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THE NINTH BAWDEN LECTURE

This lecture is arranged under the auspices of
The British Crop Protection Council
in memory of the first President of the Council
Sir Frederick Bawden

The use of chemicals in modern farming — a farmers view

by

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BAWDEN MEMORIAL LECTURE

THE USE OF CHEMICALS IN MODERN FARMING - A FARMER'S VIEW

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I wish to begin by thanking those who were responsible for inviting me to speak to you today. Your conference has an international reputation, and to be invited to speak to it at all is a great honour, but to be asked to give this particular lecture, associated as it is with the name of Sir Frederick Bawden, is for me a special pleasure. I first met Sir Frederick whilst I was serving as a farmer-member of the Agricultural Research Council - a body that I fear he viewed with some suspicion : jealous as he was of the unique history and tradition of the Lawes Agricultural Trust, and anxious, I suspect, lest its work at Rothamsted should be interfered with by those who were more concerned with "pure" scientific work than with some of its more practical applications. Brilliant scientist though he was, he was also tremendously concerned with what was happening in the field, and I hope that I succeeded in reassuring him that as a farmer I shared his concern that research should not be conducted in narrow compartments in remote and isolated laboratories, nor be directed according to the short term dictates of politicians or economists but rather that researchers should, like him, be constantly aware of the wider world around them. I hope he would feel that in recent years the ARC has become more successful in achieving its avowed object. Not only of advancing scientific knowledge relevant to agriculture, horticulture and food supply but also of exploiting that knowledge to increase the efficiency of the agricultural, horticultural and food industries, and to safeguard and improve the quality of food for the community. Certainly by his work he did a great deal to ensure that farmers were able to follow the motto of the Royal Agricultural Society and to "practise with science", and I am very proud to have my lecture to you this morning associated with his memory.

May I begin by making it quite clear that whatever other peripheral activities I may occasionally have undertaken, I speak to you as one whose bread and butter depends on his success - or lack of it - as a farmer. I represent no organisation, and the responsibility for what I have to say is entirely my own. It would perhaps be appropriate to say a brief word about my farming activity as a background to my paper. I was brought up in the Cambridgeshire Fens, in an area where my family have farmed for over 200 years. A great deal of it is below sea level, although some 30 miles inland from the sea, and our safety as well as our farming depends on the maintenance of secure river-banks, supported by adequate pumps. Without them our farm, and many others, would soon revert to the swampy waste from which it was reclaimed, and although this might be popular with some of those naturalists who deplore the loss of our "wetlands" it would be a disaster for our local economy. This drainage has however to be continually paid for so that in addition to recent and other outgoings we have an annual drainage cost of some £10 per acre: low cost farming is not an available option for us. Our soils when they were first reclaimed were deep black peats, but especially over the past 40 years with more efficient drainage and intensive cultivation these have steadily "wasted" to leave us with high organic matter "skirt" soils of high potential productivity, but more difficult

physical character. Our cropping has reflected this change. The far too intensive rotation of sugar beet : wheat : potatoes which was adopted for economic survival between the wars has been replaced by one with steadily increasing acreages of cereals - now amounting to over half our total - and a corresponding reduction in the acreage of roots. This has contributed to the reduction of number of men employed on the farm which has been striking. Where one man was employed to every 20 arable acres in the 1940s the corresponding figure today is approaching one to every 100.

What has been the role of chemicals in this? Soon after I had been invited to give this paper I was approached by one of the Organising Committee who had had a dreadful thought. Perhaps in this day of increasing influence of the Ecologists' party I was one who deplored the use of all modern chemicals, and all unwittingly a cuckoo had been invited into the nest. Much to his relief - and I am sure that of everyone else here - his anxiety was unjustified. Without the use of modern chemicals our farming could not possibly have gained the increase in efficiency that we have achieved, and we are now as thoroughly "hooked" as the rest of the industry, and like every other addict very grateful for our drug.

We started from small beginnings. For protection from potato blight we were using frequent and not very successful applications of various copper mixtures. For weed control in wheat we relied on "burning off" the field with concentrated sulphuric acid in April, relying on the crop recovering more rapidly than the weeds. Sometimes it worked well, and often it didn't - but there was no other alternative available - until the "break through" with the first selective broad leaf herbicide for use in cereals, which I remember applying as a powder with a horse drawn artificial manure distributor. It seemed like magic at the time, but it was of course the beginning of a new "way of life" in cereal growing.

Looking back at our farm accounts for 1954 I see that for every £1 we spent on chemical sprays we spent £25 on labour and £9 on machinery costs of one sort or another. Last year the comparable figures were £5 on labour and £3 on machinery costs, and spray chemicals have exceeded fertilisers in our expenditure. What have we to show for this huge new extra cost for our farming business?

First, and perhaps most obviously - the ability to control the growth of most weeds in almost all our field crops. The vanishing poppy may be mourned by the casual passer-by, but its virtual elimination as a field weed of importance is typical of the change in appearance of our fields, where clean weed free crops are almost taken for granted. If it is thought that the benefit is only cosmetic, we know that it has been very real in financial terms. Crop yields have increased substantially in the absence of competition from weeds, especially when moisture was limited, and harvesting of all crops has been made much easier, especially in wet years. The use of herbicides has also allowed us to vary our traditional pattern of cultivations, so as to save expense or time or moisture loss. Direct drilling of cereals is probably the most obvious illustration of a change that has been made possible by the use of herbicides, but there are many more. Savings in labour have also been stupendous, especially in our fen area where so many man hours were spent in summer on weed control, and full advantage could never have been taken of the advances in mechanisation of cultivation or harvesting without simultaneous developments in herbicides for weed control.

Secondly, the increasing ability to control crop diseases has had a very

significant effect on crop yields, and especially the reduction in fluctuation of yield from year to year, which has made possible the sounder organisation of the farm business, and better planning of resources, especially for storage and marketing, as well as for the production of crops of more consistent and uniform quality, which has become increasingly important especially where crops for packaging or processing are involved. As a farmer one is always nervous of tempting providence, but epidemic years of severe potato blight (which occurred far more recently than the classic years of Irish famine - indeed as recently as 1956 I remember spraying large acreages of King Edwards with acid before the end of July) are now so rare that one is sometimes tempted to wonder if we have seen the last, and the worthwhileness of cereal breeders attempting to include disease resistance in their new varieties is today sometimes questioned, so successful have we been in recent years in containing outbreaks of leaf diseases.

Similarly the ability of chemicals to give us control of many previously serious crop pests has considerably reduced the losses due to their attack. Wheat bulb fly, troublesome though it can sometimes still be, is nowhere near the scourge that it was in the early 1950's, and good crops of potatoes can now be grown in the presence of surprisingly high eelworm populations. I fear that with the control of aphids, and the diseases spread by them, we are on less certain ground - as recently as 1974 our yield of sugar beet was so depressed by virus yellow as to have made it the lowest for over 20 years - but at least we now have more weapons in the armoury than when we were attempting to control black fly on beet by hand treatment with nicotine dust.

So far this all seems solid gain which should reassure the salesmen in the audience that I have been well aware of the positive benefits that we have enjoyed from using their products. Now, what about the snags.

First, of course, there has been the cost. Last year on our farm we spent an average of £30 per acre on cereals, £60 per acre on potatoes and £30 per acre on sugar beet all on chemicals (excluding fertilisers) and like many other farmers on many individual fields we have spent far more than this. This has represented over 30% of the variable cost of growing these crops. Of course we thought that it was worthwhile or we wouldn't have done it, and yet it is a large financial burden, which we are keen to see reduced, especially if our products are to remain truly competitive in the market place. Any contribution that manufacturers can make in reducing the cost of their products would of course be very welcome although we realise that with the dependence on oil prices for many products on one hand, and the escalating costs of getting new materials to the market on the other, there is perhaps little scope for rational price cutting. For our part, we shall certainly be trying to avoid uneconomic use of chemicals, and hence the tremendous interest that has been shown in reduced dose rates.

Here I would like to pay a tribute to the work of Jimmy Elliott and his colleagues under the direction of John Fryer at WRO. Their activities may not always have endeared themselves to manufacturers but by their work, their interest, and their enthusiasm, they have done a great deal to encourage the sensible use of herbicides in this country from which everyone has benefited. We were delighted that the WRO had now "come of age", but its job is certainly not finished and the farming industry at least will continue to watch it with much interest.

We are often told of the problems that exist in agricultural development and

research because of the artificial boundaries created by history or accountancy. The Rothschild Report looked at the whole area of statefunded research and development work - not only in agriculture - and made various recommendations including the customer contractor arrangement for commissioning work. I was involved with the Joint Consultative Organisation set up by the ARC and the Ministry of Agriculture to look at work in which both were concerned, and came increasingly to the conclusion that such problems as there were, were not really solved by committee structures or accounting procedures. They were solved by people - people who were prepared to communicate, to collaborate, and to take an energetic interest in seeing that field practice benefited from their work, and from that of everyone else able to help. Whether they were employed by Institute A, Institute B, EHFs or ADAS or by commercial firms was quite immaterial, and it has been our good fortune in arable farming that generally this cooperation and preparedness to work together has existed and flourished. Direct drilling and reduced cultivation techniques would never have expanded as they have were it not for people in commercial firms such as ICI, or institutes such as WRO and Letcombe, enthusiasts in ADAS or innovator farmers and there has generally been a most refreshing lack of petty jealousy over who got the credit for which successful contribution. As farmers we must be grateful for this, and hope that a similar generous spirit of team work amongst the various workers who have done so much to help us in the past will help us to develop other new techniques in the future - Controlled Droplet Application and low ground pressure machines, to mention but two potential solutions to present problems which seem to be attracting this kind of attention.

And this leads me to another problem that the farmer has to face. With such a wide selection of possible chemicals at our disposal - and the list grows steadily longer - how are we to select which is likely to be the most worthwhile for us to use? With so many bombardments from high pressure advertising for competing products, how are we to make a sensible judgement of their relative value for us? I am incidentally surprised at the amount of money that manufacturers choose to spend on advertising: presumably they have done some market research to convince them that it pays, but I would have thought that some farmers were much more influenced by demonstration plots and properly controlled trials, especially those carried out by impartial bodies such as ADAS, than by an advertisement that they happened to see on TV. I do know that work of this kind done by ADAS, followed up as it is by intelligent advice based on knowledge and experience of the local conditions, is valued very highly by farmers, and I am sure that it is in everyone's best interests that it should be continued on at least the present scale. I have also been pleased to see the steps that have been taken by The British Crop Protection Council in the Annual Usage Review to assist in gathering more information about competing chemicals, which must be well worthwhile. Of course many new techniques are adopted in farming by watching the neighbour, or listening to the conversation between drives at a "shoot", but I see an increasing role for crop consultants or advisers, be they employed by ADAS, by the manufacturers or their distributors, or quite independent operators, to advise farmers about the increasing complexity of compounds that are now available.

We are of course very grateful for all the information that is contained in the Ministry's most valuable list of Approved Chemicals: the only problem with it is that it has become too long, and it would be more helpful if it contained a more selective list of materials likely to be the best suited for particular problems. I realise that there are difficulties to be overcome in maintaining a list of chemicals that can safely be "approved", as opposed those that are positively recommended for a particular purpose, but it would be a help to us if no new chemicals were added to the list unless they were clearly in some way superior to those already on it. Are there real problems in applying the NIAB-style approach on new varieties to new

chemicals? If so, can they not be overcome?

"Tank mixes" are another problem. Anyone who has ever attempted to combine manganese sulphate with DNBP and ended up with their own brand of ready mixed concrete will know exactly what I mean. Some chemicals mix together and work perfectly safely, and others equally do not. Some manufacturers have been much more helpful about this than others, and I think we should applaud the pioneering work that has been done by BCPC, Shell and Farmers Weekly in attempting to provide more information about what may safely go with what. So often in the past the farmer was on his own to "suck it and see" at his own risk.

It is not just a question of knowing what material to use: when and how are often just as difficult to determine, especially in our climate when no two seasons are ever alike, and conditions change from hour to hour. Selecting the right combination of material and dose rate, and timing according to the stage of growth of the crop and the pest, and the local weather, past, present and anticipated, has become steadily more difficult as the number and complexity of compounds has increased, and has placed an increasingly heavy burden of decision making on the man on the spot on the farm. Spare a thought for the farmer in our climate confronted with the label that tells him to avoid using the product at least 48 hours before wet, or dry, or frosty weather. What a pay off there would be from really accurate local weather forecasting! How often one has been caught with a tank half full of mixed product when an unexpected storm blew up, or else missed a whole day's possible spraying in good conditions for fear that this might happen.

The need for more precise timing - quite apart from the increased amount of spraying that has to be done (some of our cereal fields were sprayed as many as six times during this past year) - has of course forced us to give a lot more attention to the actual operation of spraying. We are more than ever aware of the "time-and-motion" aspects of the operation - the need for the right capacity machine, with rapid filling facilities near the fields, precise bout marking aided by the increased use of "tramline drilling" and so on. We are equally interested in other factors that may aid the spraying process, such as nozzles that do not frequently block or drip, and are easily changed to allow for different application rates or spray patterns - booms that do not bounce, and yet are easily converted from field to transport width, and whose height can be rapidly adjusted to allow for crops of varying height - products packed in containers which pour easily (if only more managing directors had to spend a day in the field filling up sprayers what changes we might see!) and clear labelling of container contents. These may all sound little things but taken together they can make such a difference in the field - and the actual sprayer operator deserves all the help that we can give him. Tribute is frequently and quite rightly, paid to the agricultural worker, his conscientiousness, his loyalty, his versatility and his adaptability, and of no one is this truer than the sprayer operator. It is to him that we owe much of what has been achieved - vast acreages of successful spraying with a minimum of accidents due to mis-application or drift, and almost no incidents affecting the health of the operator or anyone else, in spite of the potent nature of many of the substances involved.

We are of course very conscious these days of the requirements for adequate Health and Safety, which we must all support. We have attempted to ensure that all sprayer operators are properly trained and equipped, but this does not mean that theirs is an easy task. Reading instructions in small print and often downright bad English is but the first hazard to be overcome. Wearing the right protective

clothing, especially for mixing and filling is often cumbersome as well as hot. Getting chemicals to mix or dissolve may not always be easy, although we are grateful for the attention that this is continuing to receive. No one should be very happy about the difficulty of disposing safely of empty containers on the farm, and my personal feeling is that suppliers should have far greater responsibility for this, being required to accept back from farmers all empty containers supplied by them, so that central and properly supervised arrangements may be made for their safe burning, burial or destruction. Until this can be done, the fully soluble container which we first used this year, is an imaginative acknowledgement of the problem, which I personally applaud.

Greater uniformity of pack size would also be more helpful than the present hotch potch of weights and measures. Quite apart from the various acre or hectare packs, which may or may not coincide with our required dose rates we have this year taken delivery of liquids in 10 different sized containers, and solids in 10 different weights of pack: it does not make for easy stock taking! Colour coding of containers according to the toxicity of the contents is another long overdue reform: we still find men handling Part II substances without adequate precautions because they are unaware, or failed to read or remember, that part of the small print in the instructions.

And what to do with spilled chemicals? Should they be mixed with earth - or sand - or may they be safely swilled into the nearest drain - or does the operator just go away and hope they will have evaporated by his return? Most labels offer little constructive help once one has failed to obey the bland command to "Avoid Spillage"!

We must however be grateful for what has been achieved by the Pesticides Safety Precaution Scheme, in spite of some rather emotional outbursts about one particular product in recent months. The industry had to have an organisation where objective scientific assessment of the true risks and hazards associated with different compounds could be reliably made, and there is no evidence that the existing Committee has ever failed in this onerous task. We can never afford to ignore the risks, but we do ourselves a great disservice if we do not evaluate them carefully and objectively - and then accept the evidence that is presented to us.

Having reviewed something of the past, and considered a few of the current developments I would like now to give some attention to the future. What are our greatest outstanding problems - and here of course I am on speculative ground because many of them have not yet shown their nasty face. Just as nature abhors a vacuum, so when one pest has been almost overcome, we can be sure that another will be waiting in the wings to take its place. Our future success will depend upon our ability to meet these varied threats, hopefully by always having yet one more weapon left in our armoury, and never allowing a pest to develop resistance by careless or improper use of a potentially valuable material.

I suppose that on our farms today our worst problems in the world of weeds are largely those of crop contamination no doubt aggravated by earlier drilling and reduced cultivations. Driving round the country this summer I did not think we were alone in growing wheat in barley, barley in wheat, and sugar beet and potatoes over the whole farm, but every farmer will have his own list of special problems. What has been most exciting in the past few years has not necessarily been the arrival of any new materials, but the more varied use of those that we already have such as the

pre-harvest use of glyphosate (Round-up) to cereals, or frequent low-rate applications of phenmedipham (Betanal) to sugar beet, and I foresee this type of development continuing. What are the effects in practice of differing pressures or droplet sizes are other questions to which we should like more answers.

In addition to the various possible improvements in application machinery and compound formulation and packaging that I have already mentioned, anything which extends the effective use of a compound in different stages of crop or weed growth, or of weather, so that we have more possible days in which to use it, is obviously important. Wind speed and the problem of spray drift has a special significance for us in the Fens where the wide open spaces contain so many susceptible and high value crops which may be at risk. It really is surprising how few days there seem to be at the critical season when winds are light during normal working hours. We have been forced to meet this problem by having a reserve of spraying capacity so that we can cover our acreage in fewer hours when conditions are right, and our men have helped by their preparedness to spray at what for most people would definitely be regarded as "unsociable" hours, but each year there are still problems, as no doubt the insurance companies can testify. Anything that can be done to reduce the risk by formulation or method of application is obviously going to be very helpful to us as farmers - it might even help manufacturers to sell more chemicals as well!

Soil conditions are another problem and we must welcome the work that is going on to develop satisfactory low ground pressure machines, for every farmer must have had experience of the problem that these machines are designed to solve. I have always admired the courage and skill of pilots attempting to apply chemicals accurately in spite of the trees, roads, river banks, buildings and the maze of electricity and telephone wires which surround or cross so many of our fields, but I really cannot foresee a great expansion of aerial spraying. Quite apart from the cost, and the very understandable public alarm or concern when insecticide falls short or over shoots its target meaning that the operation can only be done by the extremely skilled and well supervised contractor, so often a field requires attention not tomorrow or later today, but NOW, and the farmer feels so much happier if he has the remedy in his own hands, or at least in those of a contractor who does not have all the extra problems of flying conditions with which to contend, in addition to all the other more predictable hazards of crop spraying.

I am concerned, as I have already indicated, about the possible build up of resistant pests or diseases, particularly as a result of insurance type low dose "blanket" sprays. All of us farmers have I am sure been guilty of it at one time or another - "while you are going through that field with X put on a half dose of Y with it as well: it may not be needed but it might do some good, and will cost far less to do it now and be more effective rather than waiting until we have actually seen the trouble start" - and this has often paid, and has therefore been publicly advocated by many farmers and commentators. Guilty though I may sometimes have been, I am far from happy at spraying to kill things that I have not identified, or do not know what damage they might cause - just on the off chance that such spraying might be beneficial.

The effect of agro-chemicals on the environment, and on the world of nature both inside and outside our fields, brings us to an area of public concern and controversy, in which much opinion and comment, however well intentioned, is frequently emotional, irrational and ill-informed. It is sometimes suggested that farmers are so eager to make a "quick buck" that they will happily acquiesce in the longer term destruction of their environment from which of course they or their

successors would be the first to suffer. More responsible commentators are concerned at the possible reduction in variety of wildlife which may result from the development of a more efficient and more specialised agriculture. Others have questioned the need to maintain the current level of food production in this country - let alone increase them at a time of apparent surpluses in Europe, small in relative terms though these may be. One lady has even gone so far as to suggest that the production of food in this country is a positive drain on our resources entailing allegedly large direct subsidies to farmers costing far more than would the purchase of all our food from supposedly more efficient producers overseas. What a mine-field this all is! We may be irritated by this apparent interference in our "work shop" but these are legitimate questions which deserve answers, and we have no need to be ashamed.

First, and perhaps easiest, what is the direct risk to human health whether by contamination of food or water supplies? Fortunately this has been most carefully monitored, and I know of no evidence to suggest that anyone in this country is seriously at risk. I think we must be grateful for the most thorough study that was given to the use of pesticides by Sir Hans Kornberg and his fellow members of the Royal Commission on Environmental Pollution in Agriculture. Their Report published in 1979 contained much valuable information and some very balanced and sensible recommendations. None of us should ignore a Report of this kind - nor must we drag our feet when constructive proposals are made. Similarly we should welcome the initiative and prompt action on the part of the Ministry, ADAS, and commercial firms in the spring of this year which led to the rapid compilation and distribution of the new leaflet on safe spraying. I hope it was widely read - and its advice followed. We cannot afford to be complacent about safety, but present arrangements have generally seemed to be quite adequate.

What about the variety of species? It has always seemed to me that we often under-estimate nature's capacity to take defensive or evasive action, so great appears to be the survival rate of those pests which are our target species. Most at risk of course are the birds and beasts at the end of food chains, and it is the monitoring of those populations that has lead to the reduced use or withdrawal of such substances as dieldrin and DDT, which has been very properly and responsibly supported. We must welcome the concern of responsible biologists, and the continued careful monitoring of what really is happening to the wildlife in the world around us. If there is not to be an unjustified indiscriminate banning of agrochemicals we must ensure that all who are involved in their manufacture and use will support action that may prove to be necessary, as a result of their study.

Vaguer anxieties about possible changes in ecological balance are of course much more difficult to deal with. It must be remembered that evolution has been a continuous process in the development of the world as we know it, and any attempt to "freeze" the state of nature at a supposedly ideal point would be doomed to failure. Man by his very presence on the earth is bound to have an enormous influence on it, especially if he multiplies his numbers at the present rate, and at the same time settles in urban communities, often sited on the more productive agricultural land.

Ever since the time of Malthus anxieties have been expressed about the capacity of the world to feed its growing population. So far the crisis has never come, and yet the world's population is now larger than ever before - and still growing. It is tempting for us in Europe, cushioned by the existence of our current surpluses and complacent in the knowledge of our capacity to increase production, to ignore this problem at present, but it is unlikely to be so easy in the future. Many of you

here have wide knowledge of the world, and are able to assess the likely future pressure for food supplies, especially in the tropical areas. The Brandt Commission Report drew attention to the increasing disparity in living standards between the countries of North and South, and unemployment in this country has already demonstrated our vulnerability to industrial competition from countries where labour costs are low. In the longer term our fortunes on this planet are all inter-woven, and we can be certain that - in the absence of nuclear holocaust - as much food as can be produced will be urgently required. In such a world we cannot afford to ignore the advantages to food production that are given to us by agro-chemicals, as I have demonstrated on my own farm.

That is why as a farmer I have been grateful to have been invited to speak to you here today. As a farmer I have to use all available methods for efficient production, and I have appreciated the advantages that I have gained from the use of modern agrochemicals. I hope that efforts will be continued to evolve new products to meet present and future problems, and to help to make existing products work more efficiently, and to assist in seeing that they are used safely. I believe that in this we are working in the best interests of the community of the world, in doing what we can to ensure the health and food supply of our children and of ourselves when we are old.

SESSION 3

NEW COMPOUNDS, FORMULATIONS AND USES

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THIODICARB—A NEW INSECTICIDE FOR INTEGRATED PEST MANAGEMENT

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Summary Thiodicarb (UC 51762) is a highly effective new oxime carbamate insecticide that has produced outstanding control of many important Lepidoptera and some Coleoptera, Diptera and a few species of Homoptera pests of agricultural crops and forest in trials throughout the world. Thiodicarb provides consistent efficacious results on these pests at dosages of 0.2 - 1.0 kg a.i./ha. Other major features of this insecticide include: favourable mammalian toxicity; relatively good safety margins with birds, fish and wildlife; good residual activity; absence of phytotoxicity at practical dosages; and some ovicidal activity on certain insects. Thiodicarb is very active as a stomach poison insecticide and has little contact toxicity. Thiodicarb also has produced a synergistic response in combination with methomyl, carbaryl or pyrethroids.

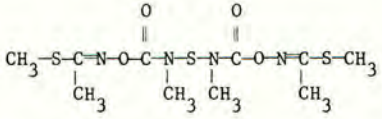
Thiodicarb is highly selective in activity and has minimal impact on important beneficial insects including bees, parasites, and predators. Therefore, thiodicarb has much potential to be utilized successfully in integrated pest management programmes designed for major crop production practices. Thiodicarb will play an important role as an effective alternate product to synthetic pyrethroids on major agronomic crops.

INTRODUCTION

Thiodicarb is the chemical name for 3,7,9,13-tetramethyl-5, 11-dioxa-2,8, 14-trithia-4,7,9,12-tetra-azapentadeca-3, 12-diene-6, 10-dione, a new oxime carbamate insecticide discovered almost simultaneously by Union Carbide research scientists in the U.S.A. and by Ciba Geigy scientists in Basle, Switzerland. Among the insecticidal carbamates, good overall effectiveness against Lepidopterous larvae is limited to relatively few members of this class of compound. Worldwide testing under code number UC 51762 and CGA 45156 in laboratories and under field trials show that thiodicarb has a performance profile which makes it unique for today's complex and dynamic world pest problems. Thiodicarb is particularly effective against most economically damaging caterpillars and it is being commercialized by Union Carbide for use worldwide on cotton, maize, soybeans, fruits, forest, forages, and vegetable crops.

CHEMICAL AND PHYSICAL PROPERTIES

Structural formula:



Empirical formula: $C_{10}H_{18}N_4O_4S_3$

Molecular Weight: 354.5 g per mole

Vapour pressure: 4.3×10^{-5} mm Hg at 20°C

Physical & Chemical properties:

Physical form	Crystalline Solid
Technical purity	95%
Colour	White to light tan
Odour	Slightly sulfurous
Melting point	173 - 174°C
Density	1.44 g/ml at 20°C
Solubility at 25°C (g/l.)	Water - 0.035 Acetone - 8.0 Methanol - 5.0

Hydrolytic stability: The rates of hydrolysis of acetaldehyde 1 - ^{14}C thiodicarb in aqueous buffer solution adjusted to pH3, 6, and 9 using 10 mg/kg concentration has been determined at 25°C for 9 days with results as follows:

pH	% thiodicarb recovered
3	48
6	96
9	< 1

Photodegradation: Thiodicarb is stable in the dark. The UV component of sunlight was found to catalyze the oxidation and hydrolysis of thiodicarb in aqueous solution. These reactions occurred much faster in the presence of a photosensitizer.

Foliage and soil residual effect: The half-life residue on bean foliage with thiodicarb is approximately 10 days as compared to less than 1 day for methomyl. Persistence of thiodicarb in soil is short. Thiodicarb has a half-life of less than two days in a biologically active soil (Sousa et al 77).

Formulation: Thiodicarb is the active ingredient of the formulated product Larvin™ and is available for testing as a 375 g a.i./l. flowable; 75% WP; 80% dry flowable; 2.5% and 5% granule; 2% and 10% bait; and 2% dust.

TOXICOLOGY

Mammalian Toxicity of Technical Thiodicarb

Thiodicarb has a moderate to low acute oral toxicity and a low acute dermal and inhalation toxicity. (Table 1) In a variety of long and short term toxicological studies with thiodicarb and its major metabolite, no significant adverse biological effects, other than transient reversible cholinesterase depression was noted.

Table 1

Type of test	LD50 Values (mg/kg)
Acute oral - rat	325
Acute dermal - rabbit	>6,310
Acute inhalation - rat	121 (a)
Eye irritation - rabbit	None
Dermal irritation - rabbit	None

(a) Acute inhalation - rat expressed as LC50 mg/m^3.

Evaluation of environmental hazards

Thiodicarb has a relatively good safety margin with birds and fishes. Upland game species and waterfowl are quite tolerant to acute doses or dietary feeding. (Table 2) The toxicity of thiodicarb to fish species is several hundred fold less that of the synthetic pyrethroids. Daphnia magna and grass shrimp were the most susceptible species to thiodicarb. However, a comparison of the toxicity of thiodicarb with methomyl, permethrin, and fenvalerate shows that it is less toxic than these compounds, (Browne 1980). The 48 h LC50 for Daphnia magna are 53.0, 1.96, 0.73, and 15.8 µg/l. for thiodicarb, permethrin, fenvalerate, and methomyl respectively. Thiodicarb has a minimal effect on the fiddler crab.

The proposed agronomic crop uses of thiodicarb do not appear likely to have severe adverse effects on non-target organisms.

Table 2

Toxicity of technical thiodicarb to fish, birds, and aquatic organisms

Study type	Species	Toxicity of technical thiodicarb (mg/kg or mg/l.)
Acute oral LD50	bobwhite quail	2023
Dietary LC50	mallard duck	5620
Acute toxicity LC50	bluegill sunfish	1.21
(96-h)	rainbow trout	2.55
	brook trout	4.45
	coho salmon	2.98
	fiddler crab	2.54
	grass shrimp	0.56
(48-h)	Daphnia magna	0.053

ENVIRONMENTAL FATE

Thiodicarb is not unduly persistent in the environment. Its primary degradation products by hydrolysis, photolysis and metabolic action are methomyl and methomyl oxime fractions that are further degraded to compounds of no biological significance. Animal metabolism studies have shown no transfer of thiodicarb residues to meat, milk, and eggs, and there is no evidence of storage or accumulation in mammalian tissue. Thiodicarb does not leach readily through soil nor does it appear to adversely affect soil microbes. In soils under normal conditions of expected use, residues readily dissipate in 3 - 6 weeks. Thiodicarb does not appear to accumulate in fish or other organism foodchains.

BIOLOGICAL ACTIVITIES

Worldwide lab and field testing with thiodicarb began in 1975. Data indicated that thiodicarb is a relatively narrow spectrum insecticide but is particularly effective against fruit and leaf eating caterpillars. Its primary mode of action is by ingestion as it has only limited contact toxicity. The residual biological activity on plants is approximately 7 - 10 days. Due to thiodicarb's low vapour pressure and poor solubility in water, it has little to no fumigation or systemic activity. It has a relatively short residual life in soil and is therefore not considered an effective soil insecticide.

Cotton

Thiodicarb is especially effective in cotton for the control of a wide range of Lepidopterous pests. Numerous field trials in major cotton growing countries show that thiodicarb at rates ranging from 0.45 to 1.0 kg a.i./ha gives control of the Heliothis spp. complex including Heliothis armigera , Heliothis punctigera , Heliothis virescens , and Heliothis zea comparable to the synthetic pyrethroids or organo-phosphates. The period of control provided by thiodicarb is also equivalent to the synthetic pyrethroids. Table 3 presents data from a performance comparison conducted in Mississippi, U.S.A. in 1980 (Pitts and Pieters, 1981).

Table 3

Efficacy of Chemicals for control of Cotton Bollworm and Tobacco Budworm 1980, Mississippi, U.S.A. 1) and 2)

Treatment & kg a.i./ha	% Damaged Squares [3]	Live Larvae/ 100 Squares [3]	Yield (seed cotton) kg/ha
Fenvalerate 2.4EC .11	4a	.8a	3136a
Thiodicarb 4.18F .50	11a	1.6abc	2716abc
Permethrin 3.2EC .11	8a	3.6bcd	2614bc
Sulprofos 6EC .83	9a	.8a	2332cd
Permethrin 2EC .11	10a	4.8d	2305cd

Table 3 (Continued)

Treatment & kg a.i./ha	% Damaged Squares [3]	Live Larvae/ 100 Squares [3]	Yield (seed cotton) kg/ha
EPN + MP + Chlordimeform .83 +.83 +.14	8a	.8a	2021de
Profenofos 6EC .83	11a	1.6abc	1597e
Tox + MP.6 + 3EC 2.24 + 1.12	40b	5.6de	541f
CHECK	68c	7.2e	215f

1) Insecticide applied July 14, 18, 24, 28, August 1, 6, 11, 15, 20, 25, 29, and September 3.

2) Test Design; RCBD 4 reps, Plot Size; 2.43 x 27.36 meters. Applied at 46.8 l./ha 40 psi 3 nozzles/row.

3) Means for five dates: July 23, 31, August 5, 14, 19. Means followed by the same letter are not significantly different (P=.04).

The dosage rates for thiodicarb that give comparable control of the Heliothis complex to that of the synthetic pyrethroids are stated in Table 4.

Table 4

Dosage of thiodicarb and synthetic pyrethroids giving comparable control of Heliothis spp.

Country	Pests	Thiodicarb kg a.i./ha	Synthetic Pyrethroids kg a.i./ha
U.S.A.	H. virescens H. zea	0.45	fenvalerate 0.1
Australia	H. armigera H. punctigera	0.5	cypermethrin 0.075
Brazil	H. virescens	0.45	permethrin 0.1
Thailand	H. armigera	0.55	cypermethrin 0.075
Mexico	H. virescens H. zea	0.5	cypermethrin 0.125
South Africa	H. armigera	0.5	cypermethrin 0.05

On cotton foliage feeders such as the damaging Spodoptera species, thiodicarb appears to be especially effective at 0.5 - 1.0 kg a.i./ha. In Egypt, thiodicarb at 0.675 kg a.i./ha rate demonstrated outstanding control of Spodoptera littoralis initially and nine days after application with 96% and 79% mortality respectively.

Thiodicarb has also controlled Diparopsis castanea , Earias insulana , Alabama argillacea , Trichoplusia ni , Bucculatrix thurberiella , and Dysdercus sp. at rates ranging from 0.3 to 1.5 kg a.i./ha in many parts of the world. Preliminary observations show that at rates as high as 1 kg a.i./ha, it is only marginally effective against Anthonomus grandis . Lygus spp. and Trialeurodes abutilonea are suppressed at high rates of application. In the U.S.A., where boll weevil and cotton bollworm occur together, thiodicarb at 0.3 - 0.5 kg a.i./ha as a tank mix with OP compounds such as methyl parathion or azinophos-methyl at standard boll weevil rates provides excellent control of both pests.

In studies by the U.S. Department of Agriculture and various universities, there have been indications that thiodicarb posesses some ovicidal activity on Heliothis virescens eggs. However, as an ovicide, it was approximately half as effective as methomyl at similar rate, 0.15 kg a.i./ha. Tank mixes of thiodicarb with methomyl or chlordimeform have shown promising results especially in fields infested with large numbers of eggs.

Thiodicarb is not effective against aphids, spider mites, thrips, or leafhoppers. However, field trials in Arizona indicated that at seven applications of thiodicarb with a total of 4.0 kg a.i./ha applied, it did not aggravate mite populations. No plant phytotoxicity has been reported in over 100 trials on cotton worldwide with thiodicarb used at practical rates ranging from 0.4 kg a.i./ha to 1.5 kg a.i./ha.

Soybean

The excellent activity of thiodicarb against Lepidoptera pests in cotton is also shown in soybean. Extensive field trials indicate that the dosage rates needed to control all the prominent caterpillar pests with the exception of loopers range from 0.15 - 0.45 kg a.i./ha. The soybean looper is effectively controlled by applying 0.45 - 1.0 kg a.i./ha. The green cloverworm (Plathypena scabra) and velvetbean caterpillar (Anticarsia gemmatalis) can be controlled at rates of less than 0.15 kg a.i./ha. Thiodicarb is not effective on mites, aphids, stinkbugs, and other sucking insects on soybeans. For effective control of the Mexican bean beetle (Epilachna varivestis) and the bean leaf beetle (Cerotoma trifurcata), thiodicarb rates greater than 0.45 kg a.i./ha are required but even these rates are less effective than the standard carbaryl or pyrethroids. The effective dosages of thiodicarb against the major soybean pests are summarized in Table 5.

Table 5

Effective dosages of thiodicarb against major soybean pests

Crop	Pests	Dosage kg a.i./ha
Soybean	Armyworm (Spodoptera spp.)	0.25 - 0.45
	Podworms (Heliothis spp.)	0.15 - 0.45
	Cabbage loopers (Trichoplusia ni)	0.25 - 0.45
	Soybean looper (Pseudoplusia includens)	0.45 - 1.0
	Green cloverworm (Plathypena scabra)	< 0.15
	Velvetbean caterpillar (Anticarsia gemmatalis)	< 0.15

Table 5 (Continued)

Crop	Pests	Dosage kg a.i./ha
Soybean	Mexican bean beetle (Epilachna varivestis)	0.45 - 0.75
	Bean leaf beetle (Cerotoma trifurcata)	0.45 - 0.75

Deciduous Fruit and Vine

In the U.S.A., thiodicarb has been very effective against grape berry moth (Endopiza viteana) by reducing the number of infested berries. The 1979 and 1980 data showed that thiodicarb at 1.0 kg a.i./ha reduced the number of infested berries by the greatest percentage although it is not significantly different from fenvalerate and permethrin at 0.23 kg a.i./ha or methomyl at 0.8 kg a.i./ha (Williams 1979; Williams and Ellis 1980). Table 6 summarizes the control of grape berry moth by these insecticides.

Table 6

Control of grape berry moth on 'Concord' grape in U.S.A. 1979, 1980

Treatment 1)	kg a.i./ha	Mean number infested berries/ 10 cluster at harvest 2) 1979	1980	% reduction infested berries at harvest 1979	1980
Thiodicarb	1.0	4.75a	2.75a	91	77
Methomyl	0.8	24.75a	10.75ab	51	11
Fenvalerate	0.23	11.25a	3.75ab	78	68
Permethrin	0.23	--	6.25ab	--	47
Untreated Control		51.0b	11.75b	--	--

1) Rows were nine feet on center with nine feet between vines. Each row was a randomized complete block containing a single replicate of each treatment. A replicate consisted of two adjacent vines, with four replicates/treatment. Insecticidal applications were made on July 6 in 1979 at the rate of 879 l. of water/ha; on June 27 and July 7 at the rate of 935 l. of water/ha as foliar sprays using CO_2 sprayer operated at 60 psi and equipped with Teejet DZ disc and No. 25 cone.

2) Ten clusters were taken at random from each plot at harvest on October 1, 1979 and September 30, 1980. Data analyzed by DMRT at 0.5 level.

In France, excellent activities on grape berry moths (Polychrosis botrana) and (Clysia ambiguella) were obtained with thiodicarb at rates ranging form 0.3 - 0.45 kg a.i./ha.

Data obtained from thiodicarb trials in apple and peaches in the U.S.A., Japan, and France indicated that 1.0 - 2.0 kg a.i./ha controlled major deciduous fruit pests, such as codling moth (Laspeyresia pomonella), oriental fruit moth (Grapholitha molesta), red-banded leafroller (Argyrotaenia velutinana), oblique banded leafroller (Choristoneura rosaceana), Tufted apple budmoth (Platynota idaeusalis), and plum curculio (Conotrachelus nenuphar), resulting in high quality marketable fruit. Thiodicarb did not appear to enhance mite build-up but had a tendency to increase woolly apple aphid (Eriosoma lanigerum)infestations. However, this aphid was controlled by combinations with carbaryl or other OP compounds.

Other Uses

The excellent activity of thiodicarb against Lepidoptera pests has also been demonstrated on vegetable crops, field/sweet corn, forage, pasture, sorghum, tobacco, tea, rice, and other row crops. At 0.25 - 1.0 kg a.i./ha, thiodicarb will control cutworms (Agrotis spp.), corn earworm/fruitworm (Heliothis spp.), European corn borer (Ostrinia nubilalis), western bean cutworm (Loxagrotis albicosta), imported cabbageworm (Pieris rapae), tea tortrix (Adoxophyes spp.), cabbage armyworm (Mamestra brassicae), rice stem borer (Chilo suppressalis), and rice leafroller (Cnaphalocrocis medinalis). For control of diamond back moth (Plutella xylostella) on vegetables, thiodicarb rates of greater than 1.0 kg a.i./ha are required in the far East, while in the U.S.A., the effective dosage is at 0.5 kg a.i./ha.

Thiodicarb has also been tested by the U.S. Forest Service for the control of western spruce budworm (Choristoneura occidentalis). Preliminary results from a simulated aerial trial indicated excellent activity with thiodicarb rate as low as 0.2 kg a.i./ha. Thiodicarb will most likely be recommended for field testing in 1982 by the U.S. Forest Service.

Another potential use for thiodicarb is in combination baits with metaldehyde (2% thiodicarb © 1.75% metaldehyde) at 0.5 - 1.0 kg a.i./ha for the control of slugs and snails around orchids, ornamentals and home and garden.

SYNERGISM WITH OTHER COMPOUNDS

It has been reported that thiodicarb in combination with methomyl (1:1) resulted a synergistic action against soya fly larvae (Table 7).

Table 7

Synergistic effect of methomyl + thiodicarb against soya fly[1)]

	% Control
Methomyl 300 mg/l. + thiodicarb 300 mg/l.	95
Thiodicarb 600 mg/l.	50
Methomyl 600 mg/l.	65

1) Belgium patent application number 870790 published in March 27, 1979 to DuPont De Nemours Co.

There is another report of synergistic effects between certain pyrethroids such as cypermethrin and thiodicarb at a mixture of 5:1 against aphids (Aphis fabae). (Table 8)

Table 8

Synergistic effect of cypermethrin + thiodicarb against Aphis fabae[1)]

Test Compounds	LC50 (% by wt)	Coefficient of Co-toxicity
Thiodicarb	0.0044	--
Cypermethrin	0.00031	--
Thiodicarb + Cypermethrin 5:1 mixture	0.00096	140

1) European patent application number 8474, published in March 5, 1980 to Shell International Research.

Preliminary laboratory studies from the National Institute of Agr. Sciences in Japan indicated that synergism may exist with mixtures of thiodicarb + carbaryl at 1:1 ratio against OP and carbamate resistant green rice leafhopper (Nephotettix cincticeps). In India, preliminary laboratory studies with this mixture indicated potential synergistic effect against Heliothis armigera . The synergistic response of thiodicarb with other classes of insecticides is being investigated on a variety of other pests in our laboratories. The practical significance of these mixtures in the field is also being investigated.

BENEFICIAL INSECTS

Preliminary laboratory and small plot field data indicated that thiodicarb permits a favourable survival coefficient when many of the prominent predators and parasites are exposed to it. Geocoris spp., Trichogramma spp., Orius spp. and spiders are least affected. Nabis spp. are reduced by about 60% with rates up to 0.45 kg a.i./ha but the population recovered after 2 - 7 days after application. These data are being confirmed under large scale aerial application trials in 1982.

Based on laboratory and field studies, thiodicarb has been classified as only moderately toxic to honeybees, (Atkins et el, 1981). Based on laboratory data, thiodicarb is approximately five times less toxic to honeybees than methomyl. The µg/bee LD 50 value for thiodicarb is 7.08 versus 1.29 for methomyl.

The possibility of using thiodicarb in IPM programmes has considerable potential based on its low level of contact action and its narrow spectrum of activity.

SELECTED BIOLOGICAL PROPERTIES OF THIODICARB AND METHOMYL

Structurally, thiodicarb is similar to methomyl which is sold worldwide as products under the trade names of Lannate® and Nudrin®. Bridging of the carbamoyl nitrogen of methomyl with a sulfur atom as has been achieved with thiodicarb resulting in dramatic changes in physical and biological properties as illustrated in Tables 9 and 10.

Table 9

Comparison of solvent solubilities of thiodicarb and methomyl

Solvent	Solubility (g/l.) Thiodicarb	Methomyl
Water	0.035	58
Acetone	8.0	422
Methanol	5.0	500

Table 10

Comparison of selected biological responses for thiodicarb and methomyl

	Thiodicarb	Methomyl
Rat: Acute Oral LD50	325 mg/kg	17 mg/kg*
Aphis fabae LD50	8 mg/l.	4 mg/l.
Spodoptera eridania LD50	11 mg/l.	7 mg/l.
Spodoptera frugiperda; (resistant to methomyl and carbaryl; LD50	1.6 $\mu g/cm^2$ foliage	16.0 $\mu g/cm^2$ foliage
Heliothis virescens LD50	10 mg/l.	19 mg/l.
Leaf residual half-life for *S. eridania* larvae	10 days	1 day
Injury to cotton	None	Phytotoxic
Mode of Action	Ingestion >> contact	Contact $\geq$ ingestion

* Caplan, A.M. & Sherman, H. 1977.Toxicity studies with N - {(methyl amino) carbamoyl} oxy {ethanimidothioate} Toxicology and Applied Pharmacology 40: 1-17.

CONCLUSIONS

Thiodicarb is a new carbamate insecticide which fits the requirements of many integrated pest management practices with pesticides for agronomic uses. It also offers a new alternative to synthetic pyrethroids for controlling many species of caterpillars worldwide.

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SESSION 4B

BEHAVIOUR AND FATE OF PESTICIDES AFTER APPLICATION

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RELATIONSHIPS BETWEEN CHEMICAL STRUCTURE AND THE BEHAVIOUR AND FATE OF PESTICIDES

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Summary Many aspects of chemical behaviour in the environment depend on partitions of chemical between air, water, soil and organisms. Soil-water distributions and bioconcentration factors from water can be estimated from the octanol-water partition coefficient which can be calculated from the structure. Vapour pressure and water solubility can be calculated from the structure if the melting point is known. Air-water and air-soil distributions can be estimated directly from the structure without knowledge of the melting point because the melting point term used to calculate water solubility and vapour pressure cancels out in the ratios. Systemic behaviour in plants, particularly after root application, can be related the octanol-water partition coefficient as can aspects of soil insecticide toxicity to soil insects from a combination of the partition coefficient and the vapour pressure. It is also possible to indicate routes and rates of breakdown for some compounds from the structure.

The physical principles of pesticide behaviour have been thoroughly discussed by Hartley and Graham-Bryce (1980). The aim of this paper is to show that many aspects of redistribution and biological performance of chemicals can be predicted from the structure of the chemical.

In any biological system the same factors determine the fate of a chemical although their relative importance differs. Redistribution from an initial application depends on evaporation, solution in organic of aqueous phases and subsequent partition between aqueous, organic, inorganic and air phases. Persistence in the system depends on the intrinsic stability of the chemical to chemical reactants and enzymes which it encounters during redistribution, the level of biological activity in the system and the distribution of the chemical in relation to sites of degradation.

The key physico-chemical properties are solubility, vapour pressure, partition coefficients and intrinsic stability.

For partition coefficients the Collander (1950) equation relating partition coefficients in different solvent-water systems should apply.

$$\log K_1 = a \log K_2 + b \qquad (1)$$

All partition related properties should therefore be inter-related and log-log relationships between almost any combination of partition coefficients, reversed phase HPLC retention volumes, GLC retention times, R_f values from reversed phase TLC or soil TLC, soil adsorption, soil mobility and bioconcentration factors are to be expected. Many of these relationships are in the literature and theoretical values of a and b in the Collander equation have been derived and shown to agree well with

experimental results. (Briggs 1981a).

An estimate of the partition coefficient in one system leads to an estimate of many others and the octanol-water system is the obvious choice. K_{ow} can be calculated from the structure with reasonable precision using pi-constants or fragment constants (Hansch and Leo 1979). Water solubility and vapour pressure can also be calculated so that important properties such as soil leaching, air-water and air-soil distributions can be estimated within limits narrow enough to predict behaviour

Soil-water distribution

The soil-water distribution, K_d, for unionised compounds is proportional to the soil organic matter content. K_{om}, the soil organic matter-water distribution is more or less a constant.

$$K_{om} = \frac{100\ K_d}{\%\ om} \qquad (2)$$

K_{om} is related to K_{ow} by (Briggs 1973, 1981a,b)

$$\log K_{om} = 0.52 \log K_{ow} + 0.65 \qquad (3)$$

K_d is therefore given by $K_d = \frac{4.5 \sqrt{K_{ow}} \cdot \%om}{100}$ (4)

Table 1 gives a number of examples of experimental soil K_d values and calculated values using equation 4 with either measured or calculated values of K_{ow}. The calculated K_{ow} values were obtained using the parachor (Briggs 1981a).

Table 1
Experimental and calculated K_d values

Chemical	K_d experimental	K_d calculated via experimental K_{ow}	via parachor
aldicarb sulphone	0.11	0.14	0.20
dimethoate	0.19	0.39	0.50
aldicarb	0.87	0.97	1.09
diazinon	4.7	5.7	8.7
parathion	21.2	15	14
tetrachlorobenzene	47	26	17
simazine	0.97	0.90	1.09

Movement on soil tlc plates depends on K_d and so can be predicted from K_{ow} (Briggs 1973, 1981a) or from HPLC retention times (McCall et al. 1980).

Air-water distributions

The air-water distribution is obtained from the ratio of the saturated vapour concentration and the water solubility.

Water solubility

Water solubility is essentially a distribution of the chemical between itself and water and so should be related to other partitions by the Collander equation. For organic liquids, water solubility in moles/litre is given by

$$\log WS = 0.84 - 1.18 \log K_{ow} \qquad (5)$$

and can therefore be estimated directly from the structure (Briggs 1981a).

For a solid to dissolve the crystal lattice must be broken up and hence a term for the latent heat of fusion must be included in calculation of the solubility. Yalkowsky (1978) has shown that this term is approximately $0.01\ T_m - 0.25$ at 25°C where T_m is the melting point in °C. Water solubilities for pesticides are given to within a factor of 2-3 fold (Briggs 1981a) by

$$\log WS = 0.01 - \log K_{ow} - (0.01T_m - 0.25) \quad (6)$$

$$\text{Hence } WS = \frac{1}{K_{ow} \cdot 10^{(0.01T_m - 0.25)}} \quad (7)$$

Values calculated from this equation are compared with experimental data (Furer and Geiger 1977) in Table 2. The K_{ow} values used were either

Table 2
Calculated and experimental water solubilities

Chemical	Water solubility (ppm)	
	Experimental	Calculated
bromophos	1.0	3.4
chloropropylate	1.5	1.8
fenchlorphos	2.5	5.3
bromophos ethyl	3	0.8
chlorobenzilate	13	13
carbaryl	50	65
chlorfenvinphos	145	286
fenuron	3700	1160
dimethoate	25000	19500
simazine	3.5	63

experimental or calculated if experimental values were not available. The water solubilities calculated by equation 7 are all close to the experimental values except for simazine. The reasons for this will be discussed later.

Vapour pressure

For liquids, vapour pressure is related to temperature (°K) by

$$\log p = -A/T + B \quad (8)$$

B is approximately 8 for many compounds an a value of 8 also follows from Trouton's rule relating boiling point and latent heat of evaporation. Vapour pressure at one temperature is therefore all that is needed to calculate vapour pressure at other temperatures. The simplest measurement is boiling point at atmospheric pressure which only requires a temperature measurement. Where T_b is the boiling point at atmospheric pressure in °C

$$\text{v.p. (mms Hg at } 25^oC) = 10^{-0.01718(T_b - 192.7)} \quad (9)$$

Many chemicals decompose well below the boiling point at atmospheric pressure so that experimentally the boiling point cannot be determined. However much work was done in the past on relationships between structure and boiling point (see reviews by Partington 1968 and McGowan 1965). Approximate boiling points can be calculated by adding increments for substituents to a parent structure of known boiling point. Vapour pressure changes by an order of magnitude with each 60° change in boiling point. Earlier investigators of relationships between boiling point and structure looked for very precise predictions but this is not necessary for an approximate estimate of vapour pressure. Experimental values of vapour pressure reported in the literature often differ by several orders of magnitude

because of the experimental difficulties in measurement.

A short list of boiling point increments is given in Table 3. These were derived from substances boiling at more than 80°C because the effect of a substituent decreases as the boiling point increases (McGowan 1965). Boiling points were taken from the Handbook of Chemistry and Physics (1965) avoiding reduced pressure measurements where the pressure recorded is generally no more than an indication.

Table 3
Boiling point increments for substituent groups

Substituent	Boiling point increment °C	
	Aliphatic	Aromatic
CH_3	15	30
Cl	80	40
CN	180	100
C_6H_5	150	150
OCH_3	80	75
NO_2		130
$CON(CH_3)_2$	200	
SCH_3	160	110
$SOCH_3$	290	
SO_2CH_3	320	

It is easily possible to build up a series of constants comparable to the f-values used for partition coefficients which allow more precisely for variations due to different molecular environments. For many compounds however it is possible to find reasonably close structures of known boiling point to which only a few substituents have to be added. A few examples are given below. Vapour pressures are from Martin and Worthing (1977).

Phorate	$(EtO)_2PSSEt$	boiling point	220°	vapour pressure
	$- CH_3$		- 15	calc. 6×10^{-4}
	$+ SCH_3$		+160	expt. 8×10^{-4}
	$+ CH_3$		+ 15	
		calc. b.pt.	375°	
Parathion	$(EtO)_2PSSEt$	boiling point	220°	vapour pressure
	$- Et$		- 30	calc. 1.7×10^{-5}
	$+ C_6H_5$		+150	expt. 3.8×10^{-5}
	$+ NO_2$		+130	
			470°	

Vapour pressures of solids

For a solid, the energy to break the crystal lattice must again be included and the same term as in the water solubility calculation is used to modify equation 9.

$$p = 10^{-0.01718(T_b - 192.7)} \cdot 10^{-(0.01T_m - 0.25)} \qquad (10)$$

Equation 10 thus allows the vapour pressure to be calculated if the melting point is known.

DDT	diphenyl methane	b.pt.	264°	melting point 108°C
	+ CH_3		+ 15	
	CH_3 - CCl_3		+163	vapour pressure
	+ 2 x Cl		+ 80	calc. 3.3×10^{-7}
		calc. b.pt.	522°	expt. 1.9×10^{-7}
aldrin	hexachlorocyclopentadiene		239	melting point 104°C
	+ 7 carbons (=CH_3)		+105	
		calc. b.pt	344°	vapour pressure
				calc. 4.1×10^{-4}
				expt. 1.4×10^{-4}

Only a few examples have been given but equally precise calculations can be done for most chemicals.

Thus K_d, water solubility and vapour pressure can all be estimated from the chemical structure together with the melting point for the last two. The melting point is extremely susceptible to changes in molecular structure and is certainly not capable of being calculated with any precision. Thus one measurement would therefore be required for absolute values of vapour pressure and water solubility.

Air-water ratio

In practice the important factors are ratios of concentration. The air-water ratio can be obtained from equations 7 and 10 (concentrations in moles l^{-1}).

$$K_{aw} = \frac{10^{-0.01718(T_b - 192.7)} \cdot 10^{-(0.01T_m - 0.25)} \cdot K_{ow} \cdot 10^{(0.01T_m - 0.25)}}{22.4 \times 760}$$

The melting point term cancels out so that the air-water distribution is obtainable directly by calculation.

$$K_{aw} = \frac{10^{-0.01718(T_b - 192.7)}}{17000} \cdot K_{ow} \qquad (11)$$

A further point is that, although an inaccurate melting point will lead to inaccurate calculations of solubility and vapour pressure, the errors will cancel in the ratio. An interesting example arises in the triazine herbicides.

Table 4
Properties of simazine and atrazine

Chemical		WS ppm	V.P. mm Hg	K_{aw}
atrazine	expt.	28	3×10^{-7}	1.35×10^{-7}
	calc.	38	8×10^{-7}	2.67×10^{-7}
simazine	expt.	3.5	6×10^{-9}	2.03×10^{-8}
	calc.	61	4×10^{-7}	8.98×10^{-8}

Calculated b.pt. atrazine 460°C, simazine 445°C.

For atrazine all the values are in reasonable agreement while for simazine K_{aw} is in reasonable agreement with the experimentally derived value but the solubility and vapour pressure calculated are both much too large. Rather than looking for an error in the relationships used in the calculations the melting point was investigated. Simazine does melt at the reported 225-227° but it is decomposition rather

than melting. If a sample is melted, cooled and melted for a second time the melting point falls to below 220°C and melting for a third times gives a melting point below 200°C. TLC examination of a once melted sample shows extensive decomposition. The melting point which fits the data is about 360°C.

Air-soil ratio

The air-wet soil ratio is

$$K_{as} = K_{aw} / M + K_d \qquad (12)$$

where M is the soil moisture content. K_{as} is therefore considerable influenced by K_d. The moisture content, generally in the range 0.1 to 0.25 for mineral soils, is important when K_d is of comparable magnitude but for K_d greater than 1 it can be neglected and substituting for K_{aw} from equation 11 and K_d from equation 4 gives equation 13

$$K_{as} = \frac{10^{-0.01718(T_b - 192.7)}}{765 \text{ om}} \sqrt{K_{ow}} \qquad (13)$$

K_{as} therefore increases as vapour pressure increases and also as lipophilicity increases. The increase with increasing lipophilicity may seem surprising at first because soil adsorption increases with increasing K_{ow} but it is proportional to the square root of K_{ow} whereas water solubility decreases in direct proportion to K_{ow}. Some calculated values of K_{as} from calculated values of T_b and K_{ow} are given in Table 5 and are in good agreement with literature values from Guth et al. (1976)

Table 5
Air-wet soil distributions

chemical	K_{as}		
	calculated	Guth. et al.	calc./expt.
DDT	1.7×10^{-6}	6×10^{-7}	2.8
parathion	5.5×10^{-7}	1.4×10^{-7}	3.9
lindane	8.6×10^{-7}	1.9×10^{-6}	0.5
atrazine	1.3×10^{-7}	8.3×10^{-8}	1.6

Vapour phase activity

The mass of chemical moving to an organism in the vapour phase by diffusion depends on the surface area of the organism and the vapour phase concentration (Hartley and Graham-Bryce 1980). The efficiency of uptake from the vapour phase is not known but the air-organism distribution should be comparable to the air-wet soil distribution so that much of the chemical arriving as vapour would be adsorbed. The rate of uptake is proportional to the air concentration and therefore, for soil applied chemicals, to K_{as}. As shown in equation 13 K_{as} depends on organic matter content, boiling point and K_{ow} and no single property will be a good guide to efficacy by the vapour route. In particular the influence of the melting point term for solids makes either water solubility or vapour pressure alone unreliable as a guide to vapour action.

This point can be illustrated in data obtained for toxicity of insecticides to insects on the soil surface. Table 6 gives the results of Nicholls et al. (1981) for Drosophila melanogaster and Harris and Bowman (1981) for the cricket, Acheta pennsylvanicus (Burmeister). Harris and Bowman related the ratio of soil LD_{50} and contact LD_{50} to water solubility by a log-log relationship while Nicholls et al. discuss the relationship between a comparable ratio and K_{as}.

The first column of Table 6 gives K_{as} calculated using equation 13. T_b for the sulphoxides and sulphones of terbufos and phorate was calculated from the boiling point increments in Table 3. Harris and Bowman showed that there was a good correlation between log water solubility and log toxicity ratio. For their data there is an equally good correlation with log K_{as} and between log K_{as} and log water solubility. For the second set of data there is a good correlation between toxicity and K_{as} but no correlation with water solubility which in turn is not correlated with K_{as}.

Table 6
Toxicity of insecticides to insects on the soil surface

Chemical	K_{as}	$\frac{LD_{50} \text{ moist soil}}{LD_{50} \text{ contact}}$ [a]	water solubility ppm
Test insect A. pennsylvanicus			
fensulfothion	1×10^{-9}	9500	2000
terbufos sulphone	3×10^{-9}	2636	408
phorate sulphone	7×10^{-9}	4987	860
terbufos sulphoxide	1×10^{-8}	5657	1100
phorate sulphoxide	2×10^{-8}	8941	8000
carbofuran	2×10^{-7}	13434	320
diazinon	2×10^{-6}	258	69
chlorpyrifos	3×10^{-6}	206	0.7
fonophos	1×10^{-5}	110	15.7
terbufos	2×10^{-5}	100	5.5
phorate	3×10^{-5}	276	17.9
Test insect D. melanogaster			
tetrachlorvinphos	3×10^{-9}	5000	11
dimethoate	2×10^{-8}	15700	25000
chlorfenvinphos	4×10^{-8}	3100	145
carbophenothion	1×10^{-7}	550	0.29
phorate	4×10^{-5}	108	17.9
thionazin	5×10^{-5}	224	1140

[a] contact activity-spray concentration for A. pennsylvanicus; topical LD_{50} for Drosophila

Systemic activity in plants

Movement of chemicals in plants depends on passage through membranes and transport through tissues capable of adsorbing solutes. Relationships between aspects of plant uptake and partition coefficients are therefore to be expected. Water solubility is likely to be a guide to behaviour only as far as it is a guide to the partition coefficient.

Translocation from roots to shoots is limited for polar compounds, increases to a maximum at log K_{ow} circa 2 and falls with further increase in lopophilicity so that there is little translocation of chemicals with log K_{ow} greater than 4. (Briggs et al.1977). In soils K_d increases with increase in K_{ow} leading to a decrease in soil solution concentration and optimum uptake from soil should be found with chemicals having log K_{ow} of about 1. Table 7 taken from data by Cossey and Phillips (1981) and Brown et al.(1981) illustrates this for 3-alkoxyuracil derivatives. Pre-emergence herbicidal activity is greatest for the two chemicals with log K_{ow} around 1. More lipophilic chemicals are less effective pre-emergence although much more active as inhibitors of the Hill reaction.

Table 7
Herbicidal activity of 3-alkoxyuracils

Hill reaction pI_{50}	log K_{ow}	Pre emergence rate for 90% kill of rye-grass kg ha^{-1}
2.6	-0.3	16
3.9	0.11	2
4.9	0.76	0.25
5.4	1.26	0.5
5.8	1.69	1
6.3	2.48	4
6.8	2.95	16

Chemicals with log K_{ow} greater than 3 are not effective in any kind of systemic action from soil application unless they are metabolised to more polar compounds.

DEGRADATION

For soils a simple two compartment model with chemical in either the water phase or the adsorbed phase with decomposition by first order kinetics in the water phase only leads to the relationship

$$H = H_w (1 + 100K_d /M) \qquad (14)$$

where H is the observed soil half life, M is the moisture content and H_w is the half life in the soil water phase. H_w is not the half life in water or buffer but that in the soil water which is a very active metabolising system. Ethyl acetate for example has a half life of 70 years in neutral buffer but only a few minutes in a soil suspension, an acceleration of several million fold.

Equation 14 shows how stability depends on both the intrinsic stability of the molecule and the distribution in the system. K_d can be calculated from the structure and H_w obtained from experimental half life. If the degradation pathway is known H_w can be obtained for different functional groups in the molecule. The intrinsic stability of a functional group will be the same in any molecule in which it occurs in a comparable steric and electronic environment. It is also possible to use steric and electronic substituent constants to estimate H_w in different environments. With a suitable data bank it is therefore possible to estimate persistence from structure. Table 8 lists some values of H_w.

Table 8
H_w values for functional groups in soil at 15°C

Transformation	H_w days	
R-S-R → R-SO-R	0.04	unhindered, phorate, disulfoton
"	0.2	hindered, aldicarb
R-SO-R → $R-SO_2R$	0.8	unhindered, phorate sulphoxide
"	15	hindered, aldicarb sulphoxide
carbamate hydrolysis	24 - 30	aldicarb, sulphoxide and sulphone
"	8	oxamyl
phosphate ester hydrolysis	2.6	phorate and disulphoton series
carboxyl ester hydrolysis	0.001 - 0.1	increasing steric effects from 2,4-D esters to deltamethrin

The relative rates of oxidation of thioethers and sulphoxides are similar to those found for chemical oxidations, as is the steric effect. Carboxylic acid esters are much less stable than phosphorus esters which accounts for the lability of organophosphates containing carboxyl ester functions. The carbamate group is apparently very stable to hydrolysis in soil. Oxamyl and the oxidative metabolites

of aldicarb are not of long persistence in soil because they are very polar molecules and are almost entirely present in the soil water phase. Other carbamates are generally metabolised in other parts of the molecule. Metabolism of either the amide or the thioether group in oxamyl to short-lived products may explain the apparently greater lability of the carbamate group in oxamyl.

Terbufos has a thioether group comparably hindered to that in aldicarb. Its degradation rate can be calculated using the data in Table 8. This is compared with phorate in Table 9.

Table 9

Calculated degradation rates of terbufos and phorate

Chemical	log K_{OW}	transformation	H_w days	H days
phorate	4.16	oxidation	0.04	6
		hydrolysis	2.6	400
phorate sulphoxide	2.26	oxidation	0.8	13
		hydrolysis	2.6	39
phorate sulphone	2.36	hydrolysis	2.6	49
terbufos	4.66	oxidation	0.2	50
		hydrolysis	2.6	643
terbufos sulphoxide	2.66	oxidation	15	352
		hydrolysis	2.6	61
terbufos sulphone	2.76	hydrolysis	2.6	69

The calculations predict a slow conversion of terbufos to its sulphoxide in soil followed by hydrolysis of the phosphate ester rather than further oxidation to the sulphone as the major metabolic route. Overall rate of loss of toxic compounds should be rather slower than phorate. Because the sulphoxide and sulphone have similar physical properties and toxicity the change in route would have little effect on biological activity. However the greater persistence of terbufos which is active via the vapour phase could lead to important differences in biological activity in the field between terbufos and phorate.

Degradation rates in different systems

There are strong parallels between metabolism rates in different systems and similar models for transport and degradation have been used for animals, soils and stored grain. Metabolism rates in soils and stored grain respond similarly to changes in temperature and moisture content and two compartment models have been used to describe degradation in both.

One would expect little difference in possible degradation pathways between systems and distribution is likely to depend similarly on the partition coefficient so that relative metabolism rates should be determined largely by the level of biological activity. Respiration rate is suitable measure of this and is in the ratio 2000 : 20 : 1 for mammals : soils : stored grain. Half lives should therefore be in the ratio 1 : 100 : 2000. Permethrin, for example, has a half-life in rats of about 3 hours, in soils about 10 days and in stored grain about 9 months in the ratio 1 : 80 : 2200. Kepone has mammalian half lives of about 3 months and soil half life, extrapolated from one year studies, of about 20 years. Table 10 lists half-lives taken from the literature for a number of insecticides in soil and stored grain which show a consistent ratio despite differences in temperature and moisture content which make strict comparisons difficult.

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Table 10
Half lives of insecticides in soil and stored grain

Chemical	soil half life	grain half life	ratio
phosphine	few hours	5 days	20
dichlorvos	1 day	14 days	14
malathion	2 days	1-2 months	15-30
pirimiphos methyl	3-4 weeks	70 weeks	20
diazinon	3-4 weeks	1 year	15-20
fenitrothion	1-2 weeks	3-4 months	12-20
methoxychlor	6 months	6 years	12
lindane	1 year	10 years	10

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FACTORS WHICH INFLUENCE THE BIOLOGICAL PERFORMANCE OF PESTICIDES

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Summary The biological performance of a pesticide depends on a large number of factors which interact to increase or decrease the overall effect on the target organism. These factors are related not only to the intrinsic activity of the compound but are concerned with distribution, penetration and persistence.

Reaching the target may be a problem. The target is occasionally located on the outside of the crop. More usually it is embedded in the host tissue or hidden within the canopy. Initial spray distribution is rarely ideal and re-distribution by weathering, vapour or by translocation within the plant may be very important. Translaminar activity and the eradication of a target which is growing within the tissue have important effects on the timing of application and the number of sprays required.

Uptake and translocation depend on the physical properties of the chemical and on the host plant. Control of the pest or disease may be increased or decreased by free translocation depending on the method of application and the position of the target organism. These topics are discussed with particular reference to fungicides but the principles involved are generally applicable to other pesticides.

Résumé L'activité biologique d'un produit phytosanitaire dépend d'un grand nombre de facteurs dont l'interaction peut augmenter ou diminuer l'effet sur l'organisme visé.

Atteindre le cible peut être un probleme. La répartition du dépôt de pulvérisation en fonction de la position de divers organismes à détruire est présentée. L'effet des conditions climatiques au moment de l'application sur la répartition et la persistance produit déposé est examiné. Le rôle joué par l'effet de vapeur dans le contrôle de certaines maladies est discuté.

L'absorbtion et la mobilité du produit ont un rôle vital en matière d'éradication et d'activité translaminaire. Ces propriétés peuvent éventuellement modifier les programmes de traitement. Le mode de transport d'un produit dans un végétal depend des propriétes physiques du produit et de la plante hote. Le contrôle des maladies peut etre amelioré ou diminué par une mobilité totale du produit, cela dépendant de la méthode d'application et de la position de la cible visée. Ces divers points sont discutés avec référence particulière envers les fongicides mais les principes sont généralement applicables aux autres types de produits phytosanitaires.

INTRODUCTION

Scientists engaged in the search for pesticides are acutely aware that there is much more to the discovery of a chemical which will be useful in agriculture than just finding a molecule active against a particular target organism. The correlation between *in vitro* and *in vivo* tests is very poor and the order of efficiency in which chemicals are placed may reverse as they are subjected to different types of test. Compounds which have essentially the same level of intrinsic activity may differ markedly in field performance because their physical properties affect the ability of the chemical to reach the target organism.

This paper examines some of the factors which may be important in determining the practical value of biologically active compounds. The situation is examined mainly from the position of a plant pathologist but most of the factors are equally relevant to other disciplines. The discussion has been confined to biological effects and the details of chemical structures have been omitted.

POSITION OF TARGET ORGANISM

The fungus or insect pest for which a control measure is needed is rarely randomly distributed over the host. It is normally found in a particular location which will differ in some respect from that in which other targets organisms are found.

For instance, powdery mildews are normally found on the outside of the leaves. They are however most prevalent on the undersides of young developing leaves and on shoots within the canopy which may be shielded from strong sunlight. Other diseases spend much of their life cycle embedded within the mesophyll of the leaf. Downy mildews and rusts are usually found in this position. A fungus such as *Verticillium spp* lives mainly in the vascular tissue while *Venturia inaequalis* (Cooke) although relatively superficial in its development penetrates to a position within or below the epidermis. Other diseases attack particular parts of the plant such as fruit or stem, leaf sheath or roots.

Fungi usually emerge from the tissue to sporulate and disseminate but the rest of their life cycle is spent embedded in host tissue. Apart from the period of dissemination they do not move and it is therefore necessary for the chemical not only to reach the vulnerable parts of the plant but to be reasonably well distributed over those parts. Insects may move a little more than fungi but many have a fairly static feeding phase and good cover of the host plant is again usually necessary.

At the time of dissemination the fungus may be accessible to chemicals which do not enter or move through the plant, but once it has penetrated the host it is vulnerable only to those chemicals which can also penetrate the host.

If a chemical is required to control more than one target organism it may be necessary to protect several regions of the plant simultaneously. Thus in a fairly simple system, where cereals are to be protected against powdery mildew and rust, it is necessary to protect the surface of the leaf and the mesophyll. Activity against other combinations of target organisms may require the simultaneous protection of more widely separated parts of the plant. Where the chemical is entering the plant tissue and being translocated it may be difficult to provide sufficient material in both the stem and the leaves, without grossly overtreating one situation

From the foregoing it is clear that the position of the chemical in relation to the position of the target organism is likely to be a critical factor.

DISTRIBUTION OF APPLIED CHEMICALS

With many of the older fungicides activity was confined to the outside of the plant and the quality of disease control was closely related to the quality of the spray cover achieved. Organisms landing on the spray deposit were killed before they penetrated the host. If an organism penetrated unprotected tissue there was little which could be done to check its development. Many of the newer chemicals are active both inside and outside the plant, so that eradication of an already established infection may be possible and the timing of an application in relation to infection may be important. This however necessitates the chemical reaching the correct part of the plant at the right moment. A few chemicals are deliberately applied at a distance from the target site but most are applied as sprays to the above ground parts of the plant.

An examination of the distribution of spray from a typical spray boom for field crops or an air blast sprayer in an orchard reveals a number of apparent difficulties in getting the spray where it is needed. The side of the foliage nearest to the sprayer inevitably receives most of the spray and with a thick canopy many leaves are shielded from the spray by other leaves. Also, there may be several newly formed unsprayed leaves at the apex of the plant before the next spray is applied. In practice these difficulties are reduced by repeated spraying, by spraying trees from two directions and by causing turbulence in the crop which improves penetration.

The fact remains that, even with the best application possible, the distribution of the chemical is likely to be very different from that which would be dictated by reference to the position of the target organism. The pattern of uptake, translocation and re-distribution after application together with length of the period of protection available are likely to be critical in determining the usefulness or otherwise of that chemical.

RE-DISTRIBUTION AND LOSSES BY WEATHERING

Reliance on re-distribution by rain tends to be rather unsatisfactory because of its unpredictability. If the compound is dissolved readily in water or its particles are moved readily by rain, then there is a real danger of complete removal by excess rain. Nevertheless relatively large amounts of active ingredient are moved by rain and may be moved from the upper to the lower parts of the canopy.

Reductions in disease control following simulated rain can be demonstrated for many types of chemical (see Table 1.).

Table 1

Effect of simulated rain on the control of Phytophthora infestans by two standard chemicals (glasshouse)

ppm a.i in spray	mean % disease (6 leaves)+ ofurace -rain	ofurace +rain	mancozeb -rain	mancozeb +rain*
100	-	1.6	-	5.0
50	0.5	5.7	3.3	8.6
25	0.6	6.5	13	24
10	1.9	7.3	23	33
5	4.2	-	38	-

+ Disease expressed as % of untreated
Untreated (100%) = 67-85% leaf area infected
* Rain = 30 minutes simulated rain

In the case of the protectant fungicide mancozeb about 50% of the active ingredient appears to have been 'lost' by the treatment. The amount of ofurace, 'lost' is not easy to define as the chemical is systemic and the rain is affecting the total system. It is however clear that some activity has been lost during the simulated rain.

The adhesion of particles to a plant surface may be influenced by the particle-size or by the presence of formulation additives which act as stickers. Small particles tend to be less easily dislodged than large ones. However, adhesion appears to be depend on the particular active ingredient and the host surface, and is not readily predictable. Different members of a series of similar chemicals may differ appreciably in rainfastness and this factor can be important in determining the effective life of a spray deposit.

Dew is rarely heavy enough to cause much loss of deposit but the frequent wetting and drying may favour uptake of a chemical into the leaves.

Wind has little direct effect on a deposit but as it causes the movement of leaves across one another it may contribute to the transfer of deposits between adjacent leaves and from sprayed to unsprayed surfaces during rain.

The weather may also effect the deposit directly, causing losses by photolysis, hydrolysis or evaporation, but these effects are the subject of another paper.

In many practical situations rain is the dominate component of the weather and fresh applications of fungicide may be required after every significant rainfall.

IMPORTANCE OF VAPOUR ACTIVITY

The part played by vapour in moving a chemical to the target organism is not well documented. If a compound has significant vapour activity, each spray droplet will produce a zone of active vapour and a few widely spaced droplets on a leaf may effectively protect the whole leaf. Alternatively, if the droplets lie within a dense canopy, vapour may accumulate within the crop and the influence of the vapour

may control the disease on leaves above or below those which were sprayed.

This phenomenon was demonstrated recently by two chemicals with similar chemical structure which had almost identical levels of activity when applied as a uniform mist across the leaf. When the same chemicals were applied as a band of droplets across the centre of an apple leaf previously inoculated with Podosphaera leucotricha (Ellis and Everh) the pattern of disease development was very different (Fig 1). The leaf treated with chemical A which had a strong vapour activity was almost free of disease whereas that treated with chemical B had mildew growing between the droplets.

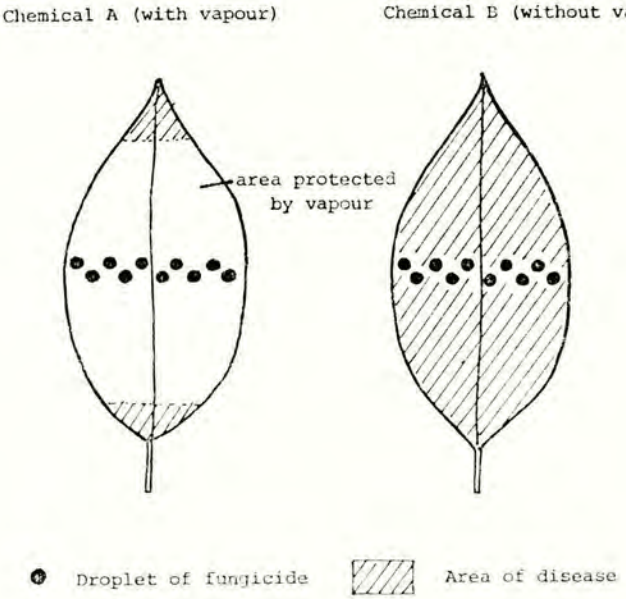

Fig 1. Importance of vapour activity in the control of Podosphaera leucotricha on apple leaves

Vapour effects are particularly important in the control of powdery mildews, where the mycelium is readily accessible on the outside of the plant. They seem to be less important for diseases where the fungus is deeper within the host tissue.

Such properties are used to good effect in the control of cereal mildews with compounds such as triadimefon.

IMPORTANCE OF UPTAKE AND TRANSLOCATION

The host plant may play an important role in delivering the chemical to the target organism. A chemical may penetrate the plant at the point of application and be taken into the tissues in the vicinity of the droplet but move only a matter of

1-2mm. Alternatively it may enter the stream of water moving through the xylem and cell walls and be carried to the edge of the transpiring surfaces. A few compounds enter the active transport system and are carried from the leaves to areas of new growth or storage.

The extent and speed of movement varies greatly between compounds and depends on both the physical properties of the chemical and the type of plant being treated. Uptake and movement can dramatically affect the biological efficiency of a compound and the effective life of a single treatment.

Thus a chemical which penetrates into a leaf may be able to stop the development of a fungus already inside the leaf or one which is about to attack the other side of that leaf. For example, with a crop such as peanuts most of the spray deposit arrives on the upper surface of the leaves. The fungus Cercospora arachidicola (Hori) however, attacks mainly from below. Chemicals with different penetrant properties behave differently in this situation. Table 2 shows that chemical D was able to penetrate the leaf and stop the sporulation of well established lesions, whereas chemical C which did not penetrate was virtually ineffective.

Table 2

Spore production by Cercospora arachidicola lesions on peanuts after spraying with a track-sprayer at 250l/ha (glasshouse)

g.a.i./ha	% spore production (4 plants) chemical C.	Chemical D.
1000	82	-
250	100	-
50	-	4
12.5	-	34
2.5	-	100

Untreated (100%) = 650 x 10^3 spores per plant
Chemicals applied 14 days after inoculation on the under surface of leaves.

In other tests (unpublished) where the same chemicals were applied to the inoculated surface both prevented the development of new infections but only chemical D eradicated established infections.

Eradicant and anti-sporulent activity is most useful where the disease development is slow. With a fast growing disease, such as Phytophthora infestans on potatoes, the leaves may be destroyed in 4-5 days. Useful eradication is then confined to a period of 2-3 days after inoculation. In contrast, a slow growing disease such as Hemileia vastatrix (Berk. and Br.) on coffee may take 30 days to produce a visible lesion which will then sporulate for a further 30 days or longer.

Table 3 shows the effectiveness of chemical E when applied to coffee seedlings 35 days after inoculation with Hemileia.

Table 3

Anti-sporulent activity against well established lesions of Hemileia vastatrix on coffee seedlings

(glasshouse test)

treatment	ppm a.i in spray+	% leaf area with lesions	mean % reduction in sporulation ** 10 days after treatment	
Untreated	-	73	0*	A
Chemical	5.0	78	93	C
"	1.0	73	67	B
"	0.25	68	31	A

\+ Applied 35 days after inoculation
* Entire surface of lesion covered with spores
** Spore numbers expressed as % of untreated

Numbers without a letter in common are significantly different at a probability of 0.05

Chemicals which eradicate established infections and stop sporulation may have important effects on both the number and timing of spray applications. In the example with peanuts (Table 2), chemical C needed to be applied before the first infection, because once an epidemic had become established it was not very effective. On the other hand the first application of chemical D might be delayed until a few days after the first infection. Further applications for C. would be at regular intervals determined by the growth of the crop whereas the second application of chemical D might be delayed until after the next infection period. This could reduce appreciably the number of sprays needed in situations of relatively low disease pressure.

With a slow growing disease such as Hemileia on coffee, the effect could be even more dramatic, with one or two carefully timed sprays being adequate for the whole season.

When a chemical moves freely through the host tissue it usually enters the transpiration stream and moves upwards and outwards from the point of application. Thus a droplet of dimethirimol applied to a cucumber leaf gives a sector of disease control and droplets applied to the proximal part of the leaf control the disease across the whole leaf (Figs 2A and 2B).

If movement is very rapid the proximal end of the leaf may be emptied and accumulation may occur at the margin (Fig 2C).

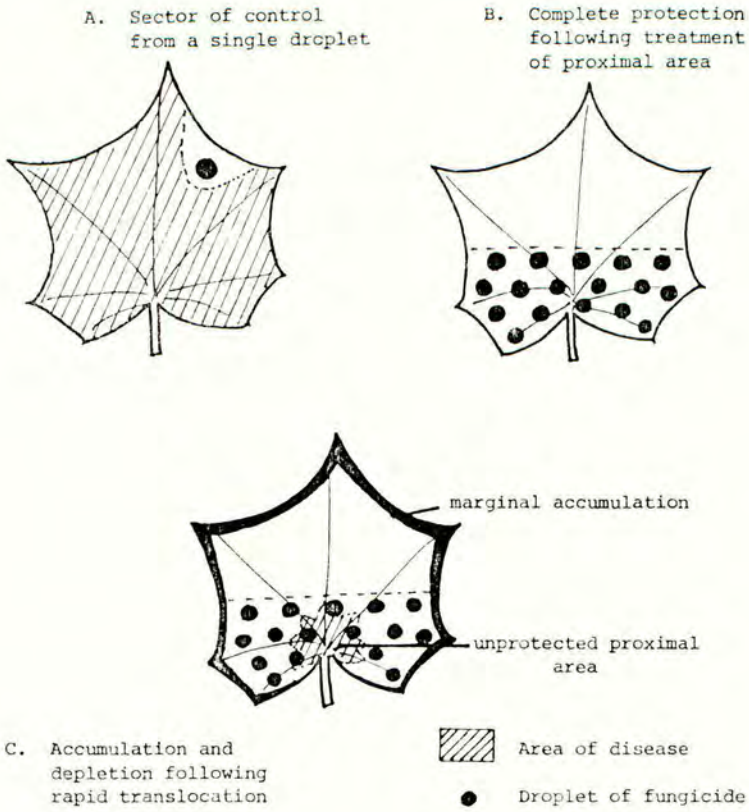

Fig 2. Patterns of disease control from droplets of dimethirimol on cucumber leaves

Rapid movement of a foliar applied chemical is usually unsatisfactory as the material is rapidly flushed out of the proximal end of the leaf which is then left unprotected, while the accumulation at the margin may cause phytotoxicity. Good uptake and limited movement within the leaf is highly desirable for foliage applied materials as it favours effects such as eradication and translaminar activity, provides disease control in the area between adjacent spray droplets, and at the same time provides protection of the whole leaf for a useful period of time.

Rapid movement is desirable for chemicals applied to the seed or soil for control of foliar diseases. Uptake follows the transpiration stream. Distribution is not uniform. Maximum uptake is into the rapidly transpiring leaves near the apex. New leaves are protected as they develop. Older leaves further down the canopy usually transpire less and disease control may breakdown first in these lower leaves.

If the plant is drawing water from soil in which the chemical is present, uptake will depend on the availability of the chemical and the uptake of water from the soil containing the chemical. If the chemical is restricted to a small volume of soil and the plant has an extensive root system, then uptake will decrease progressively as the roots extend beyond the treated soil. If the chemical diffuses through a larger volume of soil the dilution factor becomes important but uptake may continue for a longer period. For these reasons seed and soil applications are difficult to regulate. In spite of this they have been used successfully with several fungicides including dimethirimol, ethirimol and triadimenol.

The control of diseases which attack leaf sheaths or stems is difficult because of the position of the target. Conventional sprays are deposited mainly on the lamina, while root applied systemic compounds usually move preferentially to the leaves. Rice sheath blight may be treated by chemicals applied to the paddy water but the eye-spot complex of wheat remains difficult to treat effectively. Similarly neck blast of rice is difficult to control with systemic compounds which are effective against leaf blast.

The uptake and translocation of chemicals in woody species appears to be particularly difficult. Ethirimol which moved freely from the roots to the leaves of cereals was found to accumulate in the roots of apples and very little moved into the above ground parts of the plant (Shephard 1973).

Translocation of pesticides in the phloem is a relatively rare phenomenon and is not well understood. Most of the compounds which move in the phloem also move freely in the transpiration stream e.g metalaxyl. They also seem to have a high water solubility and a low partition coefficient. Factors which may be important in determining distribution between the xylem and the phloem are discussed by Price (1973) Movement in the phloem is always from areas of photosynthetic activity to areas of new growth or storage. This is desirable for some target organisms but not others.

From this brief consideration it will be obvious that uptake and translocation often have a controlling effect on the biological performance of chemicals. A large number of factors combine to influence these processes.

Observations on many different types of compounds (unpublished data), reveal that partition coefficient, concentration, and degree of ionisation appear to be dominant factors. The processes which control initial entry may be different from those which control movement. Thus an ester such as bupirimate may enter a leaf more easily than ethirimol, the hydroxy-pyrimidine from which it is derived, but it may be translocated less freely after entry. Formulation additives which increase the concentration in the droplet and humectants which increase the drying time may also increase uptake. Thus the performance of a foliar application of dimethirimol was markedly increased by the use of a formulation in which the active ingredient was very soluble. Once inside the plant compounds with low partition coefficient and high solubility in water-move most freely. Compounds with slightly higher partition coefficient or which ionise may be retained by cell components, and move less freely, but still have the desired features for eradication and translaminar activity. The critical partition coefficient for translocation in woody species appears to be lower than in herbaceous species. The reason for this is not known.

PERSISTENCE OF ACTIVITY

The persistence of activity of a compound is often linked with its uptake and

translocation. Compounds which remain on the surface of the plant are subject to loss by weathering. Those which are taken up into the plant may be protected from the weather but are then exposed to metabolic degradation. For instance dimethirimol is generally stable in aqueous solution but in a cucurbit plant is demethylated relatively rapidly.

Compounds which accumulate in non-target parts of the plant or which move too rapidly away from the target site may have a short effective life. Thus metalaxyl applied to potatoes in the glasshouse appears to lose its potency very rapidly (Table 4). It is not known whether this is due to metabolism, translocation or a combination of these features.

Table 4

Control of Phytophthora infestans with metalaxyl

at two intervals after spraying (glasshouse)

g.a.i./ha applied *	Mean % disease (6 leaves)+ Interval between spraying and inoculation (days)	
	1	7
100	-	16
50	0	16
20	0.8	52
10	0.8	100
5	2.2	-

+ Disease expressed as % of untreated
Untreated (100%) = 60-69% leaf area infected
* Applied by track sprayer at 200l/ha

CONCLUSION

In a practical situation the biological activity of a pesticide is the product of its intrinsic activity and all the factors which have combined to take it to or remove it from the site of action. A chemical with extremely high potency but instability in the biological system or an inability to penetrate the host plant may be much less effective than a related compound with lower intrinsic activity but the right physical properties to take it to the target site and keep it there for an appropriate length of time.

It is the difficulty of finding the right combination of properties to achieve this end which keeps the structure/activity teams busy in most of the major companies. Although our understanding of the factors involved has increased, the accurate prediction of some of the parameters is not yet possible and much of the searching still has to be done by trial and error.

Acknowledgement

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SESSION 5A

CEREAL PEST AND DISEASE CONTROL (I)

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AUTUMN DISEASES OF CEREALS AND THEIR CONTROL

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Summary The incidence and significance of cereal diseases in the autumn are discussed in the light of experiments carried out in the Eastern Region of England. Of the diseases considered, mildew (Erysiphe graminis) on winter barley is by far the most important and trials have demonstrated that on susceptible cultivars and on light drought prone soils substantial yield increases can be achieved. Yield responses are usually the result of an increase in the number of fertile tillers and are greatest if tillering has been inadequate or if an unusually severe winter has caused serious tiller loss.

Trials have shown that autumn spraying against eyespot (Pseudocercosporella herpotrichoides) can occasionally provide an economic control of this disease in both barley and wheat, but more consistent results have been achieved from spring spraying.

Foliar diseases are seldom as serious in the autumn on wheat as they are on barley and there is currently little experimental evidence on yield responses resulting from their control.

Résumé L'existence et l'importance des maladies céréales en automne sont discutée en considérant les expériences pratiquées dans la région est de l'Angleterre. Des maladies étudiées, l'oidium (Erysiphe graminis) sur l'orge semée en automne est de loin la plus importante et les essais ont prouvé que sur des variétiés susceptibles et sur des sols à tendance sèche et sableuse, des augmentations impressionnantes de rendement peuvent être achevées. L'amélioration de rendement est généralement le résultat d'un accroissement de nombre de pousses fertiles et est plus importante si la production de tiges a été insuffisante ou si un rare hiver rigoureux a causé une perte sérieuse de plantes.

Essais ont montré que l'usage de produits chimiques en automne contre la maladie des feuilles notres (Pseudocercosporella herpotrichoides) peut parfois apporté un contrôle valable de cette maladie sur a la fois l'orge et le blé mais des résultats plus consistants ont été obtenu en utilisant les products chimiques au printemps.

Les maladies de la feuille sont rarement-aussi sérieuses sur l'orge en automne qu'elles sont sur le blé et de nos jours il y a peu d'évidence expérimentale que l'amélioration du rendement résulte de leur contrôle.

INTRODUCTION

The past few years have been marked by a considerable expansion in the UK acreage of winter sown cereals, more particularly of winter barley. This expansion has been associated with, and to some extent, made possible by, the widespread adoption of minimal cultivation and direct drilling techniques which have taken the place of the laborious and time consuming process of mould board ploughing.

The increase in the autumn sown acreage, the trend towards earlier drilling and non-plough husbandry have had their effect on the development of diseases in the autumn and have contributed to the increasing interest in the application of fungicides at that time of the year on both barley and wheat.

AUTUMN DISEASES

The most important of the autumn diseases is mildew (Erysiphe graminis) - more particularly barley mildew - though in some seasons early sown crops of wheat may also suffer severe attacks in the autumn. Plants may be infected as early as the $2\frac{1}{2}$ leaf stage and early infections will restrict the production of tillers and, especially, of roots (Wolfe, 1969). Moreover the tillers that are produced on badly infected plants tend to be weak and subject to winter kill - a risk which is increased by the fact that badly mildewed tissue is particularly susceptible to frost. Early sown crops are more susceptible to mildew attack as they emerge when the weather is still warm enough to favour the spread of the disease, and when infected volunteers in unploughed stubbles are still providing a potent source of inoculum. Early sowing will of itself, however, promote root and tiller production so the effects of mildew on such a crop may be less deleterious than those of the attack which, in a very mild autumn, can occur on later sown fields. Interestingly, the early sown crops which suffer most severely from mildew in the autumn consistently carry lower levels of the disease in the following spring and summer (Jenkyn 1976).

Volunteer plants provide the main source of inoculum, not just of mildew but also of yellow rust (Puccinia striiformis) and the brown rusts of barley and wheat (P. hordei and P. recondita f. tritici). As with mildew, therefore, early infection is most likely to occur on crops emerging before surrounding stubbles have been ploughed under or sprayed off. Very rarely, however, do any of the rust fungi reach damaging proportions in the autumn though P. hordei may be found causing premature senescence of the lower leaves of early sown barleys in the late winter. P. striiformis seldom becomes obvious before the spring and P. recondita commonly persists at no more than trace levels until its epidemic spread is favoured by the high temperatures of mid-summer.

Of the trash-borne leaf diseases, net blotch of barley (Pyrenophora teres) is the first to appear in the autumn and severe infections can often be found in the pre-Christmas period - especially where non-plough husbandry has left a lot of infected debris from the previous crop on the surface of the field. Net blotch, however, declines very markedly with the onset of frosty weather and recent work by ADAS (Locke et al 1981) and at Long Ashton Research Station (Jordan 1981) suggests that unless the disease is very severe there is little yield advantage to be gained by controlling it in the autumn.

In the East of England barley leaf blotch (Rhynchosporium secalis), though it may sometimes be found in late autumn, seldom reaches damaging proportions until well into the new year. In the East, therefore, autumn sprays are seldom if ever applied specifically against this disease, but a broad spectrum fungicide applied

in December for the control of mildew will often give useful reductions in leaf blotch levels later in the winter.

Of the two Septoria species that cause leaf spotting of wheat, S. nodorum seldom becomes obvious until the spring. Extensive lesions of the speckled leaf spot caused by S. tritici can however be found, especially in coastal districts, in late winter. The perfect stage of the fungus (Mycosphaerella tritici) is found on stubble after harvest and ascospore spread on to early sown crops occurs during the autumn period.

Eyespot (Pseudocercosporella herpotrichoides), although trash borne is often less severe where non-plough husbandry has been used (Brooks and Dawson, 1968, Yarham and Norton, 1981). It is however encouraged by early sowing, the microclimate in early sown crops being very conducive to the development of the disease during the late autumn and winter. The long incubation period of the fungus means, however, that although infection can occur in the autumn the disease seldom becomes manifest before late winter or early spring.

It will be seen from the above that while many fungal diseases can infect cereal crops in the autumn only barley mildew regularly causes actual damage to the crop during the autumn period (attention should also be drawn to barley yellow dwarf, but the control of this virus disease falls outside the scope of this paper). Not surprisingly therefore it is against barley mildew that most autumn applied fungicides are used - though the effects of such applications in delaying the development of other diseases in late winter and spring should not be overlooked.

WINTER BARLEY

Early work using ethirimol seed treatment on the mildew susceptible cultivar Maris Otter showed that autumn mildew control in winter barley could stimulate root and tiller production and increase final yield by increasing the number of ears per unit area (Finney and Hall 1972). Experiments at Rothamsted Experimental Station using the very susceptible cultivars Astrix and Hoppel, confirmed that autumn spraying could give very useful yield increases in some years, but indicated that in other seasons the control of a moderate autumn infection could have little effect on yield (Bainbridge et al 1981). Early trials conducted by ADAS, on winter barley however, showed an inconsistent response to autumn spraying.

The advent of the triazole fungicides with their persistence and broad spectrum of activity offered a new and potent weapon for use against the over-wintering complex of diseases on winter barley. Even with these, however, although autumn spraying sometimes produced substantial yield increases, it often produced little or no yield benefit and in some instances it appeared actually to reduce yields. Some of the reasons for this variation in response are discussed in the light of experiments carried out at the Norfolk Agricultural Station and by ADAS.

The N.A.S. work was carried out using the same cultivar on the same soil type and in the same rotational situation each year so that the main variable was the season. On the other hand ADAS conduct a large number of trials in each season, thus testing different cultivars and encountering many different soil types in the same season. By studying the results that follow it is possible to obtain some indication of the interaction of autumn disease control with other factors.

Work carried out by Norfolk Agricultural Station (N.A.S.)

The first trials at N.A.S., using fungicides from the triazole group, were carried out in 1975. It was soon evident that triazole materials such as triadimefon were very active against mildew, leaf blotch and the rusts. At that time most of the winter barley in East Anglia was of the cultivar Maris Otter which is susceptible to attack by all of these pathogens. A trial to last three years was therefore commenced in the autumn of 1976 to investigate the effect of spraying at different times during the growing season.

The dates of the major husbandry operations are shown in table 1 and it will be noted that the crops were not early drilled by current standards. In each year the crop was grown as a second cereal crop after a single break crop of sugar beet. The soil was a sandy loam containing 14-18% clay and overlying Chalky Boulder Clay at a depth of 0.5-1.0 m.

The aim was to apply triadimefon as single foliar sprays in the autumn or spring. In addition there were double applications in autumn + spring or in spring + summer. 'Autumn' applications were made as soon as 2-3% mildew was observed on lower leaves of the crop but in 1978 applications were made as soon as there appeared to be a reasonable leaf area (Growth stage 12-13 Zadoks et al 1974). A Drake and Fletcher knapsack sprayer was used to apply 0.125 kg a.i./ha of triadimefon in 250 l/ha of water.

In each year the trials consisted of 4 randomised blocks of plots each measuring 22 m x 3.6 m. The whole of each plot width was sprayed where appropriate but only a 2.3 m width was harvested from each plot so that a small guard area was left between each harvest area to help reduce the effects of spray drift, vapour action and other edge effects.

Table 1

Dates of husbandry operations - winter barley

	1977	1978	1979
Drilling	13 October 1976	4 November 1977	4 October 1978
Autumn fungicide spray	20 December (G.S. 13)	4 January (G.S. 12-13)	7 November (G.S. 21)
Spring fungicide spray	14 May (G.S. 31-32)	28 April (G.S. 30)	5 May (G.S. 30)
Summer fungicide spray	8 June (G.S. 49)	26 May (G.S. 31)	30 May (G.S. 39)
Nitrogen fertilizer	80 kg/ha, 4 April	88 kg/ha, 4 April	108 kg/ha, 15 April
Harvest	11 August	11 August	28 July

Disease levels

The 1979 crop suffered the highest level of autumn mildew infection with 8% being recorded on the lower leaves of untreated plots on 13 November. This increased to about 30% by mid-December and caused considerable yellowing of the crop. In the other two years, only traces of mildew were observed. Rhynchosporium was found at low levels in the crop in December or January in each year and by March this had developed so that most plants showed low levels of infection on the lower leaves. In all three years mildew failed to develop in these crops in the spring and Rhynchosporium became the dominant disease, especially in 1979. The levels of Rhynchosporium in the following summer are shown in table 2. Yellow rust and brown rust failed to develop.

Table 2

Percentage of leaf area infected by Rhynchosporium - winter barley

Treatment with triadimefon	1977 Leaf 2 assessed 4 July	1978 Leaf 3 assessed 19 June	1979 Leaf 2 assessed 22 June
S.E.D. untreated/ treated	(±1.65)	(±0.37)	(±7.21)
Untreated	20.6	5.1	81.3
S.E.D. between spray treatments	(±1.91)	(±0.42)	(±8.33)
'Autumn'	14.0	3.7	33.8
'Spring'	4.0	2.6	39.5
'Autumn'+'Spring'	4.0	1.5	6.0
'Spring'+'Summer'	1.5	0.3	3.8

The application of triadimefon gave virtually complete control of mildew following application during the autumn but in addition it gave useful control of the developing Rhynchosporium so that less inoculum was present when the rapid spread of the disease occurred in the spring. It was also noted that plots that had been sprayed in the autumn started growth more quickly in the spring. This was even more evident following the severe winter of 1978/9 where the 'Autumn' treated plots were still 5 days ahead of untreated plots at the time of ear emergence. This treatment resulted in stronger and more uniform tillers and an absence of late tillers so that a change in crop structure may also have affected the incidence of Rhynchosporium.

Crop structure

The number of plants established was within the range 274-296/m^2 each autumn and few plants were lost over winter, except in 1978/9 when some loss occurred on untreated plots.

Table 3

Components of yield, N.A.S. trial 1977-79 - Maris Otter

Ears/m^2	1977	1978	1979
(S.E.D. untreated/ treated	(±27.0)	(±43.4)	(±47.4)
Untreated	676	886	879
(S.E.D. between spray treatments)	(±31.1)	(±52.5)	(±54.6)
'Autumn'	769	847	1074
'Spring'	689	922	933
'Autumn'+'Spring'	767	876	1097
'Spring'+'Summer'	706	893	938
Grains/ear			
(S.E.D. untreated/ treated	(±0.44)	(±0.42)	(±0.51)
Untreated	16.7	19.0	20.4
(S.E.D. between spray treatments)	(±0.49)	(±0.49)	(±0.58)
'Autumn'	16.4	19.0	19.0
'Spring'	16.4	19.3	20.8
'Autumn'+'Spring'	18.5	19.0	18.8
'Spring'+'Summer'	16.4	18.6	20.7
Total grains 000's/m^2			
Untreated	11.3	16.8	17.9
'Autumn'	12.7	16.1	20.4
'Spring'	11.3	17.8	19.5
'Autumn'+'Spring'	14.2	16.6	20.6
'Spring'+'Summer'	11.7	16.6	19.3

Table 3 shows that in 1977, ear numbers were low and were increased by autumn treatment. Grains per ear were not affected except where the autumn treatment was followed by a spring application. In 1978 the fungicide treatments had no significant effect on crop structure but in 1979 autumn treatment considerably increased ear numbers. Ear numbers were already higher in 1979 and were increased to well over 1,000/m^2. At this level it appears that competition between the ears resulted in a reduction of grains/ear. However the total number of grains/m^2 was still improved by autumn treatment.

Grain size and yield

It has already been shown that in two of the three years (1977 & 1979) grain numbers were increased by the use of an autumn fungicide application. However table 4 shows that in one of these two years (1977) there was a significant reduction in grain size where the autumn treatment was used alone, thus indicating that autumn treatment was affecting the number of grain sites while spring treatment improved grain size. Therefore autumn and spring treatment were contributing to yield in different ways and where the two treatments were applied to the same plots the benefits were cumulative.

In 1977 when ear numbers were low, the 'Autumn' or 'Autumn' + 'Spring' fungicide applications were the most effective treatments. In 1979 when ear numbers were adequate and Rhynchosporium in the spring was particularly severe, it was the 'Spring' + 'Summer' treatment that gave the highest yield. However the autumn treatment still made a contribution by improving the over-wintering ability of the crop and increasing the number of grain sites.

Table 4

Effect of fungicide treatment on grain size and yield - winter barley

T.G.W. (g) at 100% d.m.	1977	1978	1979	Mean
(S.E.D. untreated/ treated)	(±0.34)	(±0.34)	(±0.62)	(±0.27)
Untreated	32.3	34.1	26.9	31.1
(S.E.D. between spray treatments)	(±0.40)	(±0.40)	(±0.72)	(±0.31)
'Autumn'	31.4	33.9	27.0	30.8
'Spring'	33.6	35.4	27.9	32.3
'Autumn'+'Spring'	32.6	34.4	29.3	32.1
'Spring'+'Summer'	33.0	35.6	30.0	32.9

Table 4 continued

Yield (t/ha) at 85% d.m.	1977	1978	1979	Mean
(S.E.D. untreated/ treated)	(±0.11)	(±0.06)	(±0.13)	(±0.06)
Untreated	5.1	5.6	5.1	5.3
(S.E.D. between spray treatments)	(±0.13)	(±0.07)	(±0.14)	(±0.07)
'Autumn'	5.5	5.9	5.4	5.6
'Spring'	5.3	6.0	5.6	5.6
'Autumn'+'Spring'	5.8	6.2	5.9	6.0
'Spring'+'Summer'	5.3	6.1	6.2	5.9

Table 5

Fungicide x seed rate trial 1980 winter barley (Maris Otter)

Treatment	Vegetative tillers/m^2 on 29 April	Ears/m^2	Grains /ear	T.G.W. @ 100% d.m.	Yield(t/ha) @ 85% d.m.
Spring + Summer Fungicide	(SED - ±56.7)	(±31.0)	(±1.29)	(±0.42)	(±0.151)
60 seeds/m^2	776	469	24.9	43.3	5.95
120 "	945	518	26.0	39.9	6.31
180 "	947	573	25.9	37.5	6.52
240 "	1103	632	25.0	36.4	6.74
300 "	1089	622	24.9	36.9	6.72
Autumn + Spring + Summer Fungicide					
60 seeds/m^2*	778	529	23.7	40.1*	5.92*
120 "	907	628	23.8	37.7	6.57
180 "	1101	643	24.9	36.4	6.80
240 "	1113	668	24.0	35.5	6.66
300 "	1257	684	23.7	35.4	6.73
	(SED - ±32.2)	(±17.3)	(±0.64)	(±0.08)	(±0.112)
Mean without aut. fung	972	563	24.0	38.8	6.45
Mean with aut. fung	1031	630	25.3	37.0	6.54

*Both autumn fungicide and very low seed rates increased straw length and lodging. This treatment lodged severely.

In 1980 and 1981 the effect of autumn treatment has again been investigated using triadimenol as a seed treatment or triadimefon as a foliar application. Disease control from these autumn treatments was excellent and crop vigour in the spring was improved though no benefit to final yield was recorded.

In another trial conducted over the same two years the use of seed rates from 60/m^2 to 300/m^2 was investigated using the cultivar Maris Otter. The varying seed rates were tested with and without autumn fungicide but all plots received a spring and summer treatment. In the 1980 crop, the autumn triadimefon treatment increased tiller and ear production and thus helped to compensate for the lower seed rates which were limiting yield, as shown in table 5. However, as seen in the other N.A.S. fungicide trials in 1980, where seed rate was adequate there was no benefit from autumn fungicide in that season. The provisional results from 1981 show no consistent benefit from autumn treatment.

It is evident that there is a seasonal variation in response to autumn fungicide and it was apparent that much of the benefit shown in the 1979 harvest was due to better winter survival in the severe winter of 1978/9. The seasonal variation of weather is shown in the meteorological summary given in table 6.

Table 6

Summary of meteorological data showing severity of winters at N.A.S. 1976/7 - 1980/81

		Normal	1976/7	1977/8	1978/9	1979/80	1980/81
Mean temp(°C)	Dec	4.4	1.8	5.8	4.1	5.4	4.7
	Jan	3.3	2.3	2.3	-1.3	2.0	3.9
	Feb	3.3	4.8	1.6	1.2	5.3	2.6
	Mar	5.0	6.7	6.3	4.4	4.8	7.7
Minimum temp (°C)	Dec	-	-4.9	0.1	-2.3	-1.9	-3.7
	Jan	-	-4.8	-5.0	-16.5	-6.1	-3.7
	Feb	-	-3.1	-13.1	-5.1	-1.8	-5.3
	Mar	-	-3.1	-2.1	-2.2	-3.6	-0.9
Number of air frosts	Dec	-	16	0	9	6	6
	Jan	-	12	14	26	16	11
	Feb	-	6	19	23	5	18
	Mar	-	5	3	13	8	3

Clearly, 1978/9 was the most severe of the five winters

Work carried out by ADAS

The trials carried out at the N.A.S. well illustrate the year to year variation in response of winter barley to autumn fungicide that can occur at a single site. ADAS experiments carried out elsewhere have shown the marked variation which, in any one year, can occur from site to site.

In a national series of nitrogen x fungicide trials carried out in 1978, for example, the addition of an autumn fungicide to a spring + summer programme improved the apparent response to spraying in only 8 out of the 20 sites, and at only 5 of these would such increase in response have been sufficient to pay for the cost of applying the extra fungicide. Unfortunately the design of these particular trials was such as to preclude the statistical analysis of fungicide effects at individual sites but examination of the results did point to soil type as one major factor which seemed to be influencing the response to autumn spraying. When the series of trials was broken down according to soil type the pattern shown in Table 7 emerged.

Table 7

ADAS Soil Science winter barley nitrogen x fungicide trials 1978

Soil type	Number of sites	Yield of plots sprayed autumn, spring and summer as % of those sprayed spring and summer only
Shallow soil over chalk or limestone	5	107.1
Coarse textured (sandy soil)	5	102.7
Medium textured soil	7	98.2
Heavy soil	3	93.2

In a similar series of eight trials carried out in 1978/79 (when the winter was much more severe than in the previous year) responses to the addition of an autumn fungicide to a spring and summer programme were more consistent but once again they appeared to be much better on the four light land sites (13% yield increase) than on the 4 heavy land sites where an average response of only 2% was achieved.

Results obtained in the three Eastern Region trials in the same series carried out in 1979/80 are summarised in Table 8.

Table 8

ADAS Soil Science winter barley nitrogen x fungicide trials 1980

Site			Tuddenham,Sfk	Saxham,Sfk	Keysoe,Beds
Soil type			Loamy sand	Sandy loam	Clay loam
Variety			Athene	Sonja	Sonja
Sowing date			25 Sept	18 Sept	5 Oct
% mildew (leaf 2) early Nov			15%	50%	8%
Control yield (t/ha)	Low N*		4.72	6.55	5.35
	High N**		5.45	6.67	6.62
Yield of spring + summer sprayed treatment (as % control)		Low N*	101	109	100
		High N**	99	113	103
Yield of autumn + spring + summer sprayed treatment (as % control)		Low N*	118	111	93
		High N**	130	116	100

* mean of 30, 60 and 90 kg/ha

** mean of 120, 150 and 180 kg/ha

It would obviously be unwise to draw too many conclusions from a series of trials the design of which did not allow fungicide effects to be properly analysed, since it aimed primarily at investigating nitrogen response curves in the presence and absence of fungicides. The trials were useful however, in that they first drew our attention to the possible effect of soil type on the response of winter barley to autumn fungicide.

Because of the geographical separation between light land and heavy land areas it is difficult to obtain data from directly comparable experiments carried out on light and heavy soils. Moreover groups of trials covering a number of soil types have often given rather variable results, with high standard errors in individual trials. Nevertheless, examination of the data from some 40 replicated trials carried out by ADAS plant pathologists between 1972 and 1980 does support the general conclusion that responses to autumn spraying are better, and more reliable, on light soils than on heavy.

There is evidence that a severe attack of mildew in the autumn will reduce tiller production and, by increasing frost susceptibility, it can result in greater tiller loss during the winter period. It also appears that by restricting root growth it can make plants more susceptible to frost lift. Poorly rooted plants will also be more prone to the effects of drought and less able to support high tiller numbers in summer - which may explain why tiller losses on untreated plots may be higher than on sprayed plots not only during the winter but also, in some cases, during the summer as well. In addition, as was clearly shown in ADAS trials in 1980/81 (S. Hosken pers. comm.), severe autumn mildew will reduce the number of spikelet primordia in the developing ear.

Severe attacks of autumn mildew occur more frequently on light land than on heavy. Light soils tend to lose heat very rapidly in the autumn, and crops grown on them are very prone to frost damage in the winter. Moreover, some light soils, especially those over chalk or limestone, are very subject to frost lift problems. Finally, and perhaps most importantly, light land crops are naturally more subject to drought stress. It is not surprising therefore that it is on light soils that responses to autumn mildew control have been greatest and most consistent.

Considerations such as this have led to the often reiterated opinion that in East Anglia light land winter barley growers may expect useful increases from the autumn application of fungicides in most years. Although at the time of writing the information has not all been assembled it would appear that 1980/81 proved an exception to this rule. A very late mildew epidemic had less effect than usual on root development in the autumn, and by the time the mildew became very active over the Christmas period the effectiveness of sprays applied in November had already begun to wane. In one or two trials, however, good responses were obtained from sprays applied in late January before the onset of harder weather in February. (In such a season the very mild January and early February could be considered as an extension of the autumn. An "autumn" spray should perhaps be defined as one applied before the onset of frosty weather kills the badly mildewed leaves and shoots of untreated plants). 1981 also provided circumstancial evidence that very thick crops (early sown, autumn sprayed and liberally supplied with early nitrogen) can sometimes yield much less well than later, thinner crops. If, as often happened in 1981, the main factor limiting rooting is not autumn mildew but root disease or high soil moisture levels in the spring, then autumn application of fungicide and the very thick crop which it can produce, may be counter productive. The autumn spray will assist tiller survival - but if rooting is not adequate to support the extra tillers then poorly filled ears may result.

WINTER WHEAT

Disease levels observed in the autumn on winter wheat have generally been much lower than on winter barley. Therefore very few trials have been carried out testing autumn applications of fungicide on this crop. The situation on winter wheat appears to be as follows:-

1) MILDEW Although autumn mildew levels may occasionally be high on early sown crops of susceptible varieties no data is currently available on the benefits of controlling this disease in the autumn.

2) SEPTORIA Work in New Zealand has shown that autumn application of benzimidazole fungicides can give a good control of Septoria tritici by preventing ascospore infection of the young plants (P. Sanderson, pers. comm.). Recent ADAS investigations have indicated that in some circumstances autumn spraying may give some control of S. tritici under UK conditions (W. Morgan pers. comm.). At the moment however we have insufficient data from which to draw firm conclusions.

3) EYESPOT So far as eyespot is concerned autumn spraying can reduce the levels of disease in the crop during the winter and if sporulation of the fungus ceases early in the year a single autumn spray may be sufficient to keep disease levels low throughout the following season. However, in years when the fungus continues to sporulate until the spring, autumn spraying is not enough to control the disease (Jordan and Tarr 1981). More consistent responses have been achieved from the application of a fungicide to check the development of infections in the spring rather than to prevent the establishment of infection in the autumn. The situation is further complicated by the fact that the sprays used for eyespot control will control other pathogens (such as S. tritici) as well and this may explain why the responses achieved by both autumn and spring sprays are not always

related to the degree of eyespot control achieved.

Occasionally autumn plus spring spraying will give an economic return. In a recent trial at Terrington EHF for example, sprays applied in mid-December and in the spring at G.S. 30 gave yield increases of 0.25 t/ha and 0.41 t/ha respectively, and sprays applied at both these times gave an increase of 0.69 t/ha. (In this trial final levels of severe eyespot were low even on the unsprayed control plots and the yield increases could not be attributed solely to the control of this one disease). The inconsistency with which results such as this are achieved, however, argues against the routine application of two spray programmes. Moreover, the use of benzimidazole fungicides in both autumn and spring should be discouraged as it would increase the selection pressure for benzimidazole insensitive strains of P. herpotrichoides. Certain of the newer fungicides employed against leaf diseases (prochloraz, propiconazole and triadimefon) have protectant activity against eyespot when they are applied in the autumn. While this may offer a useful bonus effect in winter barley, where the autumn mildew spray will augment the effect of the eyespot spray applied in the spring, there will be few cases where the autumn application of such fungicides is justified in wheat.

At our present state of knowledge we would advocate autumn spraying of wheat only if mildew began to build up on the upper leaves, or if eyespot lesions appeared in the autumn on a very forward crop of a susceptible variety. (Farmers should be discouraged from growing such varieties in high risk situations but the constraints of a seed contract may sometimes necessitate their being grown as second or subsequent wheats).

CONCLUSIONS

Autumn treatment is likely to be beneficial if a wheat or barley crop is likely to reach the spring in a condition where as a result of autumn disease it is unable to make full use of environmental resources during the following spring and summer. In our experience this is likely to occur on barley in the following situations:-

a) Very severe disease - such as where a cultivar is very susceptible e.g. winter barley cv Maris Otter (mildew + Rhynchosporium).

b) Where winter hardiness is marginal and is improved by controlling the foliar disease in the autumn.

c) Where an improvement in root development in the autumn gives improved drought resistance on very light sandy soils in the following spring.

Responses to the autumn control of foliar diseases on winter barley have been rather variable and in many cases unpredictable. They have tended to be greatest where susceptible varieties have been grown on light, drought prone land and where foliar disease has accentuated frost damage during severe winters.

Current ADAS advice for autumn mildew control on winter barley is as follows:-

Crops on light land and thin crops on medium land - spray as soon as the leaf area affected by mildew on the lower leaves exceeds 10 per cent on early sown crops and five per cent on later sown thinner crops.

Crops on heavier land and thick crops on medium land - spray only if mildew begins to affect the upper leaves.

Seed treatment is an alternative to an autumn spray especially where the risk of disease and damage is high, i.e. susceptible varieties sown before the end of September on light land.

The treatment of eyespot in wheat or barley has generally been found to be more economic when carried out in spring. Autumn treatment should only be contemplated when risks of severe infection are known to be high - as in a very early sown crop of a susceptible cultivar grown in an intensive cereal situation.

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SESSION 6A

PEST CONTROL IN ANNUAL TROPICAL CROPS

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CAN TROPICAL CROPS BE EFFICIENTLY PROTECTED?

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INTRODUCTION

During the time it will take me to read this paper world population will increase by about 10,000 people and most of those will be in tropical countries. If human society is to survive at all, let alone prosper, then one of the things that must be done is to increase agricultural production considerably in that part of the world.

Buringh et al (1957), using agro-climatological and soil data, computed the absolute maximum possible world food production, in terms of grain equivalents, as 50,000 million tonnes; the present production is 1300 million tonnes, so that the postulated maximum potential yield is some 39 times as great. The potential agricultural land available in the world is 3419 million hectares, of which 1406 million hectares is cultivated now. Furthermore the largest amounts of useful land, and the greatest potential for increased food production, are to be found in the tropical countries of Asia, Africa and South America, an idea developed by Professor Swaminathan (1980) in his review of "Past, present and future trends in tropical agriculture", the key note address at the Golden Jubilee Conference of the Commonwealth Agricultural Bureaux. But he was also careful to point out the numerous constraints that exist to this potential increase, especially in the tropics. These include ecological constraints such as weather, pollution, desertification, socio-economic constraints such as risk and uncertainty, credit, traditional practices and marketing, and production constraints which include water management, soil health, appropriate cultivars, farm machinery and weed, disease and pest management.

Very few in this audience need reminding that global losses to pests, diseases and weeds are of the order of 30-40%, since most of us earn our living in a constant struggle to reduce that percentage. But the hard fact is that overall we haven't been too successful; Pimentel et al (1978) have estimated that crop losses due to insects alone have increased from 7% in the 1940's to 13% today, while US Department of Agriculture statistics quoted by Metcalf (1980) show that estimated losses due to insect attack in cotton as a percentage of total crop rose from 10% in 1900-1904 to 19% in 1951-1960, and in maize from 8% to 12% in the same period. The evidence available suggests that tropical crops are among the worst cases; there are special reasons for this.

SPECIAL PROBLEMS OF TROPICAL CROPS

The tropics account for 40% of the world land surface and receive over half the total rainfall, but this rainfall is erratic, with alternating periods of drought, monsoon and flood. Indeed, so severe can these problems be that in some cases rice crop damage in Asia due to flooding or drought far exceeds damage caused by insect pests and diseases (Yamada, 1975). Also, problems such as soil erosion, leaching of nutrients and wash off of pest control chemicals abound. Temperatures are high, allowing plant growth throughout the year, thus making multiple cropping

possible but intensifying the weed problem. But frequently maximum sunshine coincides with minimum rainfall, thus requiring irrigation.

The diversity of flora and fauna is vastly greater in the tropics than in temperate regions and this has a direct effect on the pest situation. Thus in Asia, the number of major insect pests of rice is about 28, while in America it is 12. As regards diseases, rice in temperate zones is subject to 54 infections, in tropical zones over 500; for maize the figures are 85 and 125 and for tomatoes 32 and 278. As a direct consequence of higher temperatures and humidity pests and diseases can often go through two or three generations in the tropics as compared to temperate regions and the fact that there is in general no winter, which in temperate zones reduces the severity of pest disease and weed problems annually, means that infestations can continue at a high level for most of the year. The effect of this continuous onslaught can be severe as is demonstrated by data collected by the International Rice Research Institute for Asian countries, suggesting a minimum loss of 1000 kg of rice per hectare due to insect attack. (Pathak, 1968). But these rather simplistic data conceal a further range and variety of ecological problems which affect the efficiency of pest control.

In most tropical regions, there is considerable crop diversity, some, as in Africa, having evolved in relation to the great variation in length of the rainy season, some due to the traditional multi-cropping pattern of subsistence farming. While the general ecological argument that the stability of a biological community is related to its species diversity still holds in principle, in recent years several insect ecologists, notably Way (1977) and Van Emden and Williams (1974) have argued that the effects of diversity on pests and diseases is far more complex than it might appear. Thus, while it is true that in the tropics, the natural enemy complex of insects and weeds is larger than in temperate regions, its controlling effect depends not only on species numbers and density but on the manipulation and usage of the agro-ecosystem. Likewise, the extreme environmental factors in the tropics exert direct effects on control systems, with, for example, degradation of active ingredients, whether chemical or biological, by sunlight and rainfall, leaching of soil applications, and wind and thermal drift of sprays. Crop characteristics, such as height, canopy density and shade trees can affect pesticide placement, and timing of applications can be difficult because of large variations in weather conditions and in pest life cycles.

In all crops, but especially in the more rapidly responding tropical ecosystems, it is clear that wide scale use of broad spectrum insecticides almost invariably leads to ecological disaster, with the appearance of pest resistance, pest resurgence and outbreaks of secondary or induced pests. The horror stories of plant protection, such as the disasters with cotton in the Americas and rice in South East Asia, have already caused enough sleepless nights among the current audience to forbid repeating them. The problem has been exacerbated by the development and wide scale introduction of high yielding varieties - the so-called Green Revolution. While undoubtedly leading to great increases in yield in some crops in some countries - in India for example, over the last ten years overall crop production has increased from 95 to over 131 million tonnes, a compound growth rate of 2.6% per year - major pest problems have multiplied in the high yielding cultivars. Rice pests provide the classic example, with the elevation of planthoppers like Nilaparvata lugens, the Brown Planthopper, from minor pest status to the world's number one pest of irrigated rice in less than ten years, and a large increase in stem borer attack - all exacerbated by the fact that many of these species are vectors of rice virus diseases like tungro, and grassy and ragged stunt, which has led to enormous epidemic outbreaks all over South East Asia.

It is unfortunate that the general response to these problems has been the "reach-for-the-gun" syndrome, so that between 1950 and 1974 the use of insecticides

in rice increased by a factor of 33, while yield only increased by a factor of 1.5. Increased usage of insecticide brought other problems in train; on the economic front, because of price rises, the costs of plant protection began to reach unacceptable levels, so that, for example by 1975 in Taiwan, 24% of the cost of rice production was accounted for by insecticides (Kiritani, 1979). High pesticide usage induced resistance, and in the tropics this was particularly rapid because, as mentioned above, insect pests can get through two or even three generations a year. Thus in the rice leafhopper and planthopper, multiple resistance became widespread, so that while in 1965, 1-2 control applications were sufficient, by 1969 this had risen to 4-7 per annum.

But the problems are even more deep-seated than such facts suggest. The introduction of large scale monocultures of high yielding varieties not only brought into sharp focus the diversity vs. monoculture argument, but it heralded a complete change in the whole agricultural scene, not only with major technological changes in agricultural management practice, such as plant density, but in its related inputs - seeds, cultivars, irrigation and fertiliser regimes, and certainly plant protection. In many countries these changes met with resistance from traditional agricultural practice and revealed a breakdown in communication between farmers and those bodies, national and international, charged with introduction of the new technology. (Haskell et al, 1981; Nickel, 1973). I have highlighted these problems with especial reference to rice, because it is the world's major food crop, but the same problems occur in cotton and vegetables.

These major changes in agricultural practice in the tropics caused problems in two other aspects of plant protection - environmental and socio-economic. Environmental effects of plant protection encompass direct effects on non-target organisms, including man, his domestic animals and wild life, and indirect effects on, for example, soil fertility and crop yields. All these have been well documented elsewhere (see eg. the review by Metcalf, 1980) and need only be referred to here as constituting a further restraint on the development of efficient and economic tropical plant protection.

Socio-economic constraints pose particular problems in the tropics where traditional agricultural systems have evolved which are finely tuned to cope with all vicissitudes presented by the environment, both physical and social. We are now beginning to understand that any attempt to implant a new technology without a period of local adaptive research will almost certainly fail and this certainly applies to plant protection. (Haskell, 1978).

TOWARDS A SOLUTION

I have deliberately spent a good deal of time in outlining the problems so as to provide a background to the remainder of the papers in this session, which deal with possible solutions to specific problems in specific crops. I therefore now want to discuss more general approaches to a solution, within which those specific problems can be considered.

First of all, it is clear that the problems of pests, diseases and weeds in the tropics will tend to intensify as the political and economic pressures for increased agricultural production result, as they must, in more land being cultivated and higher yields required from that now in use. Such a trend is inevitable in relation to present usage and when one adds to that the effects of such schemes as large scale de-forestation to provide land for vegetable-based alcohol production, the resultant ecological upset can only increase the problems.

There will be some advantages in increased land use; for example I have commented elsewhere (Haskell, 1970) on the likelihood that the world migratory locust problem will decrease as more land is cultivated; but we now know enough about the ecology of insect pests, let alone diseases and weeds, to be sure that as one complex declines in importance another will take its place.

We also know enough now to say that chemical control systems alone cannot provide the answer, because biological organisms of all types will develop resistance to the system sooner or later. It now appears that were we to develop and use biological control systems, whether they be the release of parasites or predators, the use of semio-chemicals, or the use of resistant cultivars, to the point where sufficient selection pressure builds up, resistance to these, in the form of altered behaviour, would occur.

This may seem a dismal analysis, but I believe it is a true one; however it also suggests the basis of a solution. All the problems I have described above can be viewed as the result of application of some unilateral pressure, which could be for example, replacement of a mixed crop by a monoculture, or use of a broad spectrum pesticide, or, in the environmental and socio-economic spheres, public opinion, which distorts the overall system. A solution might thus be found by removing or reducing that pressure, or balancing it with a counter-pressure. Some obvious examples of this would be: do not try to eliminate or eradicate the pest, but only to reduce its numbers so that it does not cause unacceptable economic damage; to carry that further, reduce quality controls on produce, particularly fruit and vegetables. Use crop cultivars which offer a reasonable compromise between high yield, pest resistance and water and fertiliser inputs. Develop cultural control measures. In chemical control reduce the amount of active ingredient applied but get it to the target more efficiently; avoid single component systems and rotate the use of chemicals to reduce the rate of onset of resistance.

I am sure that you will appreciate that what I have been describing above is in fact the development of an integrated pest management approach to the problem. While it is generally recognised that this must be the favoured conceptual approach to the multiple problems of plant protection, both temperate and tropical, practical experience during the last decade has shown a number of constraints to its wide spread introduction. (IOBC, 1980).

Several of these are political or organisational; while developing countries show great variability in the status and efficiency of their plant protection services, in general these and the allied extension services are low in Government priority lists, with poorly developed infrastructure, particularly in transport, a shortage of expert manpower, and a low level of pay. There is also often instability in the personnel and funding of research institutes which cannot carry out the essential local adaptive research on new cultivars, new compounds and new techniques.

Basically these shortcomings reflect inadequate funding and one problem here is that financial allocations in developing countries, both by national governments and by aid agencies and by international organisations, are not made solely on scientific merit but are subject to political, commercial and socio-economic factors. We could perhaps learn here from our colleagues in the post-harvest protection field who during the last decade have mounted such an effective campaign that now no self respecting international conference on development of the world food problem or on global agriculture is complete without this item on the agenda, which has resulted in considerable financial support for this work in recent years.

We should therefore welcome and be ready to support the initiative now being taken by UNDP and FAO to develop international support for plant protection as an essential input to agricultural production which, for relatively low capital and

recurrent costs, could, using presently available techniques, reduce losses due to insects, diseases and weeds from the present 30-40% down to perhaps 25-30%. A minimal 5% saving would mean an extra 65 million tonnes of food; in rice equivalents, that would provide for approximately 60 million people for a year, and by chance, is around the figure that economists have suggested as necessary for a world food stabilisation reserve. (Walters, 1978). The need for efficient plant protection in the tropics is the more important because of the low yields due to the adverse factors described earlier. In cereals the average yield is only 58% of that in temperate zones, while in many vegetable crops, such as tomato, onion and cucumber it is lower still, 30% of temperate zone production (Chang, 1977), and the high pest, disease and weed incidence in the tropics of course relates directly to these figures. But there is no doubt that even with presently available techniques, could we only get them applied widely, reduction of pest losses and hence increased yields are feasible, given adequate Government support. South Korea provides a good example. In the early 1970's it was a rice importing country, but the Government set up the Office of Rural Development to boost small farmer rice production, employing a staff of 9000, of whom over 7000 are extension workers and advisers, including entomologists, plant pathologists and weed scientists; as a result, South Korea has been self-sufficient in rice since 1975 and has even exported in some years.

But in addition to such political and financial inputs there is much to do on the technical side. We have a ludicrously insufficient knowledge of the population ecology of pest complexes in most major crops in the tropics and virtually none in relation to multiple cropping, which is of course generally used by small farmers. We are thus often unable to provide economic threshold figures for pest complexes as a basis for development of IPM systems. The ecological variations in the tropics between one area and the next, often between one farm and its neighbour, emphasise the need for scouting and monitoring systems to evaluate the field pest situation, which is particularly relevant to the timing of chemical application. Systems for use in operational IPM must be quick and inexpensive and it seems that simple pheromone traps could provide the answer here; a recent review of the use of pheromone traps in developing countries (Haskell, Campion and Nesbitt, 1981) shows that this is increasing, but more research is needed to relate trap catches to the population dynamics of the pest.

But pheromones have not yet been found for all pests and in any case some do not possess them, so that other sampling and scouting techniques have to be used; many systems exist, but farmers have to be trained to use them. In crops like cotton, which does not give an economic yield unless protected from pests, correct timing of control measures can produce great economies. The Commercial Cotton Growers Association of Zimbabwe has learnt this lesson and has invested a lot of money in their own residential training establishment at Gatooma, where farmers and their assistants are taught the basics of IPM in cotton - what the major pests are, how to identify them, how to scout and how to use the information in relation to the application of control. The fruits of three years training are now being gathered in the form of reduced insecticide usage, reduced boll damage and an overall increase in yield.

But there is need for improvement in other aspects of chemical control besides timing. Reduced dosage offers direct savings of active ingredient, damages natural enemies less and has been shown in a variety of crops, including cotton, to be effective. It is well known that with spraying or dusting applications less than 1% reaches the target pest and more research is needed in relation to drop size and application, and the economic and biological effect of area distribution techniques, such as spot or alternate row spraying. Better methods of adhesion to plant surfaces and protection of active ingredient from weather could also contribute and methods such as electrostatic charging - a later paper in this

session deals with this - will provide some improvement. But spraying means machinery, which requires an energy source and maintenance facilities - two things in short supply in the tropics. Should we not then be looking at alternative formulation approaches, as suggested by Graham-Bryce (1975), not only further exploiting encapsulation and granules but looking at plastic chips, fibres, downward translocation and so on. Seed treatment with systemics offers an approach combining low dosage and ecological selectivity. Allied to that, I suggest a useful field of research is the incorporation of chemicals which aggregate the pest insect, or cause it to feed more avidly. It is clear that insect behaviour is regulated to an astonishing degree by chemical signals, particularly in relation to feeding and movement, and offers a chance of improving ecological selectivity. Trap crop efficiency could be augmented by treatment with pheromones or phago-stimulants; attractive baits, mixed with control chemicals, such as malathion laced protein hydrolysate for fruitfly, improve selectivity, and more could be done in this field. (See review by Cherrett and Lewis, 1974).

One of the main aims of the IPM approach is to conserve the natural enemy complex, which in the tropics is large. However, Way (1977) has pointed out that this does not necessarily lead to greater control efficiency, and more work is required on the manipulation of natural enemies. Alternate row spraying, for example, apart from directly reducing pesticide usage, provides refuges for natural enemies, which in some cases can also be manipulated directly by pheromones and phago-stimulants derived from their host plants, as shown by Prokopy et al (1978) and Lewis et al (1977).

While the systematic search for production of very selective pesticides is probably precluded by economic considerations, nevertheless many compounds do exist which are highly selective and can be used to advantage in IPM systems. Thus Metcalf (1980) quotes the growing use of the O.P. trichlorphon in cotton pest control and of course the group of microbial insecticides, such as Bacillus thuringiensis and B. sphaericus are very selective and act on a small group of lepidopterous and dipterous larvae and are now widely used on vegetable crops. The use of nuclear polyhedrosis viruses is in its infancy, but these seem to be virtually species specific and cheap to produce (McKinley, 1980); there are problems with their practical use, because of their slow action and vulnerability to environmental degradation, but these will certainly be overcome.

CONCLUSION

What can be concluded from this brief survey about the protection of tropical crops?

First, that better protection of these crops is urgently needed to increase the present average low yields current in the tropics and to ensure that as small a limitation as possible from pests and diseases is placed on the potential of the area for greatly increased production.

Second, that the application now of presently available knowledge would enable crop losses to be cut from the current 30-40% to 25-30% with enormous benefit to the world food situation.

Third, that a good deal of applied research and development work is required to perfect new techniques for monitoring and survey, such as pheromone traps, to bring to practical fruition the promise of new approaches such as the use of viruses, and to increase the efficiency and reduce the environmental hazards of chemical control.

Fourth, that these techniques are best applied in an integrated pest management system, to conserve the natural enemy complex, and to ensure that the plant protection input dovetails with local custom and practice and takes advantage of the local agro-ecosystem.

These proposals will not greatly impress the agro-chemical industry because they do not offer the chance for the scale of profits which interest them. Indeed, in the review of the future of integrated pest management organised by the International Organisation for Biological Control (IOBC, 1980) the industry representatives were critical of what they saw as over-inflated claims for the value and success of IPM, pointing out that where meaningful cost/benefit analyses could be made there was not much to choose between IPM and direct chemical control (Braunholtz and Tietz, 1980). This is so, but it overlooks two important factors - that the IPM systems are environmentally acceptable and that they are stable and thus can be operated for long periods of time. By contrast, what is the useful commercial life of a new pesticide introduced today? Given the increasing rate of the onset of resistance - resistance has already appeared to the new synthetic pyrethroids - and the increasing pressure for environmental acceptability, it is bound to be short - probably too short to generate sufficient profit unless its life is extended by judicious use in an IPM system. Advances in the area of tropical crop protection cannot be made without the collaboration of industry both in the development of new systems and, very importantly, in the training and demonstration field. Given their co-operation, and the essential government support, there is every reason to conclude that tropical crops can be efficiently and economically protected.

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SESSION 6B

VIRUSES AND VECTOR CONTROL

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TWO SENSITIVE SEROLOGICAL METHODS FOR DETECTING PLANT VIRUSES IN VECTORS AND THEIR SUITABILITY FOR EPIDEMIOLOGICAL STUDIES

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Summary Immunosorbent electron microscopy (ISEM) and/or enzyme-linked immunosorbent assay (ELISA) can detect cucumber mosaic, potato leafroll (PLRV) and pea enation mosaic (PEMV) viruses in single aphids, maize rayado fino and maize stripe viruses in single leafhoppers and several nepoviruses in single nematodes. Work with PLRV and PEMV has shown that the virus content of vector aphids can be estimated reliably by ELISA, that individual aphids treated similarly differ greatly in virus content, that the virus content of aphids is not closely correlated with the probability of virus transmission to test plants and that inefficient vector species may acquire and retain as much virus as efficient ones. PLRV can be detected in alate aphids caught in water traps but in a field experiment the mean virus content of aphids decreased after early July. In epidemiological studies, sensitive serological tests on virus vectors seem of most use for viruses that are retained for long periods or multiply in their vectors, and in situations where many vector individuals are to be tested and/or a substantial proportion are carrying virus.

Resumé Deux méthodes sérologiques très précises peuvent être utilizées pour detecter plusieurs virus phytopathogènes dans leur vecteurs (pucerons, cicadelles ou nématodes): la technique sérologique par microscopie électronique (ISEM) et la technique immunoenzymatique (ELISA). Mais la quantité par insecte de virus de l'enroulement de la pomme de terre (PLRV) ou de virus de la mosaique avec énation des pois determiné par la methode ELISA est très variable et est seulement faiblement liée à la probabilité de transmission du virus aux plantes tests. En plus, des vecteurs inéfficaces peuvent acquerir et conserver autant de particules de virus que les vecteurs éfficaces. Dans les études épidemiologiques, le PLRV peut être détecté chez les pucerons ailés pris dans des pièges à eau. Les tests par ISEM ou ELISA sur les vecteurs des virus dans des études épidemiologiques semblant être plus utiles pour des virus qui persistent dans leur vecteurs, et dans des conditions où plusieurs vecteurs individuels doivent être testés ou quand une forte proportion sont porteurs de virus.

INTRODUCTION

The relative insensitivity of methods of detecting and assaying plant viruses has held up several kinds of research on their epidemiology. In particular, there has been no quick and accurate method of estimating the quantity of virus particles carried by vector organisms, except for viruses that multiply in their vectors. Two serological techniques introduced in recent years promise to fill this gap. My aim is to assess the progress made in applying these tests, and to comment on their strengths and limitations.

The two techniques to which I refer are immunosorbent electron microscopy (ISEM; otherwise known as the Derrick method; Derrick, 1973) and enzyme-linked immunosorbent assay (ELISA). Both techniques are capable of detecting virus particles at concentrations of about 1 ng/ml and so can be 100- to 1000-fold more sensitive than methods that use antibody-sensitized latex particles or tanned red blood cells (Ball, 1974).

RESULTS AND DISCUSSION

Immunosorbent electron microscopy

ISEM relies on the tendency of molecules of antibody globulin to attach to the surface of the films used to cover electron microscope grids. When the films are coated with virus antibody, particles of the homologous virus bind specifically to them. The recommended procedure consists of floating carbon-filmed grids face down, first on drops of antiserum previously diluted 1:1000 in 0.06 M phosphate buffer, pH 6.5, and then, after rinsing, on drops of the virus-containing extract. Experimental details are given by Roberts and Harrison (1979). The result of using this technique is to increase by 100- to 1000-fold the sensitivity of detection of virus particles as compared to conventional methods of electron microscopy.

An important feature of this test is that only 10 µl drops of virus-containing extract are needed, and this facilitates the detection of virus in samples with small volumes, such as extracts of individual virus-carrying aphids. An example of the results of tests on individual green peach aphids (*Myzus persicae*) that had previously fed for 5 days on potato plants infected with potato leafroll virus (PLRV) is given in Table 1. Substantial numbers of PLRV particles were obtained from all the aphids but, as in other similar trials, the numbers obtained from different individuals differed severalfold.

ISEM therefore detected a virus which occurs in low concentration in source plants and accumulates in its aphid vector. Indeed it was also used successfully in tests on single aphids carrying barley yellow dwarf virus (Plumb and Lennon, 1981), another member of the luteovirus group. Similarly, the method proved suitable for assaying six nepoviruses in their nematode vectors, and in most instances was able to detect virus in extracts of single nematodes (Roberts and Brown, 1980). It should also be useful for detection of a wide range of other viruses that accumulate or multiply in their vectors.

To confirm the identity of virus particles found on an electron microscope grid coated with virus antibodies, the procedure can be taken a stage further by floating the grid on another drop of appropriately diluted virus antiserum. The result is that particles of the homologous virus become coated with antibody molecules whereas

any particles of other viruses that are attached non-specifically to the carbon films remain uncoated.

Table 1

Detection of potato leafroll virus in single *Myzus persicae* by ISEM (Roberts & Harrison 1979)

Aphid no.	Particles per 1000 μm^2		
	Grid 1	Grid 2	Mean
1	3600	2600	3100
2	11900	11700	11800
3	8400	12100	10250
4	1900	2200	2050
5	1900	1600	1750
All	-	-	5790

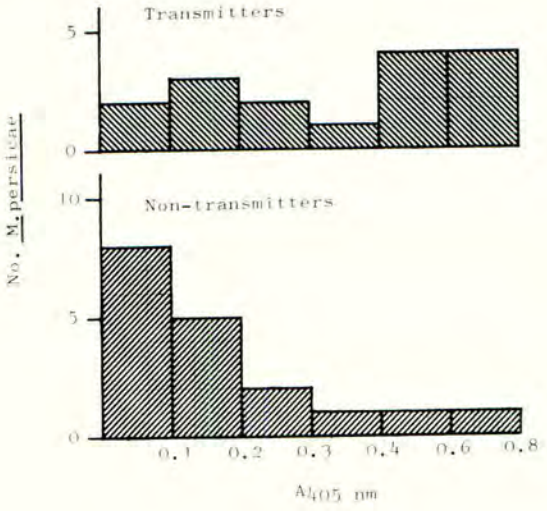
Enzyme-linked immunosorbent assay

ELISA is a serological test conducted in such a way that the extent of the reaction between virus particles and their homologous antibody is indicated by the intensity of colour produced. In practice, the 96 wells in plastic microtitre plates are coated with antibody globulin, and then each exposed to a potentially virus-containing extract. Some of the virus particles in such extracts become bound to the antibody and are not removed when the wells are repeatedly rinsed out. The wells are then exposed to a preparation of antibody molecules that have been linked chemically to a suitable enzyme (usually alkaline phosphatase; less commonly peroxidase). Some of this antibody conjugate binds to the trapped virus particles, the amount being assessed by adding a substrate that is converted to a coloured compound by the enzyme (yellow for alkaline phosphatase). The intensity of the colour produced is then measured in a colorimeter. This procedure, performed essentially as described by Clark and Adams (1977), has been used to detect and assay many plant viruses in extracts of plant tissue.

To detect viruses in their vectors some minor but important modifications are needed to minimize the non-specific reaction given by virus-free vectors without decreasing the virus-specific one. For *M. persicae* carrying PLRV the most noteworthy changes are to use 0.05 M phosphate buffer, pH 7.0, as the extraction fluid and to incubate the extracts for 1 h at 37°C before placing them in the wells of the microtitre plates. When this is done the period of incubation with substrate can be extended considerably without producing high background readings, and the sensitivity of detection may increase to 0.01 ng PLRV/aphid when batches of 20 aphids are used (Tamada and Harrison, 1981).

The effects of several factors on the PLRV content of *M. persicae* were studied with the aid of ELISA. The PLRV content of aphids increased with increasing acquisition access time before reaching a plateau after 5-7 days, and it was greater for aphids fed at 15-20°C than for those fed at 25-30°C; the maximum mean PLRV content recorded was 7 ng/aphid. The virus was detected in most single aphids kept on potato or *Physalis floridana* source plants for 6 days, but individual aphids given the same acquisition access period

Fig. 1. PLRV content of individual transmitting and non-transmitting M. persicae, measured by ELISA immediately after a 3-day inoculation access period on P. floridana. Acquisition access period was 1, 2 or 3 days.



differed up to 20-fold in virus content. After removing aphids from virus source plants, their mean PLRV content decreased in two phases, at first relatively rapidly to 1/3 - 1/2 of the initial value and then very slowly. The initial decrease, which is thought to represent the expulsion of virus from the intestinal tract, took about 2 days at 25-30°C, about 4 days at 20°C and about 6 days at 15°C. The slowness of the decrease during the second phase probably reflects the stability of PLRV particles in other parts of the aphid's body, and notably in the haemolymph. Interestingly, transmission to indicator plants (P. floridana) was only loosely correlated with the PLRV content of individual aphids, measured immediately after a 3-day inoculation access period (Tamada and Harrison, 1981; Fig. 1).

Some success has also been achieved in applying ELISA to the detection of other viruses in single vector insects (Table 2). The amount of pea enation mosaic virus (PEMV) acquired by vector aphids exceeds by more than 10-fold the amount of PLRV acquired, probably because the concentrations of the two viruses in source plants differ greatly, and PEMV approaches its maximum content in aphids after an acquisition access period of only a day. As with PLRV, the PEMV content of individual aphids differs greatly, the concentration of virus in them decreases steadily for about 6 days after leaving the source plant and transmission to test plants is not closely correlated with the subsequently measured virus content of individual aphids (Fargette et al., 1981). Similarly, Gamez et al. (1981) found that maize rayado fino virus, which multiplies in its leafhopper vector, could be detected by ELISA in several individual insects that did not transmit, as well as in those that did.

Table 2

Viruses detected in individual vectors by ELISA

Virus	Vector	Reference
Cucumber mosaic	Aphis gossypii	Gera et al., 1978
Potato leafroll	Myzus persicae	Tamada & Harrison, 1981
Pea enation mosaic	Acyrthosiphum pisum	Fargette et al., 1981
Maize rayado fino	Dalbulus maidis	Gamez et al., 1981
Maize stripe	Peregrinus maidis	Gingery et al., 1981

Perhaps the most unexpected result obtained with ELISA is the detection of cucumber mosaic virus in single melon aphids (Aphis gossypii) allowed to make brief probes on infected tobacco leaves (Gera et al., 1978). Moreover, after subsequent 1.5 min probes on healthy tobacco, the virus was no longer detectable, in agreement with the rapid decrease in infectivity of feeding aphids.

Contrasting with these successes are several examples of viruses that could only be detected in samples prepared from large groups of virus-carrying vectors or, as with alfalfa mosaic virus in aphids (Raccah et al., 1981), could not be detected unequivocally. The viruses detectable with greater or lesser ease in groups of aphids include barley yellow dwarf (Denechere et al., 1979), carrot red leaf (Waterhouse and Murant, 1980), potato Y (Raccah et al., 1981) and citrus tristeza (Cambra et al., 1981). If one can risk generalizing from this relatively small number of examples, it seems probable that viruses which multiply in their vectors, such as phytoreoviruses, fijiviruses and plant rhabdoviruses, will be readily detectable in these insects by ELISA. Viruses that accumulate and persist in their vectors for long periods without multiplying, such as luteoviruses, geminiviruses, pea enation mosaic virus, comoviruses, tymoviruses, nepoviruses and tobraviruses will probably be less readily, but in several instances still reliably, detected. In contrast, carla-viruses, potyviruses and closteroviruses seem less promising candidates for detection in individual vector aphids by ELISA.

Suitability of ISEM and ELISA for epidemiological studies

These two tests, especially ELISA, have already found many applications in studies in which there was a need to test large numbers of crop or wild plants rapidly for virus infection. There is also much interest in determining the suitability of ELISA and ISEM for tests on vector species in epidemiological work, because their use may increase greatly the speed and accuracy with which the hazard to crops presented by migrant, possibly virus-carrying, vectors can be assessed. Again, tests on aphids carrying PLRV have provided evidence that emphasizes both the strengths and limitations of this approach. A limitation is that PLRV is acquired readily and retained for many days by species, such as Macrosiphum euphorbiae, which are relatively inefficient vectors (Tamada and Harrison, 1981). Therefore there will be a continuing need to sort aphids collected in the field into species before testing them. A second factor is exemplified by the change in PLRV content of aphids collected from infected potato plants at different stages of growth. For example, the mean A_{405} values given in ELISA by single virus-carrying M. euphorbiae

collected from infected plants in the same Scottish crop on June 11, June 25, July 7, July 25 and August 13 were 0.22, 0.29, 0.48, 0.16 and 0.10 (Tamada and Harrison, 1981 and unpublished results). Indeed, on the last two dates, the amount of PLRV in some individual aphids seemed too small for unequivocal detection. In contrast, an encouraging feature is that PLRV could be detected satisfactorily by ELISA in aphids caught 1-2 days previously in water traps (Tamada and Harrison, 1981).

The picture that begins to emerge is that sensitive serological tests on vectors have a place in studies of the epidemiology of viruses that persist in their vectors for substantial periods, and particularly for testing insects that are migrating in relatively large numbers, and of which a reasonable proportion (say more than 0.1%) are carrying the virus in question. The tests would also be useful in situations where there are fewer insects but a larger proportion of them carry virus.

Whether ISEM or ELISA is the test of choice will depend on several considerations. Both tests detect viruses in crude extracts, they can detect and assay one virus in the presence of another and they do not differ greatly in sensitivity. ELISA gives the quantitatively more accurate results and is the more suitable method where many samples are to be tested. ISEM, however, can be done with a much smaller volume of sample and, where the virus content is low, many people find the sight of a few virus particles more convincing than a very weak colour in a microtitre well. Finally, both tests will become much more generally applicable in vector studies if their sensitivity can be increased by a factor of ten. With the current pace of development in serological procedures there is a real prospect that such an improvement will soon be achieved.

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CURRENT RESEARCH AND FUTURE PROSPECTS FOR DIRECT CONTROL OF VIRUS DISEASES

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Summary The course of virus disease development is divided into four phases:- infection, multiplication, virus spread and symptom expression. Current research on antiviral chemicals and resistance mechanisms in each phase is reviewed and other areas where chemical control of virus diseases may be possible are defined.

The course of disease can be interrupted or inhibited at any of these phases. Many chemicals induce resistance and some have been successfully used on crops. The most attractive aim for future work is the use of chemicals to restrict normally systemic viruses to local infections.

INTRODUCTION

Virus diseases affect all important agricultural crops and cause large economic losses. Nearly all control of virus diseases is prophylactic: once a plant is infected few practical methods for treating virus diseases are available. There are two main reasons for this. Firstly, work on antiviral chemicals has concentrated on virus/host combinations in which the virus is mechanically transmitted and localised in visible lesions which develop at the sites of infection. Little of the effort has been devoted to the economically important virus diseases which systemically invade the host and are transmitted by invertebrate vectors. Secondly, it is more difficult to control virus diseases than those caused by other pathogens. Bacteria and fungi have their own metabolic systems which differ from those of their hosts, so chemicals can be used to disrupt the pathogen's metabolism whilst having little effect on the plant. Viruses, however, use the plant's metabolism and many of the host's enzymes for replication so disrupting the pathogen but not the host is more difficult. In this paper current work and prospects for chemical control at each of the four phases: infection, multiplication, spread and symptom expression are discussed.

VIRUS INFECTION

Before a virus can multiply it has to penetrate the host's cell wall and plasmalemma. Virus on the leaf surface or in the intercellular space is rapidly inactivated, presumably by degradative enzymes; 50-60% of tobacco mosaic virus (TMV) adsorbed onto the leaf surface of Xanthi-nc tobacco is inactivated within one hour (Kassanis & Kenten, 1978). Viruses rely for entry on mechanical damage of the cell, usually caused by the virus vector.

Many environmental factors, including light, temperature and water stress affect host susceptibility (Matthews, 1970), but manipulating them is unlikely to control plant virus diseases effectively. However, exploiting the natural virus-inhibitors often present in plants could be more useful. The presence of inhibitors may be fairly general; in a survey of 169 plant species more than half were found to contain inhibitors of TMV infection (Okuyama et al., 1978b). Inhibitors of virus infection are also found in a wide range of organisms including bacteria, e.g. Pseudomonas longa (Yazykova & Mozhaeva, 1973): fungi e.g. Trichothecium roseum (Gupta et al., 1974) and Saccharomyces cerevisiae (Kovalenko & Votselko, 1977): and algae e.g. Cystoseira stricta (Grasso & Larosa, 1979). The chemical structure of these inhibitors is very diverse, ranging from polysaccharides in sugar beet to proteins in pokeweed and nucleic acids in Chenopodium amaranticolor (Table 1). The best-characterised

Table 1

The nature of inhibitors from different organisms

Plants	Nature of inhibitor	References
Boerhaavia diffusa	glycoprotein	Verma et al (1979)
Cabbage	polysaccharide?	Varma (1973)
Capsicum annuum	protein	Fischer & Nienhaus (1973)
Chenopodium amaranticolor	RNA?	Kimmins (1969)
Nicotiana glutinosa	protein & RNA	Schuster & Wetzler-Schneider (1975)
Nicotiana glutinosa	phosphoglycoprotein	Mozes et al (1978)
Phaseolus vulgaris	RNA?	Kimmins (1969)
Phaseolus vulgaris	protein	Ladygina et al (1977, 1978)
Phytolacca americana	protein	Wyatt & Shepherd (1969)
Sugar beet	polysaccharide	Ebrahim et al (1972)
Tea	catechins & theaflavins	Okada (1978)
Tomato	protein	Chadha & Macneill (1969)
Yucca	protein	Okuyana et al (1978)
Marine alga		
Cystoseira stricta	protein	Grasso & LaRosa (1979)
Bacteria		
Pseudomonas spp.	protein-nucleic acid complex	Yazykova & Mozhaeva (1973)
Pseudomonas spp.	pigments	Milchenko et al (1976)
Fungi		
Candida) Saccharomyces)	polysaccharides & RNA	Kovalenko (1972)
Trichothecium roseum	polysaccharide	Gupta et al (1974)

inhibitor is the pokeweed antiviral protein (PAP) which has been purified from Phytolacca americana. It is a heat stable protein, with a molecular weight of 27000 (Fukaya & Taniguchi, 1979) which contains a large proportion of basic amino acids, 12% by weight lysine (Wyatt & Shepherd, 1969). PAP inhibits

eukaryotic protein synthesis by specifically interfering with the interactions of the larger ribosomal subunit with elongation factors EF1 and EF2 (Dallal & Irvin, 1978) but does not decrease the amount of TMV synthesised, or the number of lesions formed, in tobacco leaf discs inoculated with TMV and then floated on the inhibitor solution (Fukaya & Taniguchi, 1979). This suggests that PAP may restrict virus infection and virus protein synthesis by different mechanisms.

Most of the inhibitors found in leaf sap have the following properties. They are most effective when mixed with the virus or applied to the leaf shortly before inoculation but when mixed with virus they do not affect it irreversibly since separation of the virus from the inhibitor restores infectivity. This indicates that the inhibitors directly affect the plant, or interfere with a plant-virus interaction which is essential for infection, and not the virus. Moreover an inhibitor from a particular plant species usually only inhibits virus infection of a different species but is much less effective in restricting infection of the species from which it was isolated. This suggests that these inhibitors are not natural defence mechanisms evolved by the plant for its own protection, but are an artefact of the way leaves are extracted before the extract is mechanically inoculated to other plants. It seems unlikely that this type of inhibitor will give long lasting protection against vector-borne virus infection.

VIRUS MULTIPLICATION

When in the cell the virus particle must dissociate into coat protein and nucleic acid and the latter must find a suitable site before replication can occur. If the cell already contains a related, replicating virus the introduced virus may be unable to replicate. This results in cross-protection, a phenomenon that has found practical application, for example a mild strain (MII-16) of TMV protects tomato plants against more virulent strains (Fletcher & Rowe, 1975). If the mechanism of this protection were fully understood it might be possible to duplicate it by chemicals.

In general, a single virus only infects a few hosts and some, for example blueberry shoestring virus, are host specific. The host range of a virus is determined by a number of factors including its ability to divert the metabolism of the host to the production of virus particles. Although viruses mainly use the host's own enzymes they also carry the genetic information for the production of a number of proteins including a replicase (Hadidi & Fraenkel-Conrat, 1973). Differences between these virus-coded proteins and those of the host, and between the metabolism of virus-infected and healthy cells, may make diseased cells more sensitive than healthy ones to various treatments including heat and chemicals. The replication of many viruses is severely disrupted if the host is kept at 35-40°C, and in some cases heat treatment has been used to free whole plants or shoots from virus (Matthews, 1970). The meristems of plants often contain fewer virus particles than other parts of the plant and meristem culture, sometimes combined with heat treatment, is widely used to produce virus-free stocks especially of plants that are propagated vegetatively. Elucidation of the mechanism(s) of these effects might provide clues to the kinds of chemicals that may be antiviral.

Pyrimidine and purine base analogues such as 2-thiouracil and 8-azaguanine have been found to decrease virus multiplication (Commoner & Mercer, 1951; Matthews, 1953). Unfortunately they also disrupt the nucleic acid metabolism of the host plant and seriously affect its growth. More recently the nucleoside analogue ribavirin was found to be a more specific inhibitor of virus nucleic

acid metabolism. Ribavirin added to the culture medium decreases virus replication in tissue culture but does not affect the host cells. Its use should therefore make virus-free cultures easier to obtain (Simpkins et al., 1981). When sprayed on whole tobacco plants systemically infected with PVX, ribavirin decreases the amount of virus produced (Schuster, 1976). Dioxohexahydrotriazine (DHT), an analogue of uracil, similarly decreases virus multiplication and symptom expression. In field trials PVX and PVY infected potatoes sprayed with DHT produced a significant increase in yield (Schuster et al., 1979). This is one of the few reports of success with direct chemical control of virus diseases on field-grown crops.

VIRUS SPREAD

a) Spread within an infected plant

Little is known about how viruses spread within a plant but the most likely routes are through the plasmodesmata, (cytoplasmic connections between neighbouring cells) and through the vascular system. Furthermore, it is not known whether viruses spread as complete particles or as nucleic acid although some viruses which do not produce a protein coat spread effectively throughout their hosts. Some viruses are confined to the infected cell in certain hosts, possibly because they are unable to pass through the plasmodesmata: others are restricted to the inoculated leaf, possibly because they are unable to enter the vascular system. However, some plants have evolved an active defence mechanism which localises the virus in a small area of the leaf, usually resulting in chlorotic or necrotic lesions.

An inducible resistance to further infection by necrotic-lesion-forming viruses was shown in tobacco by Ross (1961 a & b). Initial inoculation produced localised necrotic lesions on the leaves at the sites of infection and the virus was restricted to the cells of the lesion and immediately adjacent tissue. Challenge inoculation with the same virus produced fewer and smaller lesions both on the same leaf (localised acquired resistance) and on other leaves on the same plant (systemic acquired resistance). Work on the molecular basis of this resistance mechanism has led to the development of two lines of research on i) the antiviral factor (AVF) and ii) the pathogenesis-related (PR) proteins.

i) Antiviral factor (AVF)

AVF was purified from tobacco leaves showing localised acquired resistance and found to be a phosphoglycoprotein of molecular weight 22,000 which markedly reduced the infectivity and multiplication of TMV (Sela, 1981). AVF is present, but in an inactive form, in healthy leaves and is activated by an enzyme system when the host is infected by virus. AVF seems to be very potent; only one molecule/leaf cell is enough to induce resistance which suggests a similarity between AVF and interferon in animals. Sela (1981) reports that AVF stimulates the production of the nucleotide 2,5-A which is associated with the interferon induced resistance to virus infection in animal cells. However in collaboration with Dr. Cayley working in Dr. Kerr's laboratory at the Imperial Cancer Research Fund in London we have been unable to detect 2,5-A in leaves of Nicotiana tabacum cv. Xanthi-nc or Nicotiana glutinosa showing localised acquired resistance.

ii) Pathogenesis-related protein

Gianinazzi et al. (1970) and Van Loon & Van Kammen (1970) independently showed that leaves of tobacco resistant to TMV contain a number of soluble leaf

proteins, termed PR-proteins (Antoniw et al., 1980) which are not present in healthy leaves. Ten PR-proteins, are easily identified in leaf extracts of Xanthi-nc & Samsun NN tobacco by polyacrylamide gel electrophoresis (Fig. 1 & Van Loon, 1981). At present there is no direct evidence that these proteins, which are the products of the genetic information of the plant and not the virus, are responsible for the acquired resistance, but there is strong circumstantial evidence for this:-

i) PR-proteins are not only produced in virus-infected leaves but also in leaves showing systemic acquired resistance.

ii) When Samsun NN and Xanthi-nc tobacco plants are kept at 32°C the resistance to TMV (type-strain) acquired following local infection by TMV breaks down, the virus invades systemically and PR-proteins are not produced.

iii) When resistance is induced by chemicals (Table 2) PR-proteins are also produced.

Table 2

Chemical inducers of PR-proteins and resistance

Polyacrylic acid	Gianinazzi & Kassanis (1974)
Ethephon	Van Loon (1977)
Aspirin, salicyclic acid, benzoic acid	White (1980)
IAA, 2,4-D & BAP	Antoniw et al (1981)
2-thiouracil	Antoniw & White unpublished

At present the most effective method for eradicating virus in a wide range of plants is by meristem culture combined with heat treatment or chemotherapy. We found that callus cells grown from uninfected leaves of N. tabacum cv. Xanthi-nc contain PR-proteins (Antoniw et al., 1981) and it seems that these proteins have been induced by the plant growth regulators (IAA, 2,4-D & BAP) used in the growth media. It is an intriguing possibility that part of the reason why many plants regenerated using tissue culture are freed from virus may be the induction of the same resistance in these tissues as that associated with the presence of PR-proteins in leaves.

b) Spread between plants

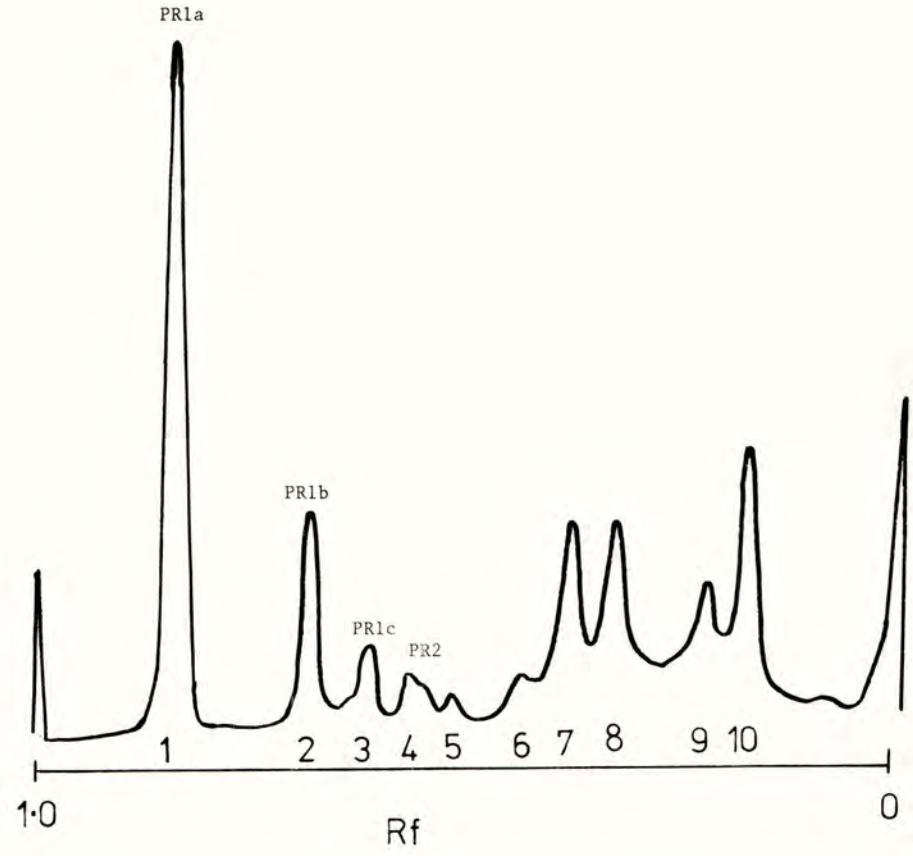
Viruses are transmitted from one plant to another either, and most frequently, by invertebrate vectors or via mechanical damage following physical contact between healthy and infected tissue. Virus spread is most often controlled by killing the vectors but non-insecticidal oil sprays protect plants from infection by aphid-transmitted viruses, (Simons, this volume) although the mechanisms involved are not well understood. However, there is evidence (Peters & Lebbink, 1975) that oil exerts some of its effect directly upon the plant as well as on the transmission process.

In some insect-transmitted-virus host systems a 'helper component' is produced by the plant which enables the insect to transmit the virus (Govier et al., 1977). Myzus persicae is unable to transmit purified PVY to tobacco plants but virus-free leaf extracts from infected plants contain a protein component which allows them to transmit the purified virus. A possible means of control therefore would be to find chemicals which would either stop production of the helper component or interfere with its function.

Figure 1

Gel electrophoresis of extract of TMV infected leaves of Xanthi n.c.

Densitometric scans of proteins extracted, from leaves of Xanthi-nc 7 days after infection with TMV, using pH 2.8 buffer and separated by electrophoresis in 10% acrylamide gels (Antoniw et al, 1980)



SYMPTOM EXPRESSION

The important affect of some viruses on their hosts is not in decreasing yield but in altering their appearance. Beet western yellows virus when it infects lettuce causes chlorosis which makes them unmarketable. Tomlinson et al. (1976) showed that carbendazim, although it does not decrease BWYV infection, multiplication or spread in lettuce, seems to stabilise the host's chloroplasts so that the chlorotic symptom is suppressed and the crop appears healthy. Carbendazim has also been reported to increase the yield, as well as suppressing the symptoms, of rice infected with Tungro Virus (RTV) (Thomas & John, 1980). One problem with symptom suppression is that unrevealed but possibly large reservoirs of virus persist, which could infect untreated crops and other plant species.

CONCLUSIONS

Some progress has recently been made towards the direct control of virus diseases in plants and in a few instances field tests have proved successful; the symptom-suppressing chemical carbendazim is effective against BWYV in lettuce and RTV in rice, and the base analogue DHT inhibits virus replication and increases yield of potatoes infected with PVX and PVY. Little evidence is available on the range of virus diseases affected by these chemicals but it seems likely that it may be limited.

At the moment the most promising use for chemical control is in tissue culture, where ribavirin helps eradicate viruses. The recently-discovered chemicals related to aspirin which induce localised acquired resistance in tobacco leaves may also be effective in this system.

Most plants have effective defense mechanisms which localise some viruses. The most attractive method of disease control would be to design chemicals which activate these natural defense mechanisms thus preventing the systemic spread of the virus. Greater research effort in this area could pay handsome dividends.

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PROSPECTS FOR IMPROVING THE CONTROL OF VIRUS DISEASES OF SUGAR BEET

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Summary The timing of aphicide sprays in sugar beet is currently based upon assessments of numbers of aphids on beet plants over a relatively large area. It is suggested here that local factors which affect aphid activity, rather than their numbers alone, should be used to determine more accurately when to spray. Knowing plant age may permit the prediction of the rate and amount of secondary virus infection, and enable calculations to be made of potential yield loss and optimum spraying times. Such improvements should be fitted into a revised programme of virus control, which may also provide forecasts of rates and timing of viruliferous aphid immigration and distinguish between the two most important viruses, beet yellows and beet mild yellowing viruses.

INTRODUCTION

The aphicide spraying tactics used to control beet yellows virus (BYV) and beet mild yellowing virus (BMYV) are based upon the assumption that a single, well timed spray will usually give maximum economic return (Hull & Heathcote, 1967). Hull (1968) described a spray warning scheme that advised spraying when the numbers of aphids in small, supervised areas of the crop exceeded a given threshold. However, there is evidence that these methods inadequately limit infection by BYV and BMYV (Dunning & Winder, 1976 ; Dunning et al 1977). Variation in many factors, such as the numbers and time of arrival of viruliferous aphids (Myzus persicae), the identity of the viruses, and the sensitivity of individual crops to severe attack, may cause the large spatial and temporal variations seen in infection and in control achieved.

It is necessary to revise the tactics used to control these virus diseases by introducing viruliferous aphid monitoring, developing improved advice on spray timing, and by taking account of cultural factors (Heathcote, 1969, 1972) which may decrease sensitivity of the crop to infection.

Determination of the need for application and correct timing of sprays depends not only on a prediction of potential yield loss due to virus infection but also on an understanding of how the diseases spread. At present, primary infection (by immigrant viruliferous alate M.persicae) cannot be effectively controlled by aphicide sprays, and systemic soil-applied aphicides only partially reduce infection. Secondary infection (which may be due to the dispersal of infection by the apterous progeny of immigrant aphids), however, may be significantly reduced if sprays are accurately timed, or if soil-applied aphicides have persisted since drilling. It is therefore necessary to distinguish the yield losses due to primary and secondary infection before the potential benefit of aphicide use can be predicted (as only the latter is suppressed significantly by aphicide spraying).

Alate M.persicae have often been considered as the most important vectors of BYV and BMYV because it was believed that only winged forms were restless enough to produce the characteristic patches of infection within fields (Watson & Healy, 1953). The progressive radial spread of virus from a focus of infection is, however, more consistent with disease dispersal by apterae which, after alate dominance at immigration, are the most common form in the aphid population while virus dispersal is occurring (Ribbands, 1964). Evidence is therefore needed for the occurrence of dispersive behaviour or restlessness of apterous aphids. It is also thought that secondary virus dispersal occurs during only a relatively limited period (Watson, 1942; Watson & Healy, 1953) because the aphid population declines in the crop relatively early in the season. If, as seems possible, this decline is caused by changes in the host plant, monitoring such changes could lead to prediction of potential virus infection and yield loss.

This paper reports on some of the work which aims to determine the factors that control secondary virus spread and to determine how these factors can be measured simply enough for them to be considered when decisions are made locally on when and whether to spray. Two examples are given, the mechanism of aphid dispersal, and the timing of secondary virus spread.

METHODS

a. The mechanism of aphid dispersal

Sugar-beet plants, cv. Nomo, were grown singly in pots in controlled environment rooms at 20°C with 16 h light and 80% r.h. The growth of plants in these conditions closely paralleled that of field plants in the early stages of development (the appearance of approximately 12-14 leaves and the maximum expansion of the first 3 or 4).

Between 2 and 5 first instar nymphs of M.persicae, maintained in clonal culture on sugar beet in the above conditions, were placed on the upper surface of the first true leaf of seedling plants (with 2-4 leaves) and confined to them by acetate barriers coated in PTFE. The area of each leaf, and the positions of the aphids, was recorded daily until the nymphs became adults and reproduced.

b. The period of aphid dispersal within the crop

As part of a field study of M.persicae, the fecundity of adult aphids was recorded. The numbers of advanced embryos (with pigmented eyespots) and immature embryos (without pigmented eyespots) within the ovaries of samples of adult aphids were determined by dissection. Crop growth stage and aphid length were also recorded.

RESULTS

a) The mechanism of aphid dispersal

Eighty eight percent of aphids observed remained on the plants for their development from nymphs to reproducing adults. They did, however, show considerable restlessness, each nymph making, on average, five moves to new leaves during the period. Figure 1 gives a typical result for a single aphid's movements on one plant, with the aphid consistently moving to leaves in the early stages of development. Figure 2a shows, for all aphids, the length of time (expressed as the proportion of total aphid day degrees) that the aphids spent on leaves of different leaf area categories (proportion of final leaf area in 10% increments); it demonstrates that a large proportion of the time when the aphids were observed was spent on leaves in the early stages of growth. However, for much of the experiment, leaves in the latter stages of expansion were not

Fig.1. The period (Day degrees above 2°C) that a single aphid spent on different leaves during its development.

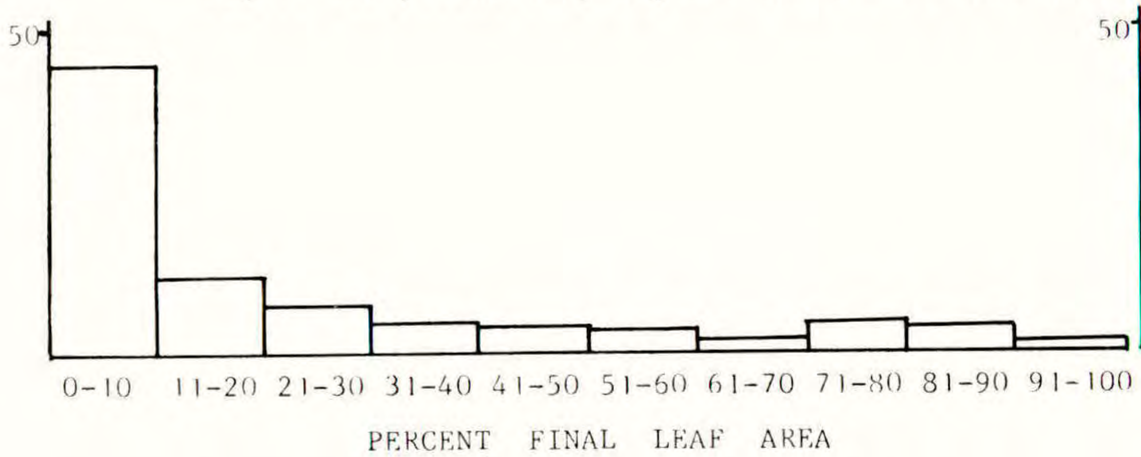

Fig.2a. Percentage of total aphid day degrees spent on different leaf expansion categories.

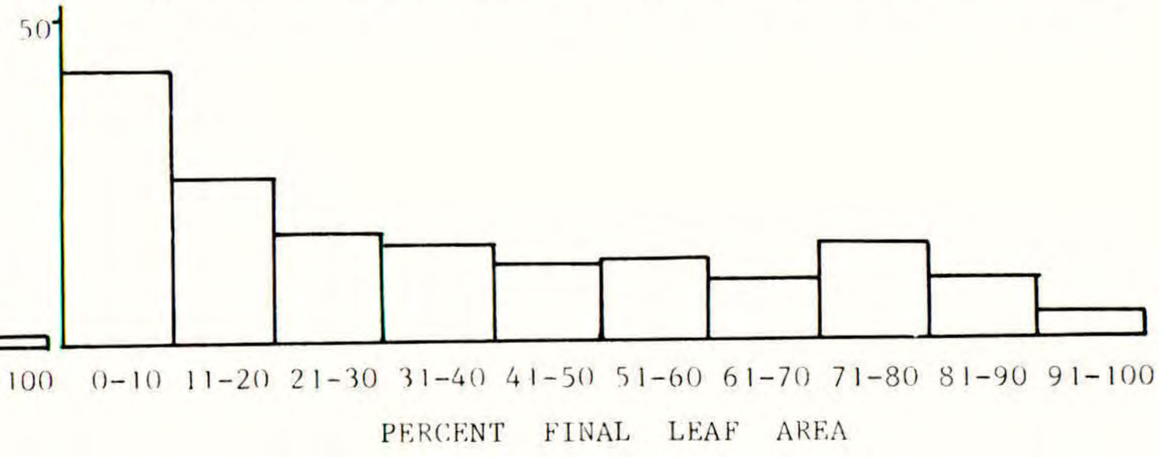

Fig.2b. Percentage of time leaves were in each expansion category that aphids were present.

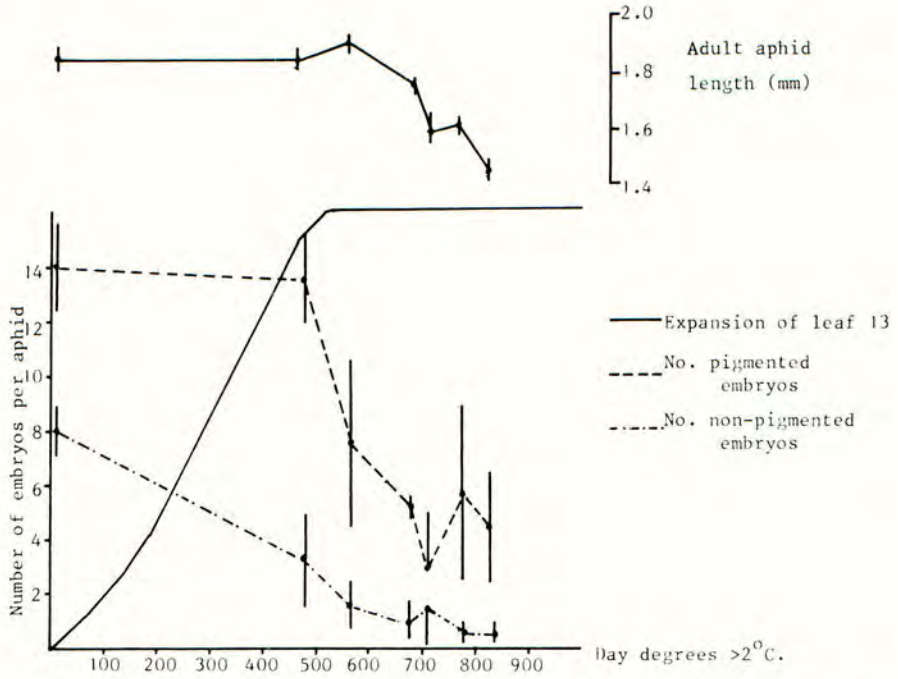

Fig.3. The decline in aphid size and fecundity with increasing plant age.

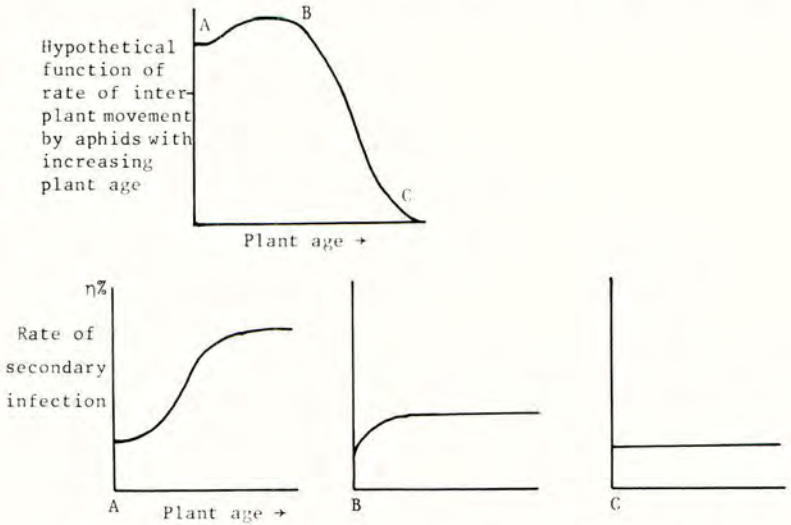

Fig.4. Predicted patterns of secondary virus dispersal by interplant movement of apterous aphids, following primary infection by alate aphids (intercept value), at plant ages A, B and C.

available for colonisation. Figure 2b shows the proportion of total leaf day degrees (number of day degrees above 2°C that each leaf was in a particular growth stage) when aphids were found for each leaf area category. This gives a measure of the response of aphids to the available leaves, but under-estimates the concentration of aphids on the smallest leaf area category (1-10% final leaf area) as it is independent of aphid numbers.

b) The period of aphid dispersal

Figure 3 shows the decline in fecundity and adult aphid size as the plants developed; the period of expansion of the largest leaf (leaf 13) is shown. The population collapsed naturally, but in the absence of predators because all records were made in a predator-free plot which was part of a field experiment.

DISCUSSION

Frequent movements of undisturbed M.persicae have also been recorded by Hodgson (1978) on turnips and Ferrar (1968) on beet. This activity may explain the results of Kennedy et al (1950), who found a bimodal distribution of M.persicae populations on beet; the greatest densities were on either leaves that were rapidly growing or senescing. No senescing leaves were present in the observations reported here; however, aphids did maintain their greatest densities on the youngest leaves by frequent leaf to leaf movements. This restlessness does not constitute proof that apterous aphids will disperse virus between plants because the aphids remained on the same plant for the whole observation period. However, they do show that M.persicae nymphs are restless on undisturbed sugar-beet plants and therefore support Ribbands (1964) and Jepson (in preparation) who found that beet plants in the field were colonised rapidly by apterous aphids, which they assumed were dispersing by walking from plant to plant.

Changes in the nutritional status of leaves may cause these leaf to leaf movements. Harrewijn (1978) reported that a decrease in nutrients or phago-stimulants caused restlessness in M.persicae. The physiological changes described by Fellows & Geiger (1974) and Giaquinta (1978) decrease carbohydrate and amino acid availability, both important aphid nutrients, during the development of beet leaves and may explain the aphid's frequent moves. Joy (1962, 1966 and 1967) found that beet leaves contained higher concentrations of amino acids when young than when mature and this may explain why young leaves are favoured. The mobilisation of amino acids in senescing leaves may explain the preference for these in the studies of Kennedy et al (1950).

If nutritional changes as leaves age are stimulating apterous aphids to disperse from leaf to leaf and plant to plant, then it is possible that aphid dispersal rate can be accurately predicted. The amount of this dispersal will depend on both the rate of aphid movement and the period over which they disperse.

Watson (1942) found that secondary virus infection rates were slower when crops were infected later in their development and Watson et al (1951) recorded a rapid and synchronous decline between fields in M.persicae populations in the late summer, which they attributed to nutritional changes in the plant. The decline in fecundity recorded here could explain this collapse. Knowles et al (1934) found that the concentration of N in beet leaves declined between May and September. If the nutritional quality of the whole plant declines in a predictable way then the time of the collapse of the aphid population due to declining fecundity may be predicted from records of plant age derived from leaf counts.

It is possible, therefore, that the rate and period of aphid dispersal may be predictable, and that simple measurements within the crop could lead to accurate assessments of the change in aphid distribution if the initial population levels are known. To relate this to virus dispersal and potential yield loss, the identity of the virus, the proportion of viruliferous immigrants, and the dispersal rate of virus in relation to the dispersal of the aphid vectors must be known. Most of these epidemiological factors remain uninvestigated; however, a hypothetical relationship between aphid and possibly virus dispersal rate and plant age can be derived from the present study (Figure 4). If a grower could modify forecasts of primary infection in his area with field specific factors that determine the susceptibility of his crop to that infection, and if he knew the age of that crop (from leaf number), he could, using the relationship described in Figure 4, predict secondary infection rate and potential yield loss. Figure 4 gives three examples where, after the same primary infection, different rates and periods of secondary infection result in different final infections. Rapid spread is to be expected early in crop development (Watson et al 1946; Blencowe & Tinsley 1951), increasing as plants meet. However, as the number of leaves suitable (including senescent) for colonisation on each plant increases, and the aphid population declines, this dispersal rate falls and eventually ceases. Aphicidal sprays applied soon after the peak of primary infection at time A (Fig.4) are likely to give an economic return because the potential amount of virus spread is high; however, sprays applied at times B or C are likely to give low or no economic return because yield loss is likely to be derived largely from primary infections. However, the pattern of primary infection has not been studied. If it was found that viruliferous immigrants entered the crop over a long period, accumulated primary infection up to given times could be used in these calculations, and the estimates of final infection could be modified by subsequent monitoring until spray thresholds were passed.

Until virus monitoring and forecasting are improved, and field specific factors are included in the information used to determine the necessity for, and the timing of, aphicide sprays, it is unlikely that beet viruses will be controlled more effectively than at present. The results of Dunning & Winder (1976) and Dunning et al (1977) are good examples of the serious consequences that can result from basing the timing of sprays on aphid numbers alone.

Farmers are already advised not to apply sprays for control of virus yellows when the crop has more than 25 leaves (Fig. 3). The next step must be to develop predictions of potential virus dispersal in crops of different physiological ages so that potential yield loss and the potential economic return for spraying can be calculated, and the need for spraying determined.

Acknowledgements

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SESSION 7A

CEREAL PEST AND DISEASE CONTROL (II)

Proceedings 1981 British Crop Protection Conference - Pests and Diseases

A REVIEW OF CEREAL PESTS IN THE UNITED KINGDOM

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Summary Although cereal pests in the United Kingdom are less damaging on a national scale than cereal diseases, the recent trend towards early sowing of winter wheat and winter barley has increased the importance of aphid vectors of barley yellow dwarf virus, frit fly (Oscinella frit) and the grass and cereal fly Opomyza florum. Wheat bulb fly (Delia coarctata) continues to be important in many areas. Direct feeding damage by cereal aphids fluctuates in severity according to the numbers and species involved and the time of attacks in relation to plant growth. Grass weeds encourage pest attacks in intensive and alternate cereal husbandry systems. Cereal monoculture has not aggravated pest damage and the threat posed by a number of potential pests has not materialised. Chemical control measures are generally adequate and no evidence of resistance to pesticides has yet been obtained in cereal pests. Seed treatments for use against slugs, which are particularly important in direct drilled cereal crops, are needed. The primary research need is to develop methods of forecasting pest outbreaks in individual cereal fields.

INTRODUCTION

Previous reviews of the status of cereal pests in the United Kingdom (Gair 1967, 1975; Stone, 1977) emphasised that pest damage was less important economically than damage caused by cereal diseases. This favourable situation, true for cereals grown in either monoculture or in alternate husbandry systems, was seen not as a permanent phenomenon but one in which a dynamic balance had been struck between the pests, their enemies and crop growth.

Experience over the past few years has shown that the incidence and importance of cereal pests is closely related to the husbandry of cereal crops. The present status of cereal pests is therefore reviewed against the background of important changes made recently in methods of growing cereals in the UK. Some of these changes have brought relatively unimportant pests into prominence; others have contributed to the decline in status of pests once regarded as being of major importance.

CHANGES IN CEREAL GROWING AND EFFECTS UPON PEST STATUS

Composition of cereal crops

Wheat and barley now dominate the UK cereal scene. The area devoted to oats, rye, maize and mixed corn is very small in comparison and gets smaller each year. Thus in 1979 cereals in England and Wales totalled 3,316,000 ha; of this 1,347,000 ha were under wheat, 1,850,000 ha in barley, while oats, mixed corn and rye occupied 94,000, 13,000 and 7,000 ha respectively.

Those pests which attack oats and rye but not wheat or barley are consequently of little significance nowadays; an example is the cereal race of stem nematode (Ditylenchus dipsaci).

Time of sowing cereals

Autumn-sown cereals occupy an increasingly large proportion of the UK cereal acreage. In 1979 approximately 576,000 ha of barley were sown in autumn and the trend from spring to winter varieties of barley and wheat has continued into the present season.

Of even greater significance is the swing towards early sowing of winter barley and winter wheat. Much of the autumn cereal acreage in 1980 was sown in September and early October and there are strong indications that this trend will continue in future years. As a result, a number of insect pests, some of which used to be of minor status have suddenly sprung into prominence.

The grass and cereal fly Opomyza florum was formerly a sporadic pest of little or no economic importance. Its larvae bore into and destroy the central tissues of cereal tillers which are usually secondary and infertile. In each year since 1979 attacks on winter wheat and winter barley have become increasingly widespread and severe especially in eastern and southern counties of England. Slope (1957) showed that damage is closely related to the time of sowing, earliest sowings (ie before mid October) suffering greatest shoot attack. The place of the cereal crop in the rotation bears little or no relation to the severity of damage by this pest, so that wheat or barley crops following cereals, cash roots, grass or vining peas are equally at risk. Elsewhere in this Conference, Short (1981) discusses in greater detail the recent outbreaks of O. florum, its biology and chemical control.

Frit fly (Oscinella frit) is a multivoltine insect pest of which the autumn generation flies lay their eggs on grass weeds, volunteer cereal plants and perhaps directly on early-sown cereal crops. Damage caused to emerging cereal seedlings was noticeably heavy in the winter of 1980/81 and almost invariably occurred in early-sown wheat or barley following cereal stubbles which had been infested with grass weeds, chiefly blackgrass (Alopecurus myosuroides). Approved chemical control measures are of some value when damage is first seen. Preventive measures applied at sowing might be more effective but would require accurate forecasting methods to pinpoint fields at risk.

Wheat bulb fly (Delia coarctata) is an important pest of winter wheat but can also damage winter barley. Eggs are laid in bare soil and attacks normally occur in wheat following full or bastard fallows, potatoes, sugar beet, onions, carrots or early vining peas. Several workers (eg Bardner, 1968) have shown that early sowing of wheat on land at risk generally produces crops which are well tillered at the onset of larval attack and are therefore able to surmount serious damage. Early sowing remains an important cultural control measure but leads to a high survival rate of immature stages of the pest. Oakley (1977, 1980) has proposed a number of alternative chemical control strategies which protect crops at risk and at the same time lead to a decline in overall numbers of wheat bulb fly.

In early 1981, attacks by D. coarctata were confirmed in winter wheat and winter barley grown in intensive cereal systems. This happened because many farmers harvested their cereal crops early in the favourable weather conditions of July and August 1980 and then immediately cultivated the stubbles before sowing another cereal in September. In some fields, such early stubble cultivation provided acceptable egg-laying habitats for wheat bulb flies and serious damage ensued.

Another insect pest whose importance is enhanced by early sowing of winter barley and winter wheat is the bird-cherry aphid (Rhopalosiphum padi). This is the chief vector of virulent strains of barley yellow dwarf virus (BYDV). Barley and wheat (and other cereals) sown before mid-October are at risk to infection, particularly in years such as 1980 when large numbers of viruliferous aphids migrated from their summer hosts which include grasses - an ubiquitous source of BYDV. A forecasting method based on an 'infectivity index' (Plumb et al, 1981) shows promise in highlighting risk years. Chemical control measures, when correctly timed, are highly effective in reducing the spread of BYDV infection (Plumb, 1977). Synthetic pyrethroid insecticides are particularly useful in this respect (Horellou and Evans, 1979).

Other cereal aphid species, notably the grain aphid (Sitobion avenae) and the rose-grain aphid (Metopolophium dirhodum), are capable of transmitting strains of BYDV from infected to healthy cereal plants. Their importance in transmitting the virus in autumn and spring months has yet to be fully evaluated. Further transmission of the virus in spring months seems to be more important in Wales and south west England than in eastern areas of England.

Choice of cereal varieties

Modern cereal varieties differ little in their susceptibility to damage by many cereal pests. This is rather surprising, as profusely tillering varieties might be expected to withstand or recover from shoot-boring insect larval damage more readily than varieties which tiller sparsely. Many of the recent cases of damage by Opomyza florum in East Anglia involved Mardler wheat but this may reflect the popularity of that variety.

Certain wheat selections including Kador winter wheat have been shown to be partially resistant to grain aphid infestation (Lowe, 1980). Kador has already become outclassed and is no longer grown to any significant extent. However, plant breeders may be able to incorporate some measure of resistance to aphids in future cereal breeding programmes.

A number of spring barley varieties, notably Tyra, which are resistant to races of cereal cyst nematode (Heterodera avenae) are now being successfully grown in infested land. Panema winter oats are resistant to this pest and to stem nematode. Such resistant varieties provide a useful cultural means of pest control, yielding well when grown in infested soils and often preventing nematode numbers from increasing after cropping.

Grass weeds, pre-sowing cultivations and drilling methods

The grass weed status of cereal stubbles has already been mentioned in connection with frit fly damage. Other pests which are attracted to grass weeds for egg-laying purposes and whose larvae may be found in continuous or intensive cereals as well as in cereals following grassland include crane flies (Tipula spp., larvae = leatherjackets) and swift moths (Hepialus spp.). As noted by Stone (1977), attacks by wireworms (Agriotes spp. larvae) have become more noticeable in recent years. The extent of wireworm damage is still very small in comparison with that which occurred before the introduction of organochlorine insecticides.

Methods of straw disposal and pre-sowing cultivations influence the severity of attacks by certain pests in the following cereal crop (Edwards 1975, 1977). Stubble burning is a useful hygiene control measure. Frit fly larval attacks in autumn-sown cereals are often worse in those parts of a field in which the preceding stubble was not effectively burned.

Inefficient ploughing of grass or of gress-infested stubbles increases the risk of BYDV infection in the following cereal crop. Direct drilling often increases the risk of slug damage on medium and heavy soils but conversely may lessen the risk of frit fly damage and favours earthworm burrowing activities (Edwards, 1975).

Fertiliser practice

With the introduction of stiff-strawed cereal varieties and/or the use of growth-regulating chemicals such as chlormequat, many farmers have adopted European continental methods of growing cereals and apply large amounts of nitrogenous fertiliser to their crops. Baranyovits (1973) suggested that increasing nitrogen usage was partly responsible for the rise in importance of cereal aphids. Henderson and Perry (1978), Hanisch (1980) and other workers have subsequently shown that the fecundity of some cereal aphid species increases with the level of nitrogen applied to cereals.

Use of cereal fungicides

Most UK cereal crops are now treated with fungicides which are applied as seed treatments, foliar spray treatments or both. Fears have been expressed that fungicides applied at or near ear emergence may adversely affect those entomophagous fungi which help to keep cereal aphids in check. The prevalence of cereal aphids in recent years has been attributed to the widespread use of foliar fungicides. Scientific evidence to support these assertions is lacking.

Use of cereal herbicides

As already indicated, grass weeds constitute a threat to cereals, not only by their competitive effects, but also by encouraging certain pests. Attacks by shoot-boring fly larvae, wireworms, leatherjackets and swift moth caterpillars often occur in fields or parts of fields heavily infested with grass weeds or volunteer cereal plants. The use of effective herbicides to deal with such weed troubles can have important side effects in terms of cereal pest control.

Use of 'tramlines' in cereal crops

'Tramlines' in cereal fields facilitate the passage of ground machines through crops during the growing season. Farmers are now prepared to enter crops at any time to apply chemicals for pest control. Late-season attacks by cereal aphids are easily countered by using ground machines as alternatives to aerial spraying tackle. The ease with which cereal crops can now be treated may explain why so many fields were sprayed unnecessarily against aphids in summer 1981.

OTHER CEREAL PESTS

The United Kingdom, in common with other countries of north-west Europe, has experienced increasing attacks by cereal aphids throughout the 1970s. These culminated in the explosion in numbers of the rose-grain aphid (M.dirhodum) in the summer of 1979. Since that year, attacks by all species on cereals at the flowering stage have been relatively light. Tentative criteria have been set as guidelines for spraying against the grain aphid (George and Gair, 1979) and the effects of direct feeding by this pest on yield and quality of wheat have been investigated (Lee et al, 1981). Further work on the direct injury caused by cereal aphids is needed, particularly for winter and spring barley varieties.

Cereal cyst nematode (H. avenae) has declined both in numbers and importance during the past few years. The use of resistant spring barley varieties (loc. cit.)

has been partly responsible but the natural control exerted by fungal pathogens of the nematode has been considerable (Kerry and Crump, 1977).

York (1980) has shown that cereal root-knot nematode (Meloidogyne naasi) can affect growth and yield of spring barley. In the field this pest affects cereals usually in association with other factors such as waterlogging or nutrient deficiency. It occurs chiefly in Wales and south-west England and its rise in importance may have resulted from the increase in acreage of spring barley in those areas.

Several species of migratory root-feeding nematodes attack cereals in the UK. Spaull (1980) has demonstrated that Paratrichodorus anemones can cause stunting and loss of yield in spring wheat and spring barley. Brown and Sykes (1975) established a relationship between numbers of Longidorus elongatus and yield of spring barley. Other nematodes including Pratylenchus fallax may contribute to yield loss in cereals but only to a minor extent.

DISCUSSION

Annual losses resulting from cereal pest attacks in the UK continue to be smaller nationally than those attributable to cereal diseases. The cereal pest complex is similar to, but less varied than, that of countries on the European mainland. Insect pests such as the saddle gall midge (Haplodiplosis marginata) and the ground beetle Zabrus tenebrioides, both of which are of some importance in Central Europe, are of little or no significance here. In fact, Z. tenebrioides has been found damaging cereals on only one occasion in this country (Bassett, 1978).

Unlike intensive potato growing, cereals grown intensively or in monoculture have still not produced any major pest problems. Pest damage in such systems, as in rotational crops, often arises from the presence of grass weeds which attract a number of egg-laying pest species.

Chemical control methods for use against the UK cereal pest complex are reasonably effective and as yet no problems of resistance to cereal pesticides have arisen. An effective molluscicidal seed treatment is needed for autumn-sown cereals especially in direct-drilled situations on heavy-textured soils.

As Way and Cammell (1979) pointed out, the rational use of pesticides relies on the establishment of economic injury thresholds and forecasting procedures for key pests. These have been developed to a limited extent in the UK and in Europe (eg Iescar, 1977). Our primary research aim should be to continue laying this groundwork as an essential prerequisite for the adoption of integrated pest management techniques for use against cereal pests in this country.

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SESSION 7B

NEW APPROACHES TO THE CONTROL OF SOIL-BORNE PESTS AND DISEASES

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A RATIONAL INTEGRATION OF METHODS TO CONTROL ONION MAGGOT IN SOUTHWESTERN ONTARIO

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Summary The onion maggot (OM), Delia antiqua (Meig.) (Diptera:Anthomyiidae) causes 20-40% damage of onions in Ontario, if left uncontrolled. It developed cyclodiene insecticide resistance quickly and while organophosphorus and carbamate insecticides have been effective, recent data indicate that it is becoming resistant to these insecticides also. Chlorfenvinphos and fonofos remain effective and a few alternative chemicals show promise, with chlorpyrifos recently being registered. Chitin-inhibiting insecticides may have some potential. Pest monitoring techniques have been implemented, generally resulting in a reduction in number of insecticide applications applied. Small-scale field trials suggest that the sterile male technique may have potential. Thirty-nine species of insects and mites have been identified as predators, and four species of insects as parasites of the OM. A technique for mass production of Aphaereta pallipes (Hymenoptera:Braconidae) has been devised and field studies have been initiated to determine the potential of this parasite for OM population suppression.

INTRODUCTION

Soil insect pests cause widespread damage to crops. They have always been difficult to control and, although non-chemical control measures such as crop rotation can be useful, farmers generally rely heavily on chemicals for soil insect control. The early literature on soil insects and their control has been reviewed (Gough, 1945; Lilly, 1956; Harris, 1972). Early efforts to control soil insects using chemicals met with limited success. However, with the development of organochlorine (OC) insecticides, effective soil insect control was finally feasible. Unfortunately many species of soil insects quickly developed resistance to OC insecticides (Harris, 1977) and this, coupled with environmental concerns about the use of these persistent insecticides (eg. Edwards, 1966; Harris and Miles, 1975) resulted in their demise. At that time, the chemical industry was actively developing new insecticides and organophosphorus (OP) and carbamate insecticides were soon available as replacements. While not quite as effective against soil insects, they did provide an acceptable level of control. Recently, some species

of soil insects have begun to develop resistance to some of the currently recommended insecticides (Harris, 1977) and, in some instances, residues of these "non-persistent" insecticides have been reported in environmental samples (Harris and Miles, 1975). With at least some species of soil insects, the useful life of currently recommended OP and carbamate insecticides appears to be limited. There are few alternative chemicals and, with the present public attitude towards pesticides, there is little incentive for industry to develop new soil insecticides. Thus there is a critical need to use currently available chemicals more effectively and to develop, where possible, complementary approaches to soil insect control.

The onion maggot (OM), Delia antiqua (Meigen)(Diptera:Anthomyiidae) is an important soil insect pest (Loosjes, 1976). It has several generations/y, each capable of damaging the onion crop. Measures taken to control OM in North America are probably more extreme than those used for any other soil insect pest. As a result, the OM often serves as an indicator of problems which will eventually arise with other species of soil insects. For several years we have been devoting a major research effort toward development of an integrated approach to OM control. In this paper we will review some of the problems encountered in the past, and some possible approaches to OM control in the future.

CONTROL MEASURES - PAST AND PRESENT

In Ontario, ca. 2000 ha of onions are grown, largely on organic soil, and the annual value of the crop is ca. £5,000,000. The OM, the most important insect pest attacking onions has 3 generations/y. In crop loss studies conducted over 2 y it caused an average of 24, 28, and 40% damage to pickling onions, sets from seed, and dry onions, respectively. This represented a loss of £720, 738, and 920/ha, respectively.

A variety of chemicals was used in early efforts to control OM (Gough, 1945). Mercuric chloride, mercurous chloride, derris + soot, soap suds, carbolic acid, and naphthalene were among the recommended insecticides. A grower using one of these treatments hoped to obtain 30-80% control.

In the early 1950's development of the OC insecticides revolutionized soil insect control. Cyclodiene insecticides, such as aldrin and heptachlor, applied as soil treatments effectively controlled 1st generation OM. Subsequently, a grower would apply one or 2 sprays of DDT to each of the 2nd and 3rd generation peaks of flies. This combination of insecticide treatments usually provided >95% OM control. Unfortunately the remarkable effectiveness of the cyclodiene insecticides was short-lived. In 1958 and 1959 serious outbreaks occurred in the northern United States and in southern Canada - the OM had developed resistance to all cyclodiene insecticides. Resistance also occurred in France, Holland, and England between 1960-69. Resistance levels were very high - x 591, x 356, and x 647 for aldrin, dieldrin, and heptachlor, respectively. There was no cross-resistance to DDT or to OP insecticides such as diazinon (Harris, 1977).

The widespread use of OC insecticides to control OM (and other vegetable insect pests) contributed to an excessive buildup of OC insecticide residues in soils used for vegetable production. In Ontario, DDT residues in these soils were often >20 mg/kg and cyclodiene insecticide residues >3 mg/kg (Harris et al., 1977). and general environmental contamination with OC insecticides was common (Harris and Miles, 1975).

OP insecticides were recommended for OM control in the early 1960's. Seed furrow treatments (SFT) with insecticides such as dichlofenthion and ethion gave acceptable control of the 1st generation, while parathion, diazinon, or naled were applied as sprays to control 2nd and 3rd generation adults. This combination of

insecticides, like the OC insecticides, generally gave >95% control. It is noteworthy that, while one or 2 DDT sprays suppressed 2nd or 3rd generation adults, more OP insecticide sprays were required, presumably because these insecticides were less persistent than DDT.

OP insecticides were effective from 1960 until the early 1970's when growers began to report unsatisfactory results in both Ontario and Michigan. In 1972, strains from both areas were cultured and tested for susceptibility to recommended insecticides. Both strains, already resistant to the cyclodiene insecticides, had developed low-level multiple resistance to OP and carbamate insecticides. The Michigan strain showed a 5-fold level of resistance to parathion and 2 to 7-fold levels of resistance to other recommended insecticides (Harris and Svec, 1976). When it was selected with parathion under laboratory conditions for 20 generations, the resistance level increased to x 24.4. Levels of resistance to other OP and carbamate insecticides increased also (Table 1). In the absence of alternatives, growers applied insecticide sprays more frequently at higher application rates.

Table 1

Resistance levels of a Michigan OM strain, as compared to a susceptible laboratory strain, in 1972 and in 1978 following 20 generations of selection with parathion

Insecticide	Resistance level	
	1972	1978
Parathion	x5.1	x24.4
Ethion	x3.0	x10.4
Fonofos	x5.1	x10.5
Carbofuran	x6.2	x10.1

By 1975, some growers were applying weekly sprays of parathion or diazinon - as many as 20 insecticide applications during the growing season! As predicted from the laboratory selection results (Table 1), field resistance levels increased - the level of parathion resistance in the Michigan strain rose from x 5 to x 10 to x 15 in 1972, 1975, and 1980, respectively; the level of resistance to fonofos doubled to x 10 between 1972 and 1980. Currently, in some onion growing areas in Ontario and Michigan, resistance has reached levels where the use of some insecticides is no longer economical. For example, in Ontario in 1972 there were 6 insecticides available as soil treatments for OM control - dichlofenthion, ethion, fensulfothion, carbofuran, chlorfenvinphos, and fonofos. By 1979, in the largest onion-growing area, the Holland Marsh, only chlorfenvinphos and fonofos were effective.

Although OP insecticides are considered to be relatively short-lived, their increased use by growers to compensate for development of resistance resulted in a second problem - unexpectedly high insecticide residues in organic soils used for vegetable production. From 1964 to 1969, OP insecticide residues in organic soils were low - generally <0.5 mg/kg. However, between 1969 and 1974, residues increased markedly - one survey indicated a 5-fold increase to an average of 2.5 mg/kg total-OP insecticide residues in vegetable soils (Harris et al., 1977). In a more comprehensive study, total OP-insecticide residues in Holland Marsh soils averaged 5.6 mg/kg between 1972 and 1975, considerably in excess of total-cyclodiene residues. The major OP insecticide residue detected in organic soils was ethion - the sole use being for onion maggot control (Miles et al., 1978). Contamination of the Holland Marsh drainage system with OP insecticide residues also was reported (Miles and Harris, 1978).

Our current research program on OM follows 4 avenues of investigation: development of new chemicals; development of pest monitoring techniques; assessment of the feasibility of introducing the sterile male technique; and assessment of the

feasibility of using parasites and predators in an integrated control program.

ALTERNATIVE CHEMICALS

In the late 1960's, at the London Research Centre, we would receive as many as 30 experimental insecticides/y from industry for assessment for activity in soil. Since 1975, we have received an average of 3 experimental insecticides a year - a good indication of lack of interest by industry in developing new soil insecticides. To assess insecticide potential in soil, experimental insecticides are screened in the laboratory (e.g. Harris and Turnbull, 1977) and then promising materials are evaluated in microplot field tests (e.g. Harris et al., 1973). For OM studies, the 1/5000 ha microplots are filled with insecticide residue-free organic soil. Usual cultural practices are followed, the required onion variety is seeded at the normal planting time, and insecticide treatments are applied as required. At the appropriate time, as indicated by monitoring data, a portion of each row of onions in the microplot is infested with OM eggs. This field bioassay technique provides very clear results (Table 2). Chlorpyrifos was registered for use for OM control in Canada in 1980.

Table 2

Control of 1st generation OM attacking pickling onions (8 cm wide rows) with granular SFT of some insecticides

Insecticide	kg a.i./ha	Avg. % plants destroyed
Fonofos	2.2	0.7
Chlorpyrifos	2.2	1.7
Chlorfenvinphos	2.4	4.3
Terbufos	3.4	4.3
Isofenphos	3.4	5.8
Control	-	82.1

Recently, Turnbull (1981) showed, in laboratory studies, that chitin-inhibiting insecticides are active in soil and toxic to OM. Microplot field tests indicated that diflubenzuron applied as a drench can be as effective as chlorfenvinphos depending on rate of application and number of applications (Table 3). Bay SIR 8514 (2-chloro-N-[[[4-trifluoromethoxy)phenyl]amino]carbonyl]benzamide) also showed some promise (Table 3) and further tests in 1981 indicated that it is effective against onion maggot both as a drench and as a granular SFT. Considering the application rates necessary to provide an acceptable level of control it would not be economical to use chitin-inhibitors for OM control at present. However, the unique mode of action of this group of chemicals could be an asset in coping with the insecticide resistance problem, or in designing an integrated pest management programme.

Table 3

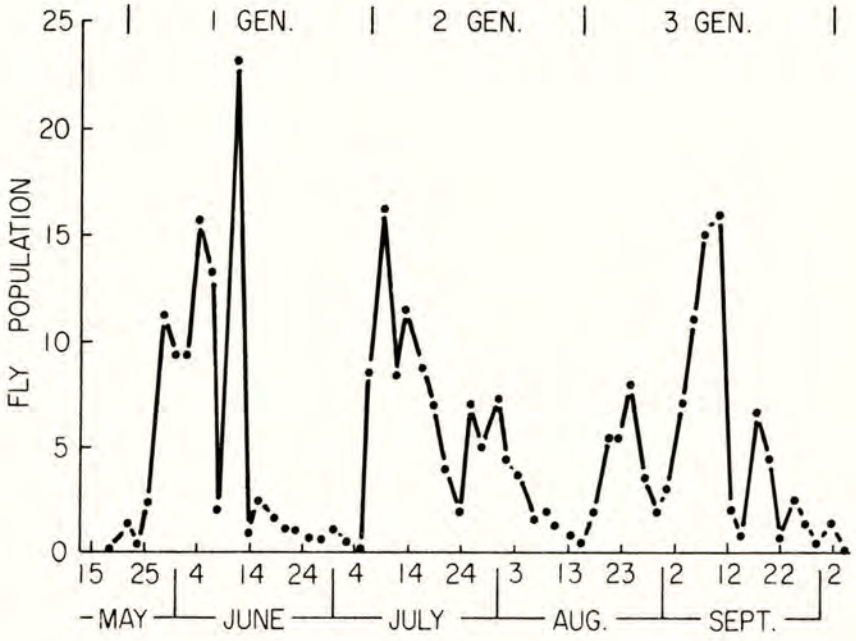
Control of 1st generation OM attacking dry onions (4 cm wide rows) with chitin-inhibiting insecticides. (Courtesy of S.A. Turnbull)

Insecticide	kg a.i./ha	Application Method	Avg. % plants destroyed
Diflubenzuron	0.6 (3x)	Drench	2.3
Chlorfenvinphos	1.1	SFT	4.5
Diflubenzuron	0.6 (2x)	Drench	11.7
Bay SIR 8514	0.6 (2x)	Drench	14.4
Control	-	-	50.5

The development of low-level multiple OP and carbamate insecticide resistance by the OM led growers to apply up to 20 insecticide treatments a season for OM control. It was felt that, with an effective monitoring programme, the number of sprays could be reduced considerably, while still achieving acceptable control. Several methods for monitoring flies were evaluated including sticky traps, degree/day integrators, and flight interception traps. Sticky traps are effective, particularly for small numbers of flies, but time-consuming. Degree/Day integrators (Buckley and McLeod, 1974) are useful research tools but did not perform reliably under practical conditions and were not trusted by growers. Flight interception traps (Loosjes, 1976) were effective, particularly when the number of flies was high (Fig. 1). Using monitoring data, spray recommendations were timed to coincide

Fig. 1

Occurrence of OM flies as monitored with flight interception traps at the Thedford Marsh in 1978 (Fly population=% of population caught/generation at each sampling date)



with peak appearance of the flies. Results of one study illustrating the value of timed, as compared to prophylactic insecticide sprays, are summarized in Table 4.

Introduction of pest monitoring programmes does not always result in such a marked reduction in number of insecticide applications. In the Thedford Marsh, several varieties of onions are grown. Tender, densely planted pickling onions and sets from seed are highly attractive to OM flies and provide an excellent food source for larvae, resulting in buildup of huge populations of flies and enormous

Table 4

Effectiveness of prophylactic vs. timed insecticide sprays in controlling OM attacking dry onions in the Keswick Marsh

Programme	No. insecticide applications		% damage
	Soil	Sprays	
Prophylactic	1	13	<0.5
Timed	1	3	<1.0
None	0	0	58

pressure on the onion crop throughout the growing season. Even with implementation of a pest monitoring programme, from 6 to 9 sprays were required to achieve satisfactory OM control (Table 5). Monitoring programmes for OM have been initiated in 3 major onion growing areas in southwestern Ontario.

Table 5

OM damage to 3 varieties of onions in the Thedford Marsh, 1978

Onion variety	No. timed insecticide applications		% damage
	Soil	Sprays	
Pickling	1	6	0.9
	0	0	30.8
Sets from seed	1	8	0.0
	0	0	30.6
Dry	1	9	0.0
	0	0	22.9

STERILE MALE TECHNIQUE

Development of alternative chemicals and implementation of pest monitoring programmes may extend the usefulness of available chemicals and reduce environmental contamination, but it is obvious that development of alternative methods of OM control is essential. Laboratory studies have shown that OM can be sterilized by irradiation of pupae or chemosterilization of adults (McClanahan and Simmons, 1966; Luckmann et al., 1967) and field tests in Holland using sterile insects have given promising results (Theunissen et al., 1975; Loosjes, 1976). From 1975-79 field tests were conducted to assess the feasibility of using the sterile male technique for OM control in Ontario. The insects were reared in the laboratory on onions using a modification of the rearing procedure of Niemczyk (1964). With the limited facilities available, it was possible to produce from 1-10 million diapause pupae/y. The OM were sterilized by irradiation of pupae or chemosterilization of adults using hempa. Field studies were done in onion fields varying from 3-10 ha. The study was planned primarily as an integrated control programme, with 1st generation OM being controlled with a combination soil treatment for maggots + sprays to suppress flies, followed by release of sterile flies during the rest of the growing season. Results of one experiment in which we compared a chemical control programme using timed sprays based on monitoring data with an integrated programme (3 ha) are summarized in Table 6. Initially, several criteria were used to assess the effectiveness of the sterile insect technique. However, for reasons similar to those discussed by Theunissen et al. (1975), criteria such as the ratio of sterile: wild flies, fertility of eggs, and no. of overwintering pupae were not reliable. Finally, we accepted % maggot damage to the crop as the key measurement of

effectiveness of the control programme. On that basis, the integrated programme was as effective as the chemical control programme (Table 6).

Table 6

Chemical and integrated control of the OM, Keswick Marsh, 1976

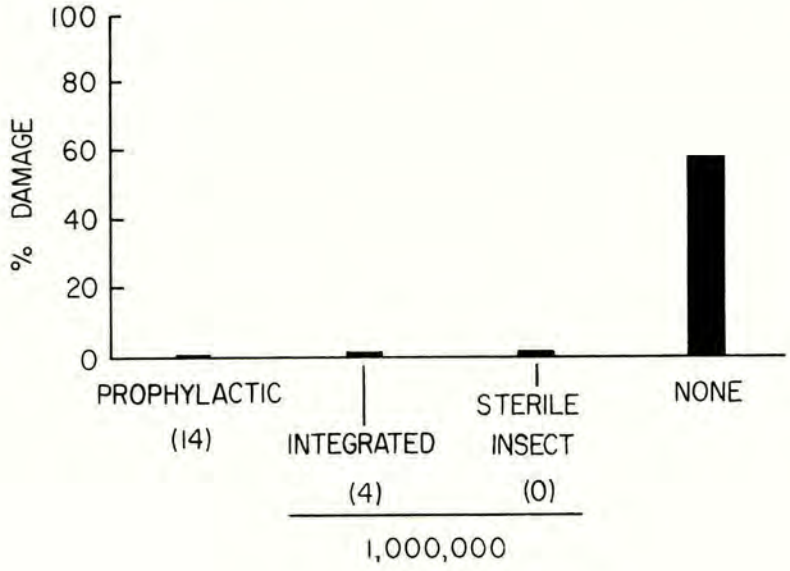
	Chemical	Integrated
Insecticide treatments	7*	3**
No. sterile flies released	0	672,000
Recapture ratio - sterile:wild	-	2.4:1
Avg. % fertility of eggs	87 (58-97)	68 (5-85)
Overwintering pupae/m^2	2.5	0.2
% maggot damage to crop	0.4	<0.1

* Soil treatment + 6 sprays; ** Soil treatment + 2 sprays.

Subsequently, a field experiment was done in which we compared the effectiveness of prophylactic, integrated, and sterile insect control programmes. Both the integrated programme which involved application of 4 insecticide treatments + release of chemosterilized flies throughout the growing season, and the sterile insect programme where no insecticides were applied, were as effective as the prophylactic spray programme where 14 insecticide applications were made (Fig. 2).

Fig. 2

Effectiveness of prophylactic, integrated and sterile insect approaches to OM control, Keswick Marsh, 1977 (1,000,000 sterile flies were released over the integrated and sterile insect plots).



An integrated programme combining timed insecticide applications and release of sterile insects may have potential for OM control. However, results obtained in small-scale field trials are not conclusive and to prove the value of the technique it will be necessary to conduct a large-scale field trial involving an entire marsh. Before this can be done, difficulties associated with mass production of OM must be overcome. This research has been delayed since 1979 pending completion of a mass rearing facility suitable for production of up to 100 million OM/y. Construction of this facility at the University of Guelph was completed in 1981 and development of a suitable mass rearing programme is now underway.

PARASITES AND PREDATORS

Although OM can be produced under laboratory conditions in large numbers, we were not satisfied that these insects were as competitive as the wild strain. We therefore attempted to produce OM under more natural (field) conditions. In mid-September, a cold frame 2 m wide x 18 m long, containing a 15 cm layer of sand was "planted" with onion halves (sliced lengthwise). Sections of the bed were infested over ca. 3 wk with eggs collected from laboratory flies. The eggs were scattered over the onion bed, which was then covered with a sheet of plastic until larvae became established in the onions. Larvae pupated in late October and November. The diapause pupae were left in the cold frame during winter and were washed out and placed in cold storage in April. We were able to produce a million pupae in a single cold frame. Production costs were considerably lower, e.g. using the original Niemczyk technique, it took 1947 man hours to produce one million pupae; with modifications to this method, by 1974, the time required had been reduced to 325 man hours; while using the outdoor technique, one million pupae can be produced with 149 man hours of labour. OM produced using the outdoor rearing procedure appear to be larger and more vigorous than those reared in the laboratory.

Initial experiments on outdoor OM production were done in mid-September to produce diapause pupae. Later, we decided to determine if it was feasible to produce 3 generations a year under natural conditions. We did not expect to obtain pupae in as large numbers during spring or summer, since onions break down more rapidly in warmer weather and we expected greater predator and parasite activity. For the latter reason, we took core samples from the cold frame while the maggots were developing and checked pupae for % parasitism. The results obtained in the spring/summer rearing programme were surprising. In a cold frame which would produce >1 million pupae in the fall rearing programme, we collected ca. 50,000 pupae in the summer. In part, the low survival of the OM was due to the quality of the food source. However, most of the reduction in OM population was due to intense predator and parasite activity. Since that first experiment in 1979, we have extended this technique to aid in the identification of OM predators and parasites. To date we have been able to confirm 29 species of Coleoptera, 5 species of Acari, and 5 other insect species as predators of the OM. Two species of Coleoptera and 2 species of Hymenoptera have been identified as parasites.

One of the parasites was Aphaereta pallipes (Say)(Hymenoptera: Braconidae). It is well known as a parasite of root maggots and its life history and behaviour have been studied under laboratory conditions (Salkeld, 1959). To our knowledge, no effort has been made to mass produce it for release. To our surprise, it has proved relatively easy to culture-using OM as the host we can obtain >40 parasites/larva (avg. 15/larva under mass rearing conditions).

Insecticides used to control onion maggot undoubtedly affect parasite populations. To parasitize OM, A. pallipes adults must work their way through the soil to the OM, i.e., the parasites must pass through the insecticide SFT applied at planting. In addition, the adult parasites can be exposed to sprays used for onion fly control. To determine the effects of these insecticides on the parasites, two laboratory experiments were done: assessment of direct contact toxicity of

insecticides recommended or being considered as OM adulticides; and assessment of soil activity of insecticides recommended or being considered for SFT. Differences in direct contact toxicity of the insecticides to the parasites were quite apparent, e.g., parathion, the most commonly used adulticide was 10x as toxic as chlorfenvinphos or permethrin (Table 7). In the soil tests fonofos, the insecticide most commonly used, was 38x more toxic, and terbufos which has been used experimentally for OM control, was nearly 900x more toxic than was chlorfenvinphos. These results suggest that chlorfenvinphos would be the material of choice in an integrated OM control program.

Table 7

Relative toxicity to A. pallipes adults of several insecticides applied as direct contact sprays or incorporated into organic soil

Direct contact		Soil treatment	
Insecticide	Relative toxicity	Insecticide	Relative toxicity
Parathion	10	Terbufos	897
Diazinon	3	Fonofos	38
Chlorpyrifos	2	Isofenphos	10
Chlorfenvinphos	1	Ethion	3
Permethrin	1	Chlorfenvinphos	1

Field studies with A. pallipes are just beginning. In field cage experiments, the parasite has been very successful in parasitizing OM. A small scale field release using parasitized OM pupae was made in October, 1980. Although done under very adverse conditions, the % parasitism in the release area was ca. 10% compared with <1% natural parasitism in the control area. During the summer of 1981, ca. 3 million parasites were produced for use in 2 field programmes: an integrated programme in which chlorfenvinphos SFT was used, followed by release of parasites throughout the 2nd and 3rd OM generations; and a late summer-early autumn release aimed at obtaining a high degree of parasitization of the overwintering OM population.

DISCUSSION

During the past 25 y, at least 10 soil insecticides have been developed and used for OM control in Ontario. Of these, only 2 remained effective in all growing areas by 1979, and the chances of developing new chemicals are limited. Nothing could demonstrate more effectively the futility of relying completely on chemicals to control an insect pest.

The need to develop an integrated approach to OM control (and to control of other soil insect pests) is obvious. From results reported here and elsewhere, it is apparent that there are other approaches to OM control such as the sterile male technique, genetic manipulation, parasites and predators, and varietal resistance, which merit investigation. However, contrary to the general impression fostered by opponents of chemicals, biological or integrated control measures cannot be introduced overnight. For example, research on development of the sterile male technique for onion maggot control has been underway for 17 y, and it still has not reached the stage where this technique can be widely implemented. Admittedly, research on integrated pest management techniques might have progressed more rapidly if those responsible for funding research believed that oral support=financial support but, nevertheless, the complexity of the research necessary to develop integrated pest management programmes should not be underestimated.

Even if integrated pest management programmes for soil insects such as the

onion maggot are developed, implementation of these programmes will be difficult, requiring close cooperation by all involved. Will a chemical company withdraw a broad spectrum soil insecticide if research indicates that a competing narrow spectrum compound is more desirable? Will growers accept control programmes which may limit their freedom of choice, and involve a greater degree of risk? And will consumers be willing to accept higher food costs to pay for the increased cost of integrated pest management? The era in which we could rely solely on chemicals to control many species of soil insects is drawing to a close. It will be interesting to see how scientists, administrators, industry, growers, and the public respond to the challenge this will create.

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