together a diverse group of people for presentations and discussion and to publish the results. Appreciation is also extended to Owen Jones and Fred Saunders, who participated in the organization of both the workshop and the symposium; to Ken Farminer, who supported the organizing committee throughout the entire process; and to Sarah Jenkins, Marilyn Parsons, Rosemary Taylor, and Beverly Slaughter, who provided administrative support. Special recognition is also extended to the authors who have contributed manuscripts to this monograph and to reviewers of the manuscripts. On behalf of the organizers and editors, we also wish to acknowledge the following sponsors, whose support made possible the presence of several of the speakers and provided partial support for publication of the proceedings: AgriSense-BCS Ltd.; AgriSense USA; Bedoukian Research Inc.; Ciba-Geigy; Cooper-Welcome Ltd.; Dow Corning Ltd.; ICI Agrochemicals; Phero Tech Inc.; Charles Valentine Riley Memorial Foundation; Siber Hegner Raw Materials Ltd.; and Trécé, Inc.

Also, we wish to acknowledge the assistance of Heinrich Arn, convenor of the working group on the use of pheromones and other semiochemicals in integrated control for the Western Palearctic Regional Section of the International Organization of Biological Control. As a leader of periodic work conferences in Europe on pheromones and co-editor of the monograph, Dr. Arn has made a significant contribution to maintaining a truly international perspective.

Finally, very special thanks are extended to Albert Minks, who has through the years provided invaluable leadership on pheromones in the scientific community and who played a special role in the communications and additional documentation after the workshop and symposium that were necessary to provide the desired balance in the material published in this monograph.

We are hopeful that the knowledge shared in Brighton and this resulting monograph will lead to the expanded use of BMCs in insect management and to more effective and environmentally compatible crop protection practices.

Richard L. Ridgway
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1.

Monograph Summary

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A symposium and workshop were held in Brighton, UK, in November 1990 to broaden appreciation for the potential of naturally occurring insect behaviour-modifying chemicals (BMCs) as environmentally desirable biopesticides, to improve the understanding of existing and proposed regulations for biochemical pesticides, and to facilitate the regulatory process. Broad concerns about pesticide residues in food and water, specific policies in some European countries designed to reduce use of conventional pesticides, and the need to decrease the chance for development of pesticide resistance were identified as justifications for efforts to expand the use of pheromones and other semiochemicals that modify insect behaviour. An overview of the material presented and the discussions associated with the symposium and workshop is presented in this summary. For the purposes of this summary and the monograph, the terms "behaviour-modifying chemicals" and "semiochemicals" have frequently been used synonymously, with the understanding that only semiochemicals that elicit a behavioural response and naturally occurring or "nature-identical" chemicals are included. Additional discussion of the terminology is provided in the Workshop Report.

APPLICATIONS

Monitoring

Attractant-baited traps are widely used for monitoring insects throughout Europe, North America, and many other parts of the world. Trap captures provide information ranging from detection of the presence of the earliest individual insects to a quantitative assessment of an insect population. This use in monitoring, involving hundreds of insect species, contributes immeasurably to the effective application of a wide range of control tactics used to reduce losses due to insect pests. However, most uses of BMCs in traps for monitoring are not regulated under current pesticide laws, and government regulations do not appear to be a barrier to expanded uses of traps. Therefore, need for facilitating the regulatory process rests primarily with "pesticidal" or control uses of BMCs.

Suppression

In the late 1970s, great expectations for the use of pheromones for insect control developed in both Europe and North America. However, real commercial successes were slow to develop and the coming and going of companies with a temporary interest became characteristic. However, after several years of uncertainty, a number of important management programs that include a BMC component have evolved. Approaches to insect control using BMCs include mass trapping, mating disruption, tree baits, and toxic baits. Practical applications for several pests in the US and Canada and intensive developmental research and some commercial sales in Europe are reviewed. These examples and others that are referenced demonstrate that a number of important practical uses of BMCs are well established. These examples also provide a basis for expecting that additional viable commercializations will be forthcoming, especially if the cooperation between industry, government, and academia can be strengthened. Although current commercial use primarily involves attractant pheromones, other naturally occurring BMCs such as aggregation and alarm pheromones, plant attractants, feeding stimulants, and insect kairomones have considerable potential. However, the view that the present regulatory process for naturally occurring BMCs is often unduly long and that a clear regulatory policy in some countries is lacking represents a significant barrier to expanded practical use of a group of desirable biologically based pest control products.

CURRENT REGULATIONS

The United States Environmental Protection Agency (US EPA) established a policy in 1979 and published guidelines in 1982 that resulted in considerably reduced data requirements for the registration of microbial and biochemical pest control agents. These guidelines incorporated a "tier-testing scheme" that limits data requirements to those in the first of three tiers of tests if no significant adverse effects are demonstrated in the tier-one tests. A provision is also made for granting waivers for data not believed to be relevant in evaluating the hazard presented by the product under consideration, when sound scientific evidence is presented to support the request for a waiver.

As in the US, most European countries require that BMCs to be used for pest population control be registered as pesticides. Although formalized policies to reduce data requirements for BMCs are lacking in most countries, flexibility has been shown by many European countries, and a number of data waivers have been granted. A Pesticide Regulation Directive proposed by the European Community provides special consideration for microbial agents but supposedly would treat pheromones and other naturally occurring chemicals as conventional pesticides. Although there is no indication that the new Directive would prevent individual countries from maintaining flexibility in regard to BMCs, the proposed Directive apparently will not contribute to clarifying policy.

NON-TARGET EFFECTS

BMCs are generally characterized by their relatively low toxicities and limited exposure potential, target-species specificity, and natural occurrence. In response to earlier suggestions that scientific documentation of relevant data might lead to reduced requirements, non-target-effect data are reviewed for three categories of BMCs: lepidopteran pheromones, coleopteran pheromones, and phytochemicals. Data on fate and potential residues of some lepidopteran pheromones are also presented.

Lepidopteran pheromones

The majority of the known lepidopteran female sex pheromone components are long-chain alcohols, acetates, and aldehydes. Available data on mammalian toxicity, fish and avian toxicity, effects on non-target species, anticipated exposures, and environmental fate of such compounds suggest that there is minimum risk associated with the use of these compounds for pest control. For example, the rat oral LD_{50}s for sixteen compounds and three binary mixtures examined were all greater than 3,000 mg/kg, and since these values were generally reflecting results of "limit testing", the actual values may be much greater. Other than skin irritation caused by one of the alcohols, no significant adverse effects were reported for these materials. Therefore, substantial reduction of toxicological data requirements for these compounds through standardized waivers, particularly for experimental use permits (EUPs) and for temporary exemptions from tolerance, would be appropriate.

Coleopteran semiochemicals

Many of the known coleopteran semiochemicals (aggregation and antiaggregation pheromones, kairomones, allomones) are monoterpenes. These relatively simple compounds, composed of two isoprene units and containing only carbon, oxygen, and hydrogen, are produced by insects and many plant species. In general, the compounds fall into one of the two lowest toxicity categories established for pesticide labelling purposes in the US. Rat oral LD_{50}s for α- and β-pinene, myrcene, camphor, and a mixture of *exo*-brevicomin, frontalin and myrcene are all greater than 2,000 mg/kg, while dermal LD_{50}s on rabbits are all greater than 5,000 mg/kg. A comparison of the estimated atmospheric concentrations of semiochemicals produced by natural infestations of bark beetles with the calculated emission rates of the chemicals from controlled-release formulations used as tree baits showed that the effect of the baits on the environment would be comparable to the effect of pheromone traps. Therefore, similar regulatory treatment for tree baits and pheromone traps is appropriate. A specific exemption of tree baits for management of the mountain pine beetle has been granted by the US EPA.

Phytochemicals

Many of the semiochemicals affecting insect behaviour arise from plants. Many of these phytochemicals, either obtained from natural sources or synthesized, are used in the flavour and fragrance industry, and considerable toxicological information has been obtained to support those uses. A review of the available data for selected groups of compounds such as acyclic terpenes, cyclic terpenoids, and aliphatic acids and esters indicates that the oral LD_{50}s in rats and the dermal LD_{50}s in rabbits are consistently greater than 1,000 mg/kg and are often greater than 5,000 mg/kg. Current annual usage of some of these compounds in fragrances and flavours ranges from hundreds to millions of kilograms. Utilization of a decision-tree approach similar to that used by the flavour and fragrance industries to make decisions on waivers from data requirements, in combination with the tier-testing approach provided under current US biochemical and microbial regulatory guidelines, could provide a process for reducing toxicology data requirements without compromising safety.

Potential pheromone residues in fruit

In a study to determine residues of pheromones in treated fruit, sixteen orchards or vineyards were treated with controlled-release formulations of various lepidopteran pheromones comprising ten different components at rates ranging from 12.5 to 316 grams/hectare. When apples, grapes and peaches harvested from these locations were analyzed, using methods with a minimum sensitivity of <5 parts per billion, no residues were detected in any samples. These results confirm the prediction of negligible residues for lepidopteran pheromones used in fruit production. It is probable that residues of other types of pheromones that are applied at low rates and are subject to rapid degradation to common metabolites would also be negligible.

PRINCIPLES FOR FACILITATING THE REGULATORY PROCESS

Principles or collective judgments to facilitate the regulation of naturally occurring BMCs, representing the consensus views of 35 workshop participants were drafted for consideration by regulatory officials and other interested parties:

- BMCs used in traps for monitoring should be regulated primarily under laws ensuring safety in manufacturing and handling.
- BMCs used for pest control should be regulated.
- BMCs are different from conventional pesticides and should be subject to adjusted and less stringent regulation.
- A tier-testing or decision-tree scheme can provide a logical scientific approach to establishing the regulatory requirements for BMCs while maintaining the critical regulatory procedures necessary to ensure minimum risk.
- Scientific advisory groups should be consulted to facilitate the development of criteria for use by regulatory agencies.
- Rationale for regulatory decisions, including case-by-case decisions on data requirements, should be made readily available to the public.

- Regulatory procedures imposed and data requirements for BMCs should be adjusted to be consistent with the potential risk associated with the use and the rate and method of application; data requirements could be reduced for:
  - BMCs applied to non-food crops as compared to those applied to food crops or to stored foods.
  - BMCs delivered by techniques in which the chemical or its formulation does not come in contact with the edible portion of the crop.
  - BMCs that are applied at very low rates
  - BMCs that are applied for small-scale experimental purposes when compared to those for commercial use.
- Requirements for data on the active ingredient versus the end-use product should be clarified.

ISSUES AND NEEDS

The regulatory burden of evaluating a new BMC and obtaining the necessary data for registration, coupled with a lack of understanding of the requirements, is proving an impediment to the development of new uses for these environmentally compatible materials. Regulatory relief to ease this burden will facilitate the use of alternatives to toxic compounds without causing undue risks to the environment. On the contrary, the overall risks may be expected to decrease, since to the extent that BMCs have an impact on reducing pesticide use, they will be reducing risk. In the US, regulatory relief can be achieved within existing regulations through the mechanism provided by the tier-testing approach and the provision for data waivers.

Up to now in the US, easing of regulations for biochemical pesticides has primarily applied to full registrations, but the need for relief in the experimental evaluation of these materials is even greater. The US system of Experimental Use Permits (EUPs) was developed for experimentation with potential conventional insecticides; it is often inappropriate for materials such as BMCs, that have completely different use patterns and modes of action. Because BMCs generally are not insecticidal and do not cause insect mortality in themselves, the areas necessary to determine effectiveness against mobile insects are usually much greater than are needed for insecticides. The potential of most BMCs for insect control cannot be evaluated without large-scale testing. Since the area that can be used in the US for experimentation without an EUP is normally limited to 10 hectares (4 acres), efficacy data for BMCs usually cannot be obtained without an EUP. This requirement substantially increases costs and may delay experimentation a year or more. Furthermore, a temporary tolerance or a temporary exemption from tolerance, which is required if a pesticide-treated food or feed crop is to be marketed, is often necessary to proceed with experimentation because the costs associated with the destruction of sizable acreages of crops would be prohibitive.

The uniqueness of very low exposure potential and low toxicity of BMCs warrants special attention in terms of waivers of data requirements and modifications of acreage limitations. Also, the rationale behind issuance of data waivers and other decisions that reduce data requirements should be well known and understood. Therefore, it is extremely important that information on data waivers be made readily available to the public at an early date. The *Federal Register* provides an appropriate outlet for this kind of information in the US.

A representative of the US EPA indicated that the ongoing analysis of available data may provide the scientific basis for adjustment of data requirements for specific classes of biochemicals. This representative also challenged scientists in the public and private sectors to participate in identifying possible alternative approaches and providing the necessary scientific justification for modifications in the regulatory process.

In Europe at the present time, the process of registration of BMCs among different countries is highly variable. In the draft *EC Pesticide Regulation Directive*, no consideration is being given to the special properties and potential of BMCs. Interested parties in Europe should pursue the opportunity to present the case for regulatory relief before the *Directive* is finalized.

POSTSCRIPT

At the close of the symposium, representatives from industry and government called for American and European interests to respond to the challenge from government officials on both sides of the Atlantic by providing information and rationale needed to accomplish desirable change.

Subsequently, North American commercial semiochemical interests formed an *ad hoc* group that held its third meeting on August 29, 1991, in Denver, CO, USA. A new trade association to be known as the American Semiochemicals Association is being formed and fourteen companies have expressed interest in being members. The purpose of this trade association will be to assist and cooperate with legislative and regulatory bodies and administrative agencies in developing means of facilitating regulatory processes relating to or affecting the use of semiochemicals in pest management and to advance the goodwill of the semiochemical industry by disseminating information for the education of the public. Representatives from European semiochemical interests met in Brussels, Belgium, on September 12, 1991, to explore and plan formation of a group to address regulatory concerns in Europe.

2.
Practical Applications

Chairman: ALBERT MINKS

PRACTICAL APPLICATIONS: THE EUROPEAN SCENE

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ABSTRACT

An overview is given of the current status of applications of insect pheromones in Europe. While pheromone-baited traps have been used for monitoring pest species for almost 20 years, recently successful applications of pheromones for mating disruption have also been demonstrated. A survey of users revealed that pheromone-baited traps were employed principally for monitoring flight activity for early warnings of pests, and less often for determination of economic thresholds. Most of the monitored species were lepidopterous pests in fruit cultures where the use of pheromones to disrupt mating is rapidly leading to their commercialization. Research has been stimulated by collaboration between research institutes and industry, in particular BASF. The IOBC/WPRS Working Group "Use of Pheromones and other Semiochemicals in Integrated Control" made a major contribution to the stimulation and coordination of research efforts.

INTRODUCTION

Insect pheromones have become an important part of the armory of modern plant protection methods. They fit well in the current plant protection policy of most European countries to reduce or to minimize the use of conventional pesticides in agriculture, which has been set in motion by the growing public concern about the deteriorating quality of the environment. Therefore, research and development of integrated pest control methods including pheromones has been encouraged strongly. In such a climate conditions are favourable to undertake serious attempts to make pheromones ready for commercial application even if they will cost more than conventional pesticides.

Since Butenandt completed the first identification of a sex pheromone (Butenandt *et al.* 1959) and Karlson & Lüscher (1959) coined the term "pheromone", European researchers have made many important contributions to the present knowledge of pheromones. These contributions have covered the whole field: from chemistry and behaviour to application studies. A major role in the stimulation and coordination of the research is played by the IOBC/WPRS Working Group "Use of Pheromones and other Semiochemicals in Integrated Control", established in 1975. Usually meetings of this group are held every two years. Most of the meetings were attended by some 60-80 participants, the greater part of them coming from Europe, but also including colleagues from other parts of the world. Abstracts of the most recent meetings (1986, 1988 and 1990) were or will be published as IOBC/WPRS Bulletins. These bulletins give an up-to-date overview of the research activities in the various European countries, particularly of the applied research.

To this important source of information we should add two recently published books, respectively edited by Jutsum & Gordon (1989) and Ridgway *et al.* (1990), reviewing the applications of pheromones. In these reviews prominent European experts have presented the most important cases of pheromone application in their part of the world.

In view of all this recent information, the present authors believe that it is senseless to write this over again. Here we shall restrict ourselves to providing some notes in the margin, discuss the latest developments and pay special attention to some important activities of the IOBC/WPRS Working Group, since we realize that outside Europe the IOBC/WPRS Bulletins are not known very well, because of their limited distribution.

MONITORING

In Europe pheromones are widely used for the monitoring of noxious insects. Pheromone traps are easy to use and have a species-specific action, which can save much time. In particular at low densities they are very effective. The popularity of this method is reflected by the sales of our institute, one of the major suppliers in Europe, which amount to many thousands of pheromone dispensers per year. Table 1 presents a list of the insect species for which pheromone dispensers are most frequently requested.

TABLE 1

Sales figures for pheromone dispensers by the Research Institute for Plant Protection at Wageningen in 1990, for each insect species expressed as a percentage of the total (data from S. Voerman)

Fruit crops	
Cydia pomonella	26.9
Adoxophyes orana	12.5
Pandemis heparana	8.7
Aegeria myopaeformis	7.5
Grapholita molesta	6.7
Anarsia lineatella	3.5
Archips podana	3.3
Phyllonorycter blancardella	2.3
Grapholita funebrana	2.1
Synanthedon tipuliformis	1.8
Archips rosana	1.4
Spilonota ocellana	1.3
Zeuzera pyrina	1.0

Vineyards	
Lobesia botrana	2.7
Eupoecilia ambiguella	1.4
Field vegetables	
Chrysodeixis chalcites	1.6
Plutella xylostella	1.1
Forestry	
Cossus cossus	5.1
Paranthrene tabaniformis	1.1
Other species	6.7

Monitoring with pheromone traps can serve different purposes, ranging from detection of the presence of the earliest individuals of an insect species to quantitative assessment of an insect population (see Table 2, after Wall 1989). Whatever the objective, the information available is in the form of trap catches, which may be sufficient data for detection, but certainly not for the determination of thresholds or population density estimations. In these cases, they must be related to data obtained from other sampling methods.

TABLE 2

Main uses of monitoring with pheromone traps
(after Wall, 1989)

Information from trap catch	Application
Detection	Early warning
	Survey
	Quarantine
"Threshold"	Timing of treatments
	Timing of other sampling methods
	Risk assessment
Density estimation	Population trends
	Dispersion
	Risk assessment
	Effects of control measures

Considering that the use of trap catches for these quantitative purposes requires much research, and impressed by the large use of pheromone traps, a group of members of the above-mentioned IOBC/WPRS Working Group organized an enquiry among the users of traps. Their main objective was to find out what the use pattern was and how the trapping data were used. In this way an excellent picture could be obtained of the European activities.

The results of the enquiry were based on 364 responses received from 27 different countries and they were summarized and published by Bues (1989). It emerged clearly that more than 90% of the monitored species were lepidopterans, and that pests in fruit cultures were involved in about 50% of the cases. As to the question of who (grower, advisor or research worker) was responsible for the operation of the traps, in roughly one third of the cases the growers operated the traps and in 40-50% of the cases the advisors, whereas researchers played a minor role. Interpretation of the trap catches demonstrated a shift of the responsibility from the grower to the advisor (30-65%), with the research worker still in a minor role (except in forestry). The question whether the monitoring could be considered as a routine operation or as an activity still in the experimental phase gave for the grape cultures a score of 66% for the former. This decreased for the other cultures from 37% for vegetable growing to 24% for annual crops. It should be mentioned here that many respondents found these questions difficult and did not answer at all (ranging from 31% for vegetable growing to 9% for grape growing).

As to the crucial question about the objectives of the monitoring with pheromone traps two answers could be given: a. for survey of the flight and b. for early warning. More than 90% of the respondents found the flight survey and in particular the determination of the flight period the principal aim and 60-70% considered the early warning as most important. Of the latter category 80-95% of the respondents working in fruit-, grape- or vegetable growing used the trap catches as the major information to decide whether to spray or not. Only a modest 20-30% used the trapping data for the determination of a threshold and even fewer respondents tried to relate trap catches to the real population density in the field.

Although the figures of the enquiry must be handled with caution because of some shortcomings in the form of questioning, it is justified to conclude that for the major part of the pheromone trapping activities in Europe much more could be done with the trap catches. This requires a drastic expansion of our research efforts, because each insect species forms a different case which also depends on many other conditions. It is quite certain that the present situation is not satisfactory, in spite of the wide use of pheromone traps, which is confirmed by the last result of the enquiry indicating that only one third of the users were fully satisfied with this method.

To conclude this part, a list is presented of what we believe are the most important routine operations of monitoring with pheromone traps known so far (Table 3).

Table 3

Most important cases of routine monitoring with pheromone traps in various countries in Europe (selected from data of Arn 1989)

Insect species	Crop	Country
Arable crops		
Ostrinia nubilalis	maize	France, Italy
Sesamia nonagrioides	cereals, maize	France, Greece
Fruit crops		
Adoxophyes orana	apple, pear	Belgium, France, Germany, Netherlands, Switzerland
Anarsia lineatella	peach	France
Cydia pomonella	apple	Austria, Belgium, Czechoslovakia, Finland, France, Germany, Italy, Netherlands, Spain, Switzerland, U. K.
Grapholita funebrana	plum	Austria, Switzerland
Grapholita molesta	peach	France
Pandemis heparana	apple	France
Prays oleae	olive	Italy
Aegeria myopaeformis	apple	France
Field vegetable crops		
Acrolepiopsis assectella	leek	France
Agrotis ipsilon	vegetables	France
Cydia nigricana	pea	Czechoslovakia, Netherlands, Soviet Union, Sweden, U. K.
Mamestra brassicae	cabbage, (sugarbeet)	France, Soviet Union
Plutella xylostella	cabbage	France
Vineyards		
Eupoecilia ambiguella		Austria, Czechoslovakia France, Germany, Italy, Switzerland
Lobesia botrana		Austria, Cyprus, Czechoslovakia, France, Germany, Italy, Switzerland
Forestry		
Ips typographus	*Picea abies*	Germany, Norway
Lymantria monacha	*Pinus sylvestris*	Czechoslovakia, Germany
Pityogenes chalcographus	*Picea abies*	Germany
Trypodendron lineatum	*Picea abies*	Austria, Germany

MATING DISRUPTION

Although the concept of mating disruption is already more than 30 years old, it took 15 years before this idea could be studied in the field. Only in the early seventies sufficient quantities of synthetic pheromone compounds became available for this purpose.

In Europe, experiments were started in 1975 by a small group of researchers working in different countries. They concentrated their efforts on the major insect pests in fruit orchards such as the codling moth *(Cydia pomonella)*, the summer fruit tortricid *(Adoxophyes orana)*, the plum moth *(Grapholita funebrana)* and the peach moth *(Grapholita molesta)*. In a later stage the two most important pests in vineyards also became involved: the grape berry moth *(Eupoecilia ambiguella)* and the grape vine moth *(Lobesia botrana)*. In these first years there was great optimism that a new reliable pest control method could become a reality very soon. This feeling was stimulated by the technical success of the large scale application of gossyplure against the pink boll worm *(Pectinophora gossypiella)* in cotton cultures in the Western States of the USA. The success could be ascribed for the greater part to a fruitful collaboration between institutional researchers and industry. The latter developed the chopped hollow fibres: a slow release formulation which made it possible to apply the gossyplure over large areas of cotton. However, real commercial successes failed to come soon enough, the company involved lost its interest and the operation gradually faded away.

In the years following, the coming and going of industrial companies with a temporary interest in the commercial application of pheromones has been an unfortunate characteristic of this field. In most cases, they realized soon after their involvement that in spite of repeatedly obtaining encouraging results in mating disruption experiments in the field there was no question of quick profits and that further commercial development required much more work and great financial investment. On the other hand, the research workers from the governmental institutions realized that they were bound to cooperate with industry, because only the latter has the technological knowledge to develop the right formulations for pheromone application.

In view of this, the stimulating role of the BASF Aktiengesellschaft in Europe must be highly appreciated. From 1980 onwards, they started collaboration with experts from governmental institutions. This resulted in 1985 in the first registration of a pheromone application, namely in Germany against the second generation of *E. ambiguella* in vineyards. (Vogt 1987; Neumann 1987). Again, the IOBC/WPRS Working Group acted as an indispensible mediator for both institutional and industrial experts of the various European countries. The three meetings organized in 1982, 1986 and 1990 respectively at Nyon (Switzerland), Neustadt (Germany) and Granada (Spain) were of crucial importance for the further development of pheromone application (Charmillot & Minks 1982; Arn 1987, 1990). At these meetings not only was attention given to the practical aspects, but also more fundamental matters related to mating disruption were discussed, such as mating behaviour, mechanisms of confusion, dispersal of male moths under disruptive concentrations in the field and the measurement of pheromone release. The development of a portable device to directly measure pheromone concentrations in the field must be especially mentioned here (Koch *et al.* 1990). Much time was also spent on the question of how to assess the effects of mating disruption, with the realization that reduced catches in pheromone traps do not provide sufficient information. Other sampling techniques such as the use of tethered females and of bait traps, the counting of infested shoots or fruits or of tree bands, at certain times during the growing season, and the damage assessment of the fruits at harvest time were evaluated.

Fortunately the involvement of BASF had a persistent character, convinced as they are that mating disruption is a viable plant protection method with good commercial prospects, in particular in view of the changing agriculture in Europe. For most of the insect pests in fruit orchards and vineyards mentioned above, experiences were favourable and reliable results over a period of some years could be reported. Table 4 summarizes the most important tests.

TABLE 4

Insect species in Europe with the most intensive development research on mating disruption application, with selected references

Insect species	References
Adoxophyes orana	Charmillot (1989); Neumann *et al.* (1990); Van Deventer & Blommers (1990, 1991)
Cydia pomonella	Charmillot & Bloesch (1987); Charmillot (1990); Neumann *et al.* (1990); Van Deventer & Blommers (1990, 1991)
Grapholita molesta	Casagrande *et al.* (1987); Audemard *et al.* (1989)
Anarsia lineatella	Audemard & Leblon (1987); Balduque *et al.* (1988); Rotundo & Viggiani (1989)
Aegeria myopaeformis	Stüber & Dickler (1987); Blommers & Freriks (1988); Van Deventer & Blommers (1990,1991)
Eupoecilia ambiguella	Charmillot *et al.* (1987); Englert (1987); Vogt (1987); Descoins (1990); Neumann (1990a); Borgo (1990)
Lobesia botrana	Descoins (1990); Schmid & Ancay (1990); Borgo (1990)

The amounts of pheromone used ranged between 50 and 100 grams per ha (20 and 40 grams per acre) and it was formulated in plastic ampules developed by BASF.

Some additional remarks should be made here: in the case of *C. pomonella* there were varying results in the application of mating disruption. In Switzerland a provisional registration was in effect during 1988 and 1989, but in other countries such as Germany, Belgium and Austria registration for commercial application was recently granted. Of particular interest in the case of *A. orana* is the use of only the minor component of its pheromone (Z-11-tetradecenyl acetate) as the active ingredient. This compound is also part of the pheromone blends of some other economically important tortricid moths in apple such as *Archips podana*, *A. rosana* and *Pandemis heparana*. In Switzerland and in the Netherlands mating disruption using this single compound was effective for all four species (Charmillot 1989; Van Deventer & Blommers, 1989, 1990).

Apart from the registration permissions for *C. pomonella* in three countries, commercial introduction is also permitted for *E. ambiguella* in Germany, Austria and Switzerland, for *G. molesta* and the peach twig borer, *Anarsia lineatella* in Italy and Spain and for *A. orana* in Belgium (Neumann, 1990b). In other European countries registrations for these insect pests are underway. So far mating disruption has not been commercialized for the apple clearwing moth *(Aegeria myopaeformis)*, in spite of the fact that considerable efforts have been made.

It is anticipated that the fruitful collaboration between the research institutes and industry in Europe will continue for many years to come. It is in the interest of both parties: both want to promote pheromone application, although with different motives but that is less important. The authors have a strong belief that the potentials of pheromone application, in spite of certain limitations of the methods, should be explored further. These magnificent methods certainly will take an important place in future integrated pest management.

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INSECT BEHAVIOUR-MODIFYING CHEMICALS: PRACTICAL APPLICATIONS IN THE UNITED STATES

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ABSTRACT

Pheromones and other behaviour-modifying chemicals are widely used in the U.S. for monitoring. In addition, after a number of years of uncertainty about the use of pheromones for insect control, a number of important practical uses have evolved. Attractant pheromones have been used for mating disruption and, to a lesser extent, for mass trapping. These uses are expected to expand. Other behaviour-modifying chemicals such as plant attractants, feeding stimulants, and alarm pheromones are likely to become increasingly important in practical insect control programs.

INTRODUCTION

For over four decades there has been a heavy reliance on conventional pesticides as the primary tactic for dealing with many pest problems. As most of you are aware, the environmental and health concerns associated with pesticide usage that emerged in the late 1950s became highly visible in the 1960s after the publication of *Silent Spring* (Carson 1962). The intensity of these concerns, after perhaps receding somewhat, reached new highs in the late 1980s with attention focusing on pesticide residues in food (National Research Council 1987) and water (US Department of Agriculture 1989). Further, practical problems in controlling insects with conventional insecticides continue to be accented by the increasing numbers of insecticide resistant species (Georghiou & Saito 1983; National Research Council 1985).

Insect problems persist as a major factor in crop production and natural resource conservation. Pests of chief concern in the US include insects in corn, cotton, fruit, vegetables, and horticultural crops, because of the monetary value of insecticides used on these crops (Anonymous 1985), and insects in forestry, because of the very large areas and the environmental sensitivities involved. World-wide, rice is a significant insecticide market. In the US, the corn rootworms (*Diabrotica* spp.) are major pests on corn. Other important pests are the boll weevil (*Anthonomus grandis*), the pink bollworm (*Pectinophora gossypiella*), the bollworm (*Helicoverpa zea*), and the tobacco budworm (*Heliothis virescens*) on cotton; cabbage looper (*Trichoplusia ni*), diamondback moth (*Plutella xylostella*), Colorado potato beetle (*Leptinotarsa decemlineata*), codling moth (*Cydia pomonella*), and tephritid fruit flies on vegetable crops and fruit; and gypsy moth (*Lymantria dispar*) and a number of other Lepidoptera and bark beetles in forestry.

COMMON GOALS

We are all becoming increasingly aware of society's concern about pesticide residues in food and desire for a more healthful and aesthetic environment. There is an opportunity to respond to this concern and desire through the development and use of additional biologically based methods of insect control. Certainly, pheromones and other behaviour-modifying chemicals can make a significant contribution to effective and more desirable means of managing pests. Europe and North America have long shared common interests in biologically based methods of insect control. Perhaps this is best exemplified by Charles Valentine Riley, who was born in England and emigrated to the United States, where his accomplishments in the late

1800s had major impacts in both Europe and North America. For example, Professor Riley is often credited with saving the French wine industry with his suggestion to graft European grapevine scions on North American rootstocks that were resistant to the grape phylloxera (*Daktulosphaira vitifoliae*). Also, he provided the leadership which resulted in the importation of the vedalia lady beetle (*Rodolia cardinalia*) from Australia into California, leading to complete control of the cottony cushion scale (*Icerya purchasi*) on citrus (Caltagirone & Doutt 1989). Complementary entomology endeavors have continued on both sides of the Atlantic Ocean, including those specifically related to insect pheromones and other semiochemicals. Examples of these contributions are documented in the recent books entitled *Insect Pheromones in Plant Protection* (Jutsum & Gordon 1989) and *Behavior-Modifying Chemicals for Insect Management* (Ridgway *et al.* 1990a). It is clear that an ongoing opportunity exists to develop and implement the use of semiochemicals as part of the solution to insect problems in both Europe and North America, especially where there is a need for effective alternative methods of control. Other behaviour-modifying chemicals, including synthetic attractants and food attractants associated with protein-based baits, are widely used for surveillance and/or suppression of tephritid fruit flies in the US. However, this review is restricted to naturally occurring behaviour-modifying chemicals.

SUCCESSES

Successful applications of pheromones and other behaviour-modifying chemicals in insect management fall into two broad categories: surveillance or monitoring and suppression or control. Uses for monitoring have increased at a steady rate since synthetic pheromones became generally available, whereas uses for control failed to meet early expectations. In recent years, however, suppression or control of insects using semiochemical-based strategies has been implemented on a commercial scale in a number of different cropping systems.

Surveillance

Pheromones and other semiochemicals have had a major impact on insect control through their use in traps for surveillance or monitoring of insect pests. The different purposes for monitoring (detection, treatment thresholds, and density estimations) have been reviewed previously (Wall 1989; Minks & van Deventer, this volume) so only a few comments will be made here on extent of use. In a survey of 41 companies, commercial availability of pheromones or other attractants for 257 arthropod species were reported (Inscoe *et al.* 1990). Of those 257 species, materials available for monitoring were reported for 230. Most of the species were moths (Lepidoptera) with 189 species reported, followed by beetles (Coleoptera) with 27 species. Crops reported in order of the numbers of arthropod species involved were field crops (89 spp.), vegetables (79 spp.), orchard (63 spp.), and forests (55 spp). Actual numbers of traps and lures used for monitoring pests in the US are not generally available. However, the fact that about one-half of the companies reporting commercial availability were US-based suggests that monitoring constitutes a major use of pheromones and other behaviour-modifying chemicals in the US. Most of the uses for monitoring are exempt from regulation under the US Federal Insecticide, Fungicide and Rodenticide Act (Tinsworth 1990), and therefore, government regulations are not likely to be a barrier to expanded use in monitoring and detection.

Suppression

Suppression tactics employing behaviour-modifying chemicals involve the use of a semiochemical in a trap for mass trapping, in dispensers distributed throughout an area for mating disruption, or in combination with a toxicant (*e.g.*, a bait). The first pheromone or pheromone component to be used in insect control in the US was approved in 1973 by the United States Environmental Protection Agency (US EPA). At that time muscalure, (*Z*)-tricosene, was formulated in a toxic bait against the house fly (*Musca domestica*) (Browne

1990). However, the first pheromone to be used for insect control as a mating disrupant was approved in 1978, when gossyplure, (*Z,Z*)- and (*Z,E*)-7,11-hexadecadien-1-ol acetate, was registered by US EPA for control of the pink bollworm (*Pectinophora gossypiella*) (Baker *et al.* 1990). The numbers of semiochemical-based products registered by US EPA to control arthropods have gradually increased, and by late 1987 there were 59 registrations of active ingredients or products for control of 15 insect and 3 mite species (Tinsworth 1990). However, registration cannot be equated with commercial success, and a number of these products were not commercially viable. An in-depth review of a wide range of uses for pheromones and other behaviour-modifying chemicals (Ridgway *et al.* 1990a) and subsequent experience demonstrate recent advances in the significant practical value of these materials.

Seven insects against which pheromones are used in the US for control are discussed here to illustrate some important niches where pheromones are having a significant impact in controlling insect populations (Table 1). These examples include mass trapping of a beetle, mating disruption of 5 species of moths, and a toxic bait for house flies. Although tree baits represent an important use in bark beetle management in both the US and Canada, this use will be discussed elsewhere (Burke, this volume).

Most of the successful examples of insect control with pheromones presented in Table 1 involve the use of broadcast or individually placed pheromone dispensers for mating disruption. In all cases, controlled- release formulations have been necessary. Total application rates per season range from a few grams or less to a hundred grams or more per hectare. Since risk is the product of exposure and toxicity, the relatively low rates of application, coupled with very low toxicity (Inscoe & Ridgway, Burke, and Bedoukian, in this volume), imply minimum risk from the use of pheromones for insect control. This risk is further reduced with those formulations that are individually placed point sources and not broadcast over the crop.

The observation has been made, and correctly so, that relatively few cases exist where "robust" systems have been developed using pheromones and other semiochemicals for pest control (Pickett *et al.*, this volume). However, some systems have had major impact in the US and in our judgment qualify as being "robust". Perhaps the best example is the areawide system for reproduction management and eradication of the boll weevil. This system, involving areawide use of insecticides to reduce boll weevil populations and the use of an aggregation pheromone, grandlure, (a mixture of (*cis*)-1-methyl-2-(1-methylethenyl)cyclobutaneethanol, (Z)-2-(3,3-dimethylcyclohexylidene)ethanol, and (*Z*)- and (*E*)-(3,3-dimethylcyclohexylidene)-acetaldehyde) in traps for monitoring and for suppression of very low density populations has been highly successful in both the southeastern and southwestern US (Ridgway *et al.* 1990b). The results can be illustrated by trap captures from the expanded eradication program in the southeastern US, where boll weevil reproduction was eliminated in southern North Carolina and essentially eliminated in eastern South Carolina between 1983 and 1986 (Table 2). Perhaps more significant are the results of economic evaluations which indicated that the value of reduced insecticide costs was about $75 per hectare ($30 per acre) and that the total benefits as a result of the program were over $190 per hectare ($76 per acre) (Table 3). In 1987, the southeastern boll weevil eradication program was expanded throughout Florida, most of Georgia, and a major portion of Alabama. The program is expected to be completed in those areas in 1991 and benefits similar to those obtained in North Carolina and South Carolina are anticipated. Over 400,000 hectares (1 million acres) were involved throughout the southeastern US in 1991.

An organized areawide boll weevil program was initiated in southern California, southwestern Arizona, and part of Mexico in 1985. Extensive trapping, insecticide applications, and cultural controls led to elimination of reproducing populations in these areas by 1987. In 1988, the program was expanded to cover the remainder of Arizona and adjoining areas of Mexico. In this southwestern program, the boll weevil pheromone trap was used primarily for detection and to aid in decision making related to insecticide applications (Ridgway & Inscoe, In press). The expanded southwestern program was completed in 1990. A buffer zone or containment program will be maintained to prevent reinfestation.

TABLE 1. Examples of pheromone products that are registered or were previously registered in the United States.

Insect	Registration no.	Method of application	Rate of application (a.i.)[1]		No. of applications per season[1]
			g/hectare	g/acre	
Boll weevil, *Anthonomus grandis*	8730-15	in traps	0.002-0.25[2]	0.001-0.1[2]	3-10[2]
Pink bollworm, *Pectinophora gossypiella*	36638-11	broadcast	0.94-5.63	0.38-2.28	>1
	36638-12	broadcast	5-25	2-10	>1
	50675-5	individually placed	78	31	1-2
	62128-2	broadcast	5-25	2-10	>1
Oriental fruit moth, *Grapholita molesta*	56336-3	individually placed	49	19	>1
	53575-1	individually placed	70	28	1-2
Grape berry moth, *Endopiza viteana*	50675-9	individually placed	42-70	17-28	1
Tomato pinworm, *Keiferia lycopersicella*	36638-8	individually applied[3]	10	4	>1
Artichoke plume moth, *Platyptilia carduidactyla*	36638-10	broadcast	10	4	>1
House fly, *Musca domestica*	multiple	bait			

[1] From the product label unless otherwise specified; rates of application are approximations because of rounding off. [2] Modified from label to include usage in areawide producer, state, and federal cooperative programs. [3] Applied as cluster of fibers in adhesive.

TABLE 2. Boll weevil captures in fields in North Carolina and eastern South Carolina, US (From Ridgway *et al.* 1990b).

Location by year	Hectares	% of fields with number of weevils captured		
		0	1-5	>5
1983				
NC	6,600	0	1	99
SC	21,240	2	5	93
1986				
NC	8,600	>99.9	<0.1	0.0
SC	34,400	>97.3	2.3	<0.4

TABLE 3. Benefits associated with boll weevil eradication in Virginia, North Carolina, and South Carolina, US. (Modified from Carlson *et al.* 1989).

Benefit	Dollars per hectare	
	Original eradication zones (VA, NC)	Expanded eradication zones (NC, SC)
Net reduced pesticide	$ 72.18	$ 75.08
Acreage expansion	33.20	34.50
Yield effect	86.25	86.25
Total monetary benefit	$191.63	$195.83

The pink bollworm pheromone, gossyplure, became commercially available for control by mating disruption in 1978. Initially, there was considerable criticism about approaches used to demonstrate efficacy, and considerable uncertainty was generated about the practicality of pheromone use. However, although quantitative economic data, including both control costs and yield effects, are not available for gossyplure, its use against the pink bollworm has evolved into an accepted control tactic, with over 40,000 hectare-applications of one commercial product being applied on over 20,000 hectares of cotton in 1986 (Baker *et al.* 1990). In addition to the original dispensing systems, two individually placed dispensers and three sprayable bead formulations are now under development or being sold commercially (Ridgway & Inscoe, In press). In 1990, the number of hectares treated had increased several-fold over that treated in 1986.

In contrast to the uses on cotton against the boll weevil and pink bollworm just discussed, pheromones have not been applied as extensively in the US for control of pests of fruit and vegetable crops listed in Table 1. The total acreages affected by these pests are lower, and registrations of formulations against some of these insects are more recent. However, these uses provide notable cases of pheromone applications, and two of the examples are particularly important because of their apparent commercial viability and the extensive documentation of efficacy. Comprehensive efficacy data are available for an oriental fruit moth (*Grapholita molesta*) pheromone formulation (53575-1) from Australia and Canada (Vickers 1990) and the

US (Rice & Kirsch 1990). Oriental fruit moth mating disruption has been adopted in California peach growing districts that were experiencing control difficulties using conventional insecticides. A commercial product was registered by the US EPA in late 1986, and by 1990, over 4,000 hectares (10,000 acres) were treated with the pheromone (Philipp Kirsch, personal communication). Efficacy data have also been developed for the American grape berry moth (*Endopiza viteana*) pheromone (Dennehy *et al.* 1990). Significant acreages received commercial applications during 1991 (Philipp Kirsch, personal communication). The other two lepidopteran examples in Table 1, tomato pinworm (*Keiferia lycopersicella*) and artichoke plume moth (*Platyptilia carduidactyla*) represent important uses of pheromone products developed in the early 1980s that evolved into small stable markets rather rapidly and have continued to be useful products (Jenkins *et al.* 1990; Haynes *et al.* 1981; Jack W. Jenkins, personal communication).

The last pheromone listed in Table 1 is used in strategies to control the house fly (*Musca domestica*). Its method of application differs from the previous examples, in that the pheromone, muscalure, is used in a bait with a toxicant (Browne 1990). Information on extent of use in not readily available, but in terms of technical pheromone, muscalure is probably sold in larger quantities than any other pheromone. In late 1990, there were 10 different commercial products containing muscalure registered for use in the US.

We have not attempted to present all of the important successes with semiochemicals in the US. However, we do believe that the examples presented clearly show that semiochemicals have become a practical tool for use in insect control. The uses of semiochemicals reviewed here and elsewhere (Jutsum & Gordon 1989; Ridgway *et al.* 1990a) should provide the basis for developing additional programs utilizing semiochemicals for suppression of insect populations.

OPPORTUNITIES

The past successes in crop protection utilizing semiochemicals have involved primarily sex and aggregation pheromones. The number of development activities underway in the US in 1990, as reflected in applications for 13 experimental use permits (EUP) (Table 4), indicates that significant efforts are continuing. Reviews are available on a number of insects included in the EUP applications but not discussed here, such as bark beetles (Borden 1990), gypsy moth (Kolodny-Hirsch & Schwalbe 1990), western pine shoot borer (*Eucosma sonomana*) (Daterman 1990), and codling moth (*Cydia pomonella*) in Europe (Charmillot 1990). Additional commercial successes can be expected to result from the developmental efforts underway.

As we consider the future opportunities for the use of insect behaviour-modifying chemicals, it is important to look beyond the attractant pheromones. For instance, phytochemicals that influence insect behaviour offer a wide range of opportunities. Perhaps one of the most exciting opportunities involves the potential use against adult corn rootworms of a granular bait containing several plant-produced attractants, a feeding stimulant, and a toxicant. (Metcalf *et al.* 1987, Metcalf & Lampman 1989, Anonymous 1991, Lindsay 1991). Results of extensive testing of this product in the 1990 season were promising (Anonymous 1991). Also intriguing is a bait station for use against the boll weevil that includes the pheromone, plant components, an attractive color, and a toxicant (Konstant 1990; McKibben *et al.* 1990; Ridgway & Inscoe, In press). This use of plant-produced attractants and feeding stimulants provides an opportunity to exploit some additional types of behaviour modification in those insects where manipulation of sex or aggregation behaviour may not be adequate to obtain the desired levels of control. Opportunities to utilize alarm pheromones in developing management systems for aphids are also being explored (Table 4; Pickett *et al.*, this volume). Likewise, semiochemicals that influence the behaviour of parasitoids and predators (Vinson 1984) have potential for increasing effectiveness of natural enemies. Chemicals that stimulate or deter feeding may also prove of value in crop protection.

TABLE 4

Experimental use permits (EUP's) issued and/or applied for in relation to the 1990 growing season in the United States[1].

Insect	EUP No.	Semiochemical(s) (common name, chemical name, or type)
EUP's issued for the 1990 season		
Corn rootworms, *Diabrotica* spp.	53575 - EUP - 2	feeding stimulant, volatile plant attractants, and toxicant
Boll weevil, *Anthonomus grandis*	11312 - EUP - 37	grandlure and cyfluthrin (Baythroid)
Mountain pine beetle, *Dendroctonus ponderosae*	56261 - EUP - 1 56261 - EUP - 2 56261 - EUP - 3	verbenone
Western pine beetle, *Dendroctonus brevicomis*	56261 - EUP - 1 56261 - EUP - 2 56261 - EUP - 3	verbenone
Pink bollworm, *Pectinophora gossypiella*	62128 - EUP - 2 62128 - EUP - 10	gossyplure
Gypsy moth, *Lymantria dispar*	8730 - EUP - 19	disparlure
Artichoke plume moth, *Platyptilia carduidactyla*	62128 - EUP - 9	(*Z*)-11-hexadecenal
Grape berry moth, *Endopiza viteana*, Nantucket pine tip moth, *Rhyacionia frustrana*, and Western pine shoot borer, *Eucosma sonomana*	62128 - EUP - 7	(*Z*)-9-dodecenol acetate
House fly, *Musca domestica*	352 - EUP - 149	muscalure and toxicant
EUP's pending as of November 16, 1990		
Codling moth, *Cydia pomonella*	53575 - EUP - G	(*E*,*E*)-8,10-dodecadien-1-ol, dodecanol, tetradecanol[2]
	56336 - EUP - E	(*E*,*E*)-8,10-dodecadien-1-ol
Aphids (Aphididae)	56336 - EUP - G	(*E*)-β-farnesene

[1] Information provided by Registration Division, US EPA, November 16, 1990.

[2] Registration (53575-6) approved by the US EPA, Feb. 27, 1991.

NEEDS AND CHALLENGES

As we look at ways to expand the use of semiochemicals, we must be sensitive to a wide range of needs and challenges. These include:

- identifying additional semiochemicals having varied types of biological activity and undertaking basic research into their modes of action,
- gaining increased knowledge of quantitative population dynamics,
- developing strategies for managing multispecies insect pest problems with highly selective control methods,
- overcoming the barriers associated with the limited private capital available for research and development where market size is limited,
- assuring adequate public commitment of resources to maintain a balance between public and private sector involvement,
- accomplishing adequate risk assessments and developing alternative procedures to address the requirements imposed by the current regulatory structure, and
- effective delivery of information to and education of the users.

Although the constraints and challenges facing those of us who wish to expand the use of semiochemicals go far beyond regulatory issues, it is our primary purpose here to focus upon ways of facilitating the regulatory process. There is a clear need for scientific and technical information to enable regulatory agencies to make sound decisions in a timely manner based on adequate but not excessive or unnecessary data. It is our sincere hope that through this symposium and related activities some specific appropriate mechanisms can be identified that will enable all of us to assist in the development and documentation of such information. To the extent each of us can contribute to expediting the total research and development process, including the regulatory component, we will likewise be contributing to the production of safer food and a more healthful and aesthetic environment, hopefully at an affordable cost.

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POTENTIAL APPLICATIONS OF SEMIOCHEMICALS IN APHID CONTROL

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ABSTRACT

Studies on semiochemically mediated behaviour are described, principally for aphid pests. Emphasis is on the use of semiochemicals in integrated strategies employing other management systems such as biological control.

INTRODUCTION

Since the identification of the sex attractant pheromone of the silkworm, *Bombyx mori*, in 1959 (Butenandt *et al.*, 1959), the potential of pheromones and other semiochemicals for pest control has been recognised, but after 30 years relatively few cases exist where robust systems have been developed. The best known semiochemicals are the lepidopterous sex pheromones and coleopterous aggregation pheromones. These can be used to catch insects for monitoring purposes, and in some cases mass trapping has been successful. An alternative approach for lepidopterous sex pheromones is to use the compound or a closely related analogue to interfere with mate location. However, for semiochemicals to realise their full potential in pest control, a greater understanding of insect chemical ecology is required. When employed alone, semiochemicals may provide inadequate control and their use must be integrated with other approaches such as biological agents, which in isolation can also be insufficiently effective.

APHID ALARM PHEROMONES

In temperate Europe, aphids are the most important insect pests, causing damage by feeding and by transmission of plant viruses. When aphids are attacked by predators, they produce an alarm pheromone, the major component of which is (E)-β-farnesene. Synthetic material, formulated in a hydrocarbon propellant and applied electrostatically, was highly effective in increasing aphid mobility in the field. This mobility can increase the pick-up of contact pesticides incorporated with the pheromone formulation (Griffiths & Pickett 1987). Similarly, the alarm pheromone can be used to improve the efficacy of biological agents. Under glass, aphids such as *Aphis gossypii* have become almost completely resistant to insecticides, although control can still be achieved with the fungal pathogen, *Verticillium lecanii*. However, the fungal spores must be acquired by the insects over a relatively short period while they are still viable. Use of the alarm pheromone improved pick-up of spores by *A. gossypii*, even though this aphid responded only weakly to the synthetic pheromone (Griffiths & Pickett 1987).

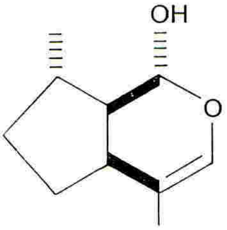
Alarm pheromone synergists have been demonstrated for the turnip aphid, *Lipaphis erysimi*, which like *A. gossypii* responded poorly to synthetic alarm pheromone. Volatiles from crushed aphids were found to be highly active, and coupled gas chromatography (GC)-electrophysiological recordings from the aphid olfactory system enabled the identification of a number of organic isothiocyanates (Fig. 1) that synergised the activity of *(E)-β*-farnesene (Dawson *et al.*, 1987a). These synergists allow the use of aqueous formulations more suitable for conventional hydraulic application systems. The isothiocyanates are thought to arise from glucosinolate precursors in the cruciferous host plants. Laboratory olfactometer studies have shown that isothiocyanates, presented alone, attract alate virginoparae of *L. erysimi* and *Brevicoryne brassicae* (Nottingham *et al.*, 1991). For *L. erysimi*, these compounds therefore have a dual role in host plant location and as alarm pheromone synergists.

allyl **3-butenyl** **4-pentenyl**

Fig. 1. Isothiocyanates identified in volatiles from crushed turnip aphid, *Lipaphis erysimi* (Dawson *et al.*, 1987a)

APHID SEX PHEROMONES

Many species of aphids reproduce sexually on their primary or winter hosts, and although the sexual morphs do not normally damage crops, they represent a vulnerable stage of the life cycle. The sex pheromones for a number of pest species, including the black bean aphid *(Aphis fabae)*, the pea aphid *(Acyrthosiphon pisum)*, the greenbug *(Schizaphis graminum)* and the peach-potato aphid *(Myzus persicae)*, have now been shown to comprise the nepetalactol I and/or the nepetalactone II (Dawson *et al.*, 1987b, 1988, 1989).



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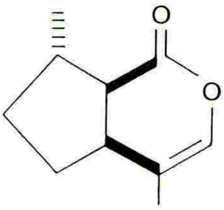

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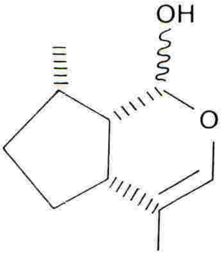

III

The sex pheromone of the damson-hop aphid, *Phorodon humuli*, has recently been identified as the nepetalactol III (Campbell *et al.*, 1991). As this aphid is highly resistant to most registered pesticides, use of the sex pheromone is being investigated as part of an integrated control strategy. The pheromone is readily available since the nepetalactone precursor can be isolated in high yield from the labiate plant *Nepeta mussinii*. Synthetic material was active in the laboratory and attracted large numbers of males when deployed in the field in yellow water traps (total number of males caught: traps with pheromone, 3045; control traps, 210).

PLANT VOLATILES

For *P. humuli*, there was evidence that volatiles from the primary host plant (*Prunus* spp.) synergised attraction of the males to the sex pheromone traps (Table 1).

TABLE 1. Numbers of *P. humuli* males caught in water traps on 18th October 1989

	Mean no. per trap[1]
Synthetic sex pheromone	52.0[a]
Primary host plant (bark extract)	7.8[b]
Sex pheromone + bark extract	119.5[c]
Control	2.2[b]

[1] Difference a from b from c, $P < 0.05$, based on chi-square test

In the spring, alate virginoparae of *P. humuli* migrate back to the hop crop, the summer host, and laboratory behavioral studies demonstrated attraction to hop leaf volatiles. The use of coupled GC-electrophysiological techniques led to the identification of a number of components which proved active in the laboratory assay.

Many traditional cultivation methods utilize intercropping with aromatic non-host plants to interfere with host location by pests. Electrophysiological studies on the antennae of *P. humuli* spring migrants

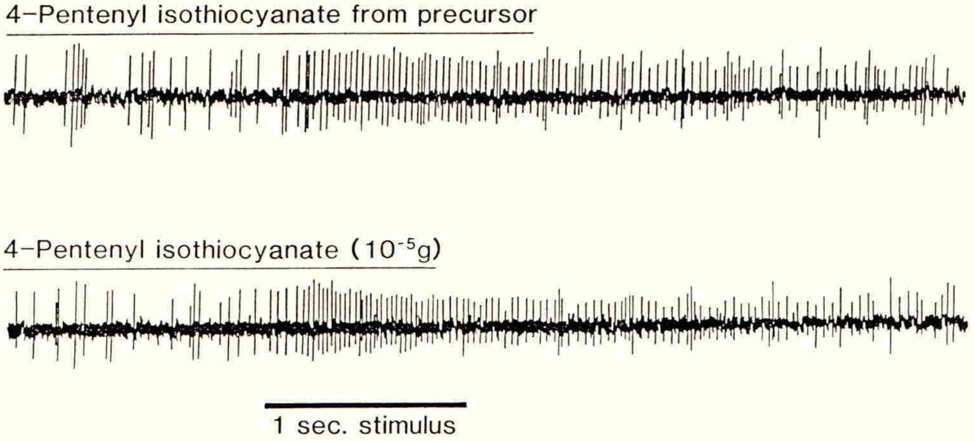

Fig. 2. Response of a *Phorodon humuli* spring migrant olfactory cell (proximal primary rhinarium) (C. M. Woodcock, personal communication)

showed the present of receptors for non-host volatiles such as the isothiocyanates, which suggested that these compounds might be used to interfere with location of the hop plants. Indeed, formulations giving slow chemical release of isothiocyanates stimulated the appropriate receptors on the antennae (Fig. 2) and, when applied to the crop, decreased colonisation by spring migrants. Use of attractants to monitor populations and to attract the aphids to trap crop areas, with the crop itself protected by masking compounds, could provide an effective control strategy for this pest.

This approach forms the basis for a number of research projects where semiochemicals are utilised in integrated control strategies, the main components of which are monitoring, manipulation of pest populations using semiochemicals, host plant resistance and trap crops, combined with selective pesticides or biological control agents to reduce the pest population. The ultimate aim is to draw together the different components into a robust push-pull (Pyke *et al.*, 1987) or stimulo-deterrent diversionary strategy (Miller & Cowles 1990), in which pests are diverted from the crop and aggregated on trap crops where they can be destroyed. This approach is being developed for coleopterous pests of oilseed rape as part of a large multidisciplinary programme (Pickett 1989).

OTHER SEMIOCHEMICALS

Involatile semiochemicals such as oviposition stimulants and deterrents could play an important role in similar strategies aimed at coleopterous or lepidopterous pests. In addition, many wild plants defend themselves against insect attack by producing antifeedants and these compounds have great potential in control programmes. Thus, polygodial, obtained from the weed *Polygonum hydropiper*, shows antifeedant activity against a broad range of coleopterous and lepidopterous pests and against aphid colonisation and virus transmission. In a field trial to reduce barley yellow dwarf virus transmission by *Rhopalosiphum padi*, yields were increased by over 1 tonne per hectare and were not significantly different from those obtained with a conventional cypermethrin treatment (Pickett *et al.*, 1987).

FUTURE PROSPECTS

The biosynthesis of semiochemicals often involves processes already occurring in crop plants or related species. Genetic manipulation of crop plants, so that pests are controlled by semiochemicals produced directly by the plant, shows considerable promise (Hallahan *et al.*, in press). Although there is more work to be done before these strategies are available, the approaches described here will pave the way for the development of robust insect control systems.

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