SESSION 8A

PEST AND DISEASE CONTROL IN FIELD CROPS (II)

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GAPPINESS, SUGAR BEET YIELD LOSS AND SOIL-INHABITING PESTS

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Summary In two sugar-beet crops damaged by symphylids, measurements were made of gaps between plants in insecticide treated and untreated plots. In some treated plots gaps were small and the damage was at random, but in others and the untreated plots, gaps were larger and damage was non-randomly distributed. It is more difficult for a crop to compensate for non-random than for random damage; therefore a non-randomly damaged crop will yield less than a randomly damaged one with the same plant population. To explain some yield differences due to pests which affect establishment, it is necessary to determine the extent to which plant distribution patterns are non-random.

Résumé En deux cultures betteravière affectées par les scutigerelles, on a fait des mesures des vides entre les plantes dans les parcelles traitées et pas traitées. Dans quelques parcelles traitées les vides étaient petites et les dégâts des insects étaient au hasard, mais dans les autres parcelles traitées et dans les parcelles non traitées, les vides étaient plus grandes et la distribution des dégâts étaient non hasard. Parce que c'est plus difficile pour une culture betteravière compenser pour les dégâts non hasard que pour les dégâts au hasard, donc, la perte de rendement sera plus grande. Si donc, il faut expliquer les differences de rendement par les dégâts des enemis des plantules il faut mesurer les effects des vides non hasard.

INTRODUCTION

Much uncertainty is involved in the control of soil-inhabiting pests of sugar-beet seedlings, symphylids (Scutigerella immaculata), spotted snake millepedes (Blaniulus guttulatus) and springtails (Onychiurus armatus). Experiments with soil-applied insecticides since 1968 have shown that damage and success of control varies enormously between sites and between years, even before differences in the effects of various treatments are considered (Dunning, R.A. and Winder, G.H. pers. comm.). Initially, the effects of different insecticides upon yield were recorded but this often produced confusing results. More recently, emphasis has been given to treatment effects on establishment percentage - the percentage of seeds sown which produce plants that will grow to the harvest stage - (Dunning & Maughan, 1978; Bryan, 1979).

Consistent treatment effects are more readily detected on establishment than on yield. Where yield losses occur as a result of soil-inhabiting pest damage they arise from three sources: a low establishment, inefficient use of space due to an excessively irregular, non-random plant distribution and the stunting of individual plants.

If a sugar-beet crop has a low establishment it will necessarily be gappy. It is known that where pest damage is not marked the positions at which seeds fail to produce seedlings tend to be randomly distributed (Jaggard, 1979), i.e. the probability that a seedling will survive is not changed if its neighbour fails.

Soil-inhabiting pests form aggregates in the rows which, with symphylids, can be up to 1m in length (unpublished data). It would therefore be expected that failures resulting from the depredations of soil-inhabiting pests would be non-random and that the probability of a plant surviving is decreased if its neighbour fails. As part of a study on yield loss caused by soil-inhabiting pests, the effects of different insecticides upon plant distribution were investigated to determine if intra-row gaps were occurring in a non-random manner in crops damaged by soil-inhabiting pests and if insecticidal treatments were preventing this. Plant distribution patterns were analysed by comparison to some standard statistical models and the importance of non-random gaps is discussed in the context of insecticidal control of sugar-beet seedling pests.

METHODS AND MATERIALS

Two plots, 30m long and 24 rows wide, were drilled with sugar beet (c.v. Nomo) at Ramsey Forty Foot, Cambridgeshire, on 26 March, 1981, at a spacing of 20cm in rows 50cm apart. One plot was treated with carbofuran at 600g ai ha^{-1} and the other was untreated. On 4 June, 1981, approximately 300 interplant distances from the middle 15m of the 8 centre rows were measured on each plot. The plants were at the 5 to 6 true-leaf stage and the crop could be considered established.

As part of a large experiment on soil-applied insecticides, a trial containing four blocks was drilled on 21 April, 1981, at North Newbald, Humberside. Each block had six plots 15m long and 5 rows wide, five treated with different insecticides and one untreated. All the insecticides were applied in the seed furrow, according to the manufacturers' recommendations, with a Horstine Farmery Microband applicator at the rates listed in Table 1. The sugar beet (c.v. Bush Mono G) was drilled with a spacing of 9.5cm and at a depth of 3.8cm in rows 50cm apart. On 11 June, 1981, the interplant distances between approximately 125 plants from the middle 10m of the 3 centre rows were recorded on each plot, totalling approximately 500 observations per treatment. The plants were in the four true-leaf stage and the crop could be considered established.

At both sites sets of 12 soil cores, 2.5cm in radius and 15cm deep, were taken, the animals contained being extracted later in Rothamsted type controlled gradient funnels. The sets were taken at fortnightly intervals from early March to mid June, at random before drilling and 6 between the rows, 6 in the rows on an untreated observation area after drilling.

Table 1

The rates of insecticides applied at North Newbald

Compound	g ai ha^{-1}
aldicarb	600
bendiocarb	300
carbofuran	600
carbosulfan	1200
aldicarb 80% lindane 20% (UCTL-1)	600

To ascertain if the plants in each treatment were randomly or non-randomly distributed, after damage had been done, the data was tested for the goodness of fit to the geometric series (which models randomness) and to the negative binomial distribution (a general non-random model) using a maximum likelihood computer program (MLP). The geometric series is:

$$p,\ pq,\ pq^2,\ \ldots,\ pq^n \qquad (1)$$

where from any given starting point the probability that the next plant is missing is q, therefore the probability that it is present is $p = 1 - q$, n = the number of observations.

The negative binomial distribution is:

$$P_x = \left(\frac{1}{qk}\right)\left(\frac{(k)\ (k+1)\ (k+2)\ \dots\ (k+x-1)}{x!}\right)\left(\frac{p}{q}\right)^x \qquad (2)$$

where x is the number of gaps i.e. P_x = the probability of finding x gaps in a row and k is a parameter of the distribution, estimated by iteration from (3).

$$N \log_e \left(1 + \frac{\bar{x}}{\hat{k}}\right) - \Sigma\left(\frac{Ax}{\hat{k} + x}\right) = 0 \qquad (3)$$

where N = the number of samples, Ax = the number of observed frequencies of units containing more than x individuals and $\bar{x}$ = the sample mean. The chi-squared test was used to assess the goodness of fit of the data to both models. The chi-squared values thus obtained were then compared, their difference having one degree of freedom, differences greater than 3.84 indicating that the negative binomial gave a slightly better fit ($p<0.05$) than the geometric series.

RESULTS

In Figures 1 and 2 the white columns represent the observed frequencies and the black columns those predicted by the geometric series - Figures 1(a), 2(a), and the negative binomial distribution - Figures 1(b), 2(b), (c), (d), (e) and (f).

Figure 1

Intra-row seedling failures at Ramsey Forty Foot

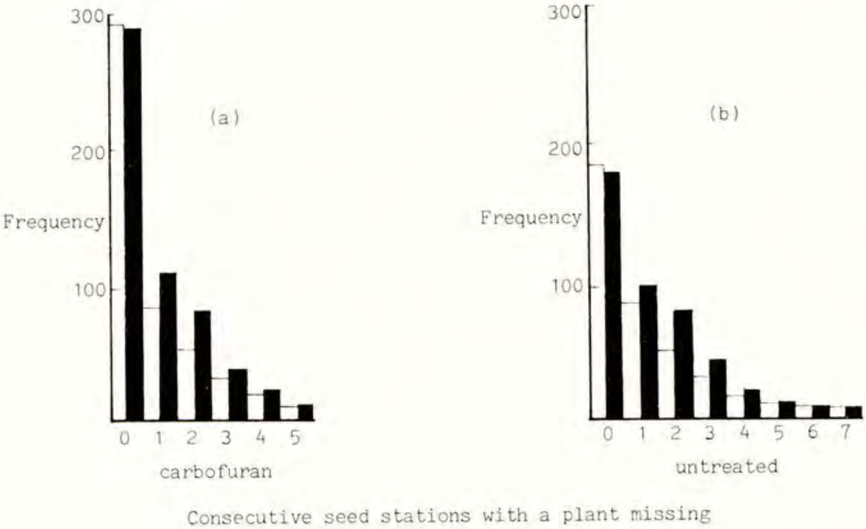
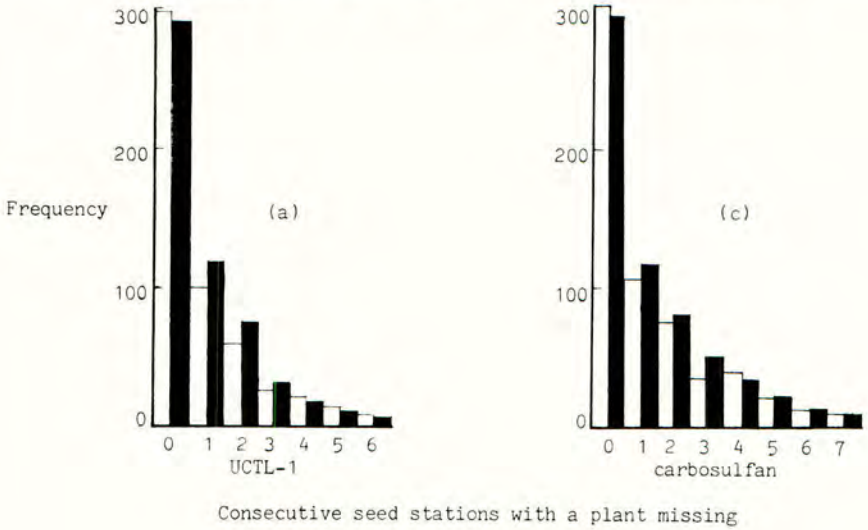
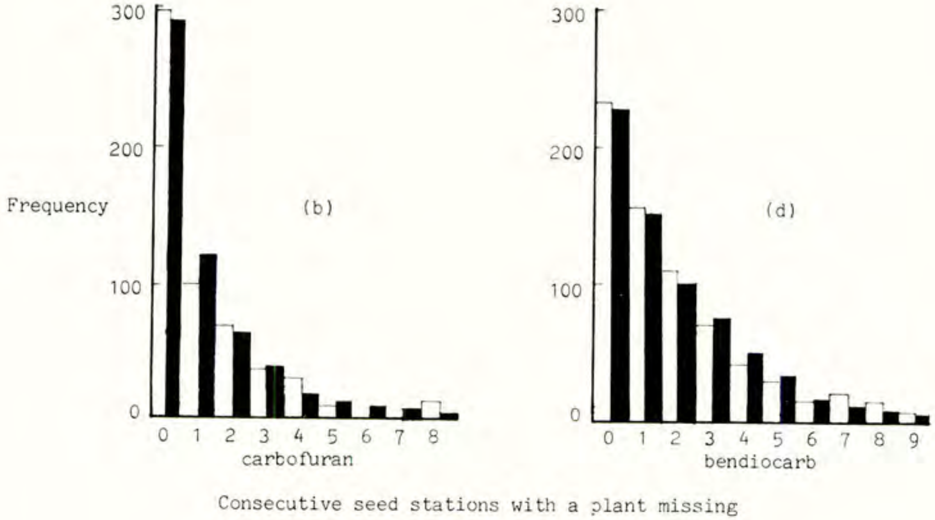
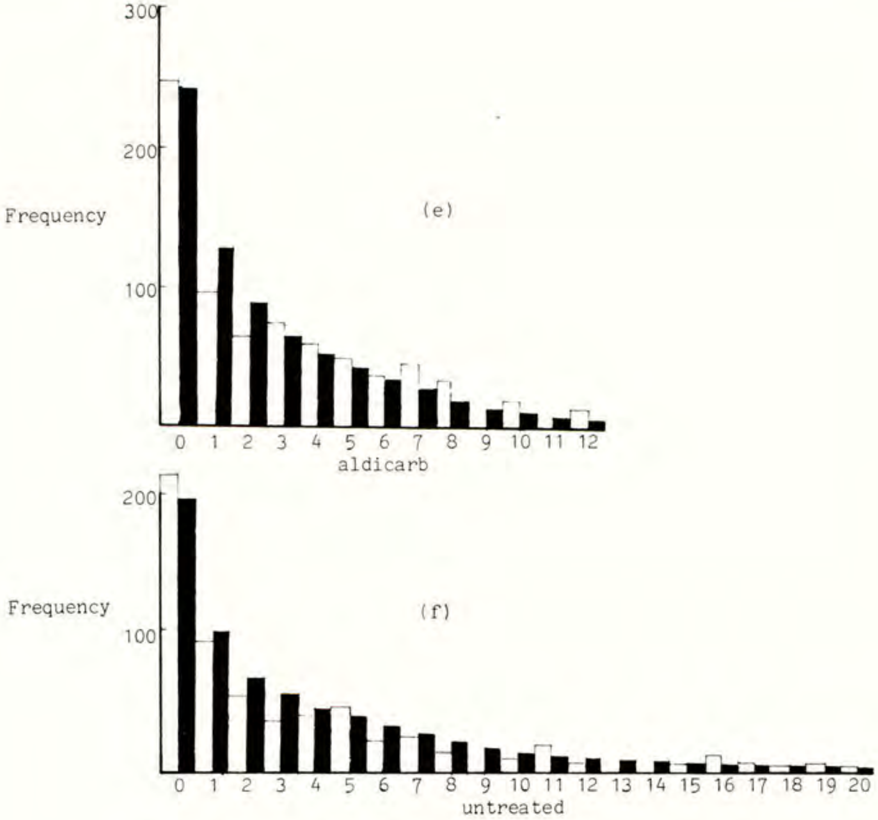


Figure 2

Intra-row seedling failure frequencies at North Newbald







Consecutive seed stations with a plant missing

Table 2

Chi-squared values for fitting the models to the data from North Newbald

Treatment	Geometric χ^2	d.f.	Neg.Bin. χ^2	d.f.	Difference (1 d.f.)	Significance of difference
UCTL-1	9.78	5	5.91	4	3.87	n.s.
Carbofuran	26.98	7	20.68	6	6.30	$p<0.02$
Carbosulfan	40.76	6	34.28	5	6.48	$p<0.02$
Bendiocarb	50.22	10	49.88	9	0.34	n.s.
Aldicarb	90.64	11	73.61	10	17.08	$p<0.001$
Untreated*	201.33	12	133.98	11	67.35	$p<0.001$

* Due to an excessively long tail to the distribution, some of the values have been pooled.

Table 3

Chi-squared values for fitting the models to the data from Ramsey Forty Foot

Treatment	Geometric χ^2	d.f.	Neg.Bin χ^2	d.f.	Difference (1 d.f.)	Significance of difference
Carbofuran	24.22	4	23.99	3	0.23	n.s.
Untreated	96.95	6	87.80	5	9.15	$p<0.01$

DISCUSSION

The chi-squared values obtained when fitting both models to the data suggest that there is a significant difference between the data and both models. This is misleading because high chi-squared values are inevitable when much of the data is either high or low in frequency, as it is in this study. To overcome this problem the differences between chi-squared values were calculated for each treatment and tested for significance. If the value obtained was greater than 3.84 then the fit of the two models was significantly different and the negative binomial judged to have given the best fit (as for all treatments it yielded a lower chi-squared value than the geometric series). If the value obtained was less than 3.84, then the fit of both models to the data was not significantly different and the simplest explanation of the data, the geometric series, has to be accepted as there is no justification for accepting the negative binomial, the model with more complex assumptions. When the negative binomial gave the best fit to the data, the plants could be considered to have a non-random intra-row distribution; however,when there was no significant difference between the fits given by the models, the geometric series was accepted and the plants assumed to be randomly distributed within the rows.

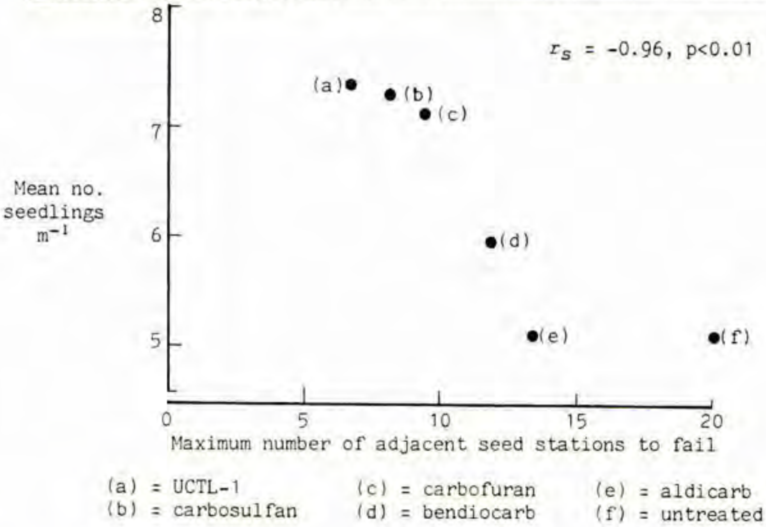
The plots at both sites had populations of the symphylid S. immaculata, many of which were found with plant material in their guts. Many seedlings had small black pits in the roots, characteristic of feeding by these animals; it seems that this symphylid was the prime cause of plant loss. Juvenile S. immaculata came to within a few centimetres of the soil surface in late April at Ramsey Forty Foot and in early May at North Newbald. Soil samples taken at the time showed that initially the symphylids were distributed at random, however, as they grew they began to aggregate in the rows and feed on the growing sugar-beet seedlings; young adult females in particular were always found in samples taken from around sugar-beet plants (unpublished data). It is rare for the feeding of a single symphylid to kill a seedling; most deaths would occur from the attentions of several. The non-random distribution of these injurious animals would be reflected in a non-random distribution of damaged and dying sugar-beet seedlings.

At Ramsey Forty Foot, the plants in the carbofuran treated plot were shown to have a random intra-row distribution, as would be expected in the absence of extensive depredations by soil-inhabiting pests. However, the untreated plot has a non-random intra-row plant distribution. In the UCTL-1 plot at North Newbald, the intra-row distribution was also random. None of the other treatments, except bendiocarb, appeared to prevent non-random intra-row plant distributions, suggesting that contagious soil-inhabiting pest damage was responsible for the observed distribution of gaps.

Figures 1(a) and (b) and 2(a) and (f), show that the obvious difference in seedling failure frequency between successfully treated and untreated plots is the length of the tail of the distribution. The lengths of these tails were plotted against the mean number of seedlings per metre observed for each respective treatment (Figure 3). In all cases it appeared that pests were responsible for the damage and that the lengths of the distribution tails recorded were not due to isolated, chance events such as drill misses.

Figure 3

The relationship between seedling density and the maximum number of adjacent seed stations to fail at North Newbald



To correlate the recorded density of seedlings with the length of the tails of the gap frequency distributions (the extent of gappiness), the observations were ranked and the Spearman rank correlation coefficient (r_s) was calculated; r_s was chosen as it can be calculated without making any assumptions about the distribution of the variables. Seedling density and the extent of gappiness were found to be significantly and negatively correlated (r_s = -0.96, p<0.01).

Gappiness would be expected on treatments with low plant numbers; however, it is interesting to note that the extent of gappiness was much greater on the untreated plots than on the aldicarb treated ones, although plant numbers were similar. Aldicarb did not prevent the loss of plants and non-random damage but it did prevent the loss of excessively long runs of seedlings. This is, perhaps, due to its stupefying effect on soil insects, which would prevent the aggregation of symphyiids.

Table 2 shows that there was no significant difference between the fits of the random and the non-random models to the bendiocarb data. The two treatments ranked immediately above and the two below all had a non-random plant distribution at North Newbald (Figure 3), therefore there is some justification in assuming the non-random model for bendiocarb.

The sugar yield of crops adequately supplied with nutrients and water is primarily determined by the amount of solar radiation intercepted by the foliage in the growing season (Scott & Jaggard, 1978). Any reduction in this interception caused by incomplete ground cover by the leaf canopy carries obvious yield penalties; the plant losses described above tend to decrease the amount of ground cover. Jaggard (1979) has shown that large gaps are incompletely exploited by adjacent plants and that yield is lost through irregularity. These losses were relatively small in Jaggard's experiments but he studied plant distributions much less irregular than those which are commonly found at pest damaged sites. Thomson (1956) has shown that losses due to extreme irregularity can be substantial. In an irregular crop in which contagious, non-random pest damage has caused long gaps, individual plants grow to greatly differing sizes because some experience little inter plant competition; this makes the crop more difficult to harvest mechanically and thus increases losses due to non-randomness.

Losses associated with the stunting of growth, rather than plant death, were not assessed in this study. Milford et al (1980) have shown that small increases in leaf cover during May can increase final yield considerably, by using more of the large amount of radiation available in that month. Small changes in plant growth during this month, when the pests are active, could be expected to affect yield even if the plants are not killed. Only data from plots infested by and free from pests, at the same site, can be used to investigate this phenomenon.

Insecticidal treatments acted with differing success on establishment losses and on the extent of gappiness in two sugar-beet crops. UCTL-1 and carbofuran so reduced damage that if it did occur it was largely at random and most gaps were short. Carbosulfan did not prevent non-random damage but restricted plant loss and the degree of gappiness. Though bendiocarb appeared to prevent non-random damage, gappiness and loss of plants was greater with this and aldicarb than with the other treatments. All treatments seemed to confer some advantage over the untreated plots.

The longer term aim is to explain apparent anomalies in yield data from soil-inhabiting pest damaged sites and to allow damage and economic thresholds to be calculated by an understanding of the effects of plant loss and stunted growth.

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SESSION 8B

PEST AND DISEASE CONTROL IN FRUIT AND HOPS

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THE PLACE OF NEW SYSTEMIC PESTICIDES IN FRUIT AND HOP MANAGEMENT

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Summary The application of pesticide research to practical fruit and hop growing has to be timely. At present, the grower is faced most significantly with the need to produce a high quality product whilst management costs are kept to a minimum. These are seen as the most important of the aims of research into the use of chemicals (including studies of application technology and chemicals with growth regulator properties).

Current practices in orchards are reviewed and the impact of new compounds and techniques on them is discussed. Likely future objectives for research are listed, and priorities for the present need to reduce management costs and improve produce quality.

INTRODUCTION

My job is as a consultant/adviser to five companies comprising some 4000 acres (1600 ha) of top fruit and soft fruit and 320 acres (128 ha) of hops. All the farms are situated in the North Kent/East Kent area of England and are on very uniform soil, largely Thanet bed or brick earth.

In my role as consultant to the five farming companies it is my aim to maintain close links with Research and Development world wide, but as Gerry Chandler is quoted as saying, "Research funding is like seed in a bag, its only good if you sow it carefully, cultivate it and harvest it at the right time". Taking up the results of research is important, but timing is more important. At the present time the greatest importance is attached by growers to research which will give rise to enhanced product quality.

The over-supply of fruit and hops is constantly giving concern in the world market place and to the fruit grower. This gives rise to further concern when it comes to making a viable return on his investment. It would however probably be more correct to say that the real problem today is one of lack of quality as well as an embarrassment of fruit! Two completely opposite parts of the world have been the source of reports which endorse the comment just made. Firstly, from the General Manager of the Deciduous Fruit Board: "There is no question that we are in the front line in this regard. I sense a movement away from preoccupation with cosmetic (appearance) qualities of fruit to a preference for real taste qualities. In this regard what is now considered a weakness may become our strength". Secondly, in the Washington Tree Fruits Commission Report on grower funding for Research in 1981 it was reported that some 140,000 dollars were set aside for Pathological and Entomological matters, 27,000 dollars for management of systems that enable growers to produce more fruit, and 4,800 dollars on the influence of storage on quality of fresh and processed apples. I would suggest that this shows that, in two very large producing areas of the world, quality is currently seen to be of paramount importance. Nothing perhaps very startling in all this, other than that there are clearly too many ordinary apples being produced and in no way can the fruit grower afford to take a risk with a chemical programme that jeopardises fruit quality.

Today, therefore, the fruit and hop industry more than ever has been forced to recognise higher costs of production with a shrinking profit margin but at the same time is forced to strive to produce more "Quality Product".

THE AIMS OF CHEMICAL USAGE AND SOME RECENT DEVELOPMENTS

The growing industry has a number of aims, and pesticides, in their widest sense, must try and meet all those aims by providing:

1. Regular crops.
2. Freedom from pest and disease.
3. Quality, colour, shape and size appropriate to the current market.
4. Cost effective programmes.
5. Ease of management decisions.

Many of the factors relating to growing generally interact and no one season is the same as another. For example the spring and summer of 1980 and 1981 had different numbers of Mills periods and incidence of apple scab (*Venturia inaequalis*). A.D.A.S. Pest and Disease intelligence reports in the South East recorded the following numbers of Mills periods between the start of the season and mid-July:

	1980	1981
Manston	33	41
Hurstmonceaux	42	31

In the previous 10 years before the 1981 scab outbreak apple mildew (*Podosphaera leucotricha*) had been the main problem in the orchard. In 1980, mildew levels were generally low. This illustrates that the grower must monitor all aspects of his aims if he is to produce what the buyer requires, and at the same time consider the effect of any one action on the future. In attempting to deal with any issue the other equally important aims must not be overlooked and the absolute requirement for fruit or hop quality is the fact of life!

The use of pesticides in modern fruit growing has been further complicated by the growing industry's desire to cut costs where possible. Moreover there are new roles for chemicals, e.g. Mesurol (methiocarb) as a bird repellant or Bayleton (triadimefon) as a growth regulator (Professor D. Strydom, Stellenbosch University, South Africa - trial development on plums, pears and apples in Western Cape; one seasons work by the author on Cox). There is new pressure from environmentalists for integrated and supervised pest and disease control, the latter in fact practised by some growers for a number of years before being given the name "supervised". Gone therefore, are the days when a timed or scheduled programme of sprays by growth stages is used. The grower today should be observing the development of the plant in relation to the pest or disease and this may mean very different action according to time of season or growth and is where a true systemic pesticide will fit in.

More recently still, a fresh look at VLV has begun, because of potential savings in chemicals and a new interest by the agricultural engineers in design of machinery to apply rates of 4 - 6 gallons per acre (45 - 55 litres per hectare). Moreover certain well known chemicals such as sulphur (reformulated) have been shown to have a profound effect on modern growing techniques (on crops such as Bramley apples, pears and sugar beet) and have given enhanced yields at reduced cost. On our farms we are experimenting with a liquid sulphur product for the control of apple mildew *(Podosphaera leucotricha)* and apple/pear scab *(Venturia inaequalis)* on such varieties as (apples) Bramley Seedling, Elstar, Golden Delicious, Jonagold, and (Pears) Conference and Comice. Even in a season such as 1981 when good spray machinery and a regular 7 - 10 day programme were adopted very substantial cost savings were obtained.

CURRENT PRACTICES AND THE IMPACT OF NEW TECHNIQUES

In general our programme starts in the autumn with urea to clean up. We then apply 2 - 3 sprays to eradicate disease commencing at bud burst, e.g. Melprex (dodine acetate) or Delancol (dithianon). This takes us up to pink bud (or white bud on pears). According to the season we then turn to a protectant programme spraying every 7 - 10 days. In the case of apple, spraying against mildew continues until mid-August.

Our policy at the present time, especially at the commencement of the season is to maintain a good spray cover when growth is rapid, and scab and mildew can colonise unprotected leaves and fruitlets. Going beyond a 10 day schedule can be very dangerous. The immediate damage is downgrading of the fruit, in the long term an increase of inoculum and three years of worry! We have seen that if we start a season with more than 5 - 6% primary mildew infection we pay a heavy penalty in fruit quality.

Our results to date with VLV have shown that those orchards that have been sprayed with this technique for 2 - 3 years have a noticeable increase each year in primary mildew infections. This may call for a revised attitude to dormant season sprays.

Later in the spraying season it is often possible to lengthen the spray timing schedule largely due to the slowing down of growth. A true systemic fungicide has not been available to fruit growers to date, and many systemic insecticides have had a short life due to resistance problems, especially on hops and apple mildew, e.g. Benomyl, hop/damson aphid products. The future is not easy to forecast, materials are coming forward, but their effective life is always in question and maybe the more promising outlook is mixing of chemicals, e.g. mephosfolan/endosulfan. Resistance is a very complex problem to the fruit and hop grower as it affects his quality and his pocket.

Probably the biggest aid to any spray programme is a knowledge of the pests or diseases present, and to this end the supervised spray control technique has assisted the fruit and hop industry greatly. The threshold levels of any pest or disease must be varied, having regard to the particular farm's history, and it is important that a record is maintained of when spraying occurred, what was used, and the degree of infection. Such past records can be very useful when agreeing the programme to be adopted in the following season. Records from the packhouse can give a great deal of information and should not be overlooked.

Integrated pest and disease control is in the development stage: in many instances the grower does not have sufficient confidence to rely on disease control against a particular level and it puts much greater pressure on crop management. We reckon that one man can manage about 20 acres (8 hectares) a day determining what levels have been arrived at. Also due to the relatively few materials that can be used, our experience is that the programme finishes up more expensive. The two publications put out, one by the E.E.C. Working Party on Integrated Control, "Les Organismes Auxiliares en Verge de Pommiers" and the Dutch publication "Verantwoorde Bestrijding van Ziekten en Plagem op appel en peer" (A. van Frankenhuyzen and P. Gruys) together with the mildew recording system developed by D. Butt at East Malling Research Station and since adopted by the Agricultural Training Board, have gone a long way to give confidence in the development of supervised control.

The modern requirements of fruit and hop farming are very demanding on any pesticide and due to cost of development by the chemical industry and the fact that our demands are small in terms of their gross sales, it is important that we understand the problems of resistance and spray cover in order to preserve the new active materials for as long as possible. A big field in which a lot of doubt exists is in "volume of wash", sprayer efficiency and speed of travel.

This is all the more important as we reduce the amount of water used when spraying. "Volume of wash" is the amount of chemical that has to arrive at the target and its mode of action. "Sprayer efficiency" is the machine's ability to project the pesticide to the target and "speed of travel" the expectancy that cover will be achieved. The lack of understanding that exists on any of these points results in poor cover and a more rapid build up of resistance. Hopefully the work of Morgan at Long Ashton Research Station, Matthews at Silwood Park and Bukovac at East Lansing will give an answer to these doubts. In the case of hop damson aphid *(Phorodon humuli)* where resistance to chemical is not uncommon in three years the question of cover is extremely important.

FUTURE OBJECTIVES

If we now turn to the aims we should try to achieve for the future:-

Regular crops There is no doubt that they can be manipulated by modern chemicals and in some instance varying rates can alter the role of the chemical in question. Thus Bayleton (triadimefon) a mildew fungicide, at changed rates becomes a growth regulator. Mesurol (methiocarb) a miticide, gives interesting results as a bird repellant. CCC (chlormequat), as used in Holland at low rates throughout the season, increases set and fruit size in pears. Alar (daminozide) at low rates in late July/early August on apples increases bud development for the following year, but also appears to reduce the amount of primary mildew infection in the terminal buds thus reducing primary infections in the following year.

Pest and disease freedom It has already been made clear that clean fruit of high skin quality can only be accepted by the fruit growing industry. Apple scab and apple mildew are still the two major diseases. Aphids are the main pest of hop growers and the various tortricids which degrade produce quality a problem on some apple and pear sites.

Quality The importance of this for the future has already been mentioned. Some chemicals that result in very good leaf quality may in fact reduce fruit colour due to shading but good leaf can also result in good fruit quality, size and shape. In fact, chemicals that cause some effect to leaf usually affect quality.

Cost Effectiveness Any chemical must obviously be cost effective, but cost cannot be the prime objective without all the other criteria having been satisfied first. The first and foremost role of any chemical is to carry out the task allotted to it. Pest or disease resistance which reduces cost effectiveness is a very real problem for the grower to contend with.

Ease of management decisions This is probably as important as anything to do with the whole role of modern pesticides. The fruit grower today has a small regular labour force, e.g. 1 man to 30 - 40 acres (12 - 16 ha). Spray timing is important relative to disease or pest control and for this reason supervised spray management is so attractive. By the proper understanding of the target being aimed at and by efficient usage, savings can be achieved. The volume any one chemical will work at efficiently needs much investigation, e.g. ethrel (ethephon) works at VLV rates, Alar (daminozide) is a failure.

PRIORITIES FOR THE APPLICATION OF RESEARCH

In the immediate future we have to decide the part VLV is going to take in management and the role of the "chemical growth manipulators" e.g. Alar, CCC, Bayleton and PP333.

VLV spraying is in an experimental phase. The provision of new chemical formulations and machinery able to supply 4 - 6 gallons per acre (40 - 60 l/ha) is necessary before it will go ahead as a normal commercial practice. Tree crops present very different targets from row crops for the droplets and until we understand how the very low rates of chemical arrive at the target VLV must remain experimental. It cannot be doubted that very real savings would be made for example with insecticides applied at 25% normal rate in 4 - 6 gallons of water. 750 acres (300 ha) sprayed with Dursban (chlorpyriphos) using this technique would save £1500! However VLV will not be adopted unless it will also control diseases, e.g. apple mildew and apple/pear scab, since the cost of tooling up with machinery for the higher volumes and VLV simultaneously would be too great. Obviously a machine with dual roles would get over this problem and we hope to try out such a machine in 1982.

Maintaining a seven day programme on a 750 acre (300 hectare) fruit farm requires 10 sprayers travelling at 4 m.p.h. (7 km/h) applying 30 - 50 gallons/acre (300 - 500 l/ha) so a systemic pesticide that could be applied via VLV would generate very real savings in terms of machinery requirements since a modern fruit tree sprayer costs around £3000 and a tractor of sufficient power £7500.

The old way of applying a single spray to control growth with resultant strong growth when the chemical had worn out, or very high rates and often biennial cropping or storage troubles is not commercially viable. However the more recent uses of the old chemicals such as Alar (daminozide), CCC (chlormequat) as a series of sequential sprays or at different stages of plant growth have opened up the whole field to another approach of chemical management.

In this context the experimental chemical PP333 can be claimed as a true "chemical pruning agent" and its action in controlling growth, reducing the risks of apple mildew and inducing the cropping of pears by limiting growth at the fruitlet stage, opens up the prospect of a new era in crop production.

Whatever new lies ahead, the prospect of quality is the key to success and a greater percentage of the crop must be first class fruit of the size demanded by the consumer; anything less than this is failure.

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NEW APPROACHES FOR CHEMICAL DISEASE CONTROL IN FRUIT AND HOPS

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Summary During the last decade a number of fungicides with unique biological properties has been discovered which are able to penetrate host plant tissues and so exhibit curative control of major pathogens of apple, grape and hops. Such properties, largely characteristic of compounds which are transported in the vascular system of plants, offer new approaches to traditional methods of chemical control.

Under this general description, the compounds can be separated into two distinct groups, those with a broad spectrum of activity and those which are specifically active against Oomycetes. In the latter group are 3 representatives of 3 different chemical classes which have already been introduced into general practice.

The former group comprises a number of fungicides belonging to the chemical classes of triazoles and pyrimidines, some of which are already in the market. Several of these show curative activity at extremely low rates. The properties of the new fungicides and the novel ways in which they can be used for disease control in apples, grapes and hops are presented and discussed.

Résumé Pendant la dernière décade un nombre de fongicides possédant des propriétés biologiques uniques furent découverts. Ils sont capables de pénétrer dans les tissus de la plante hôte et permettent ainsi un contrôle curatif des pathogènes sur pommes, vignes et houblon. De telles propriétés, très caractéristiques à ces produits dont le transport s'effectue dans le système vasculaire des plantes, offrent de nouveaux moyens de lutte qui apportent un progrès aux méthodes traditionelles de lutte chimique antiparasitaire.

Sous cette description générale, ces produits peuvent être separé en deux types de groupes, ceux possédant un large spectre d'activité et ceux ayant une activité spécifique contre les Oomycètes. Dans ce dernier groupe existent 3 représentants de 3 différentes classes chimiques qui sont déjà introduits dans la pratique.

Le groupe précédent comprend un nombre de fongicides appartenant à la classe chimique des triazoles et pyrimidines dont certains se trouvent déjà sur le marché. Plusieurs de ces composés montrent une activité curative à des doses très réduites. Les propriétés de ces nouveaux fongicides et les récentes méthodes de lutte des maladies sur pommes, vignes et houblon sont présentés et discutés.

INTRODUCTION

The history of fungicides can be divided into a number of eras, the key dates and events of which can be identified as follows : 1982 - discovery of the Bordeaux mixture as fungicide active against Downy Mildew on grapes, 1934 - fungicidal properties of the dithiocarbamates were discovered. These were the first synthetic organic fungicides. Early 1950's - introduction of the phthalimides, which like the dithiocarbamates have only protectant activity.

In the early 1960's the first systemic fungicides were synthesized, and about 10 years later, a number of new systemic fungicides was discovered.
These can be divided in two groups :
- the fungicides active against Oomycetes, or more precisely, against the Peronosporales
- the ergosterol-bicsynthesis inhibitors (or sterol-inhibitors), active against major plant pathogenic Asco-, Basidio- and Deuteromycetes.

New approaches in disease control call for new types of fungicides and it was not until the discovery of systemic fungicides that the tools were available for a positive change from the traditional methods of chemical disease control that are practised in apple, grape and hop culture. This paper attempts to trace some of the new opportunities that are available and in so doing to emphasize the following topics :
- the biological properties of the new fungicides and the rationale for their use,
- the possible role of the fungicides in existing and future disease control methods, including IPM,
- the problems linked with establishing new approaches in chemical disease control in traditional markets.

The fungicides which will be discussed in this paper are presented in table 1.

BIOLOGICAL PROPERTIES OF SYSTEMIC FUNGICIDES CONTROLLING PATHOGENS OF THE ORDER PERONOSPORALES (TABLE 1, GROUP 2)

1. Cymoxanil. The main properties are : activity against some but not all Peronosporales, not fully systemic but penetrates into the plant tissue, curative effect up to 3-4 days after infection, limited protectant activity. The compound is used in combination with conventional fungicides. Synergistic effects have been shown with such mixtures.

2. Phosetyl Al. Its spectrum of activity is not limited to Oomycetes but is centred on the downy mildews. *In vitro* efficacy is fairly weak, activity *in vivo* seems to be linked with the physiology of the host plant. Phosetyl Al is transported acropetally and basipetally. For control of airborne pathogens it is applied only in mixtures with conventional fungicides. Against soil-borne pathogens, the product alone is used as a foliar or a soil treatment.

3. Acylalanines. The acylalanines are fungicides with strong activity *in vitro* and *in vivo* against all Peronosporales. Their systemicity is expressed by acropetal transport and high curative activity. In view

of the inherent risk of resistance to this group, metalaxyl is recommended only in mixtures with residual fungicides for foliar application (Staub and Schwinn 1980).

BIOLOGICAL PROPERTIES OF ERGOSTEROL-BIOSYNTHESIS INHIBITING FUNGICIDES (TABLE 1, GROUP 1)

Although the 5 chemicals discussed here belong to two different chemical classes, the triazoles and the pyrimidines, they are believed to have the same biochemical mode of action. According to Buchenauer (1975, 1976 and 1977) and Henry and Sisler (1981), they inhibit ergosterol-biosynthesis at the stage of 14-C demethylation. They are all active against a variety of pathogens of the orders Ascomycetes, Basidiomycetes and Deuteromycetes, with individual differences in the spectrum of activity.

Uptake and translocation. All of the sterol inhibitors penetrate rapidly into plant tissues at various sites. Subsequently they show translaminar movement and, with the exception of bitertanol, are acropetally transported. None of them is transported in detectable amounts downwards towards the roots. Some of them exhibit strong activity by vapour phase. Based on retention studies (Skolnik 1980), the amount of fungicide remaining at the plant surface is probably biologically not active and is not redistributed. These chemicals should not be applied during rain as they are susceptible to wash-off.

Table 1 Recently developed fungicides

Manufacturer	Code No.	Common Name	Trade Name (s)	Chemistry
Group 1				
1	MEB 6447	triadimefon	BAYLETON	triazole
2	KWG 0599	bitertanol*	BAYCOR	triazole
3	EL 222	fenarimol	RUBIGAN	pyrimidine
4	CGA 64251	etaconazole*	SONAX	triazole
5	CGA 64250	propiconazole*	TILT, DESMEL	triazole
Group 2				
6	DPX 3217	cymoxanil	CURZATE	cyanoacetamid-oxime
7	LS 74783	phosetyl AL	ALIETTE	O-alkyl-phosphonate
8	CGA 48988	metalaxyl	RIDOMIL, ACYLON, FUBOL	acylalanine
9	RE 20615	milfuram	CALTAN, et al.	acylalanine
10	M 9834	benalaxyl*	GALBEN	acylalanine

	First publication, References
1 = BAYER	Grewe and Büchel 1973
2 = BAYER	Brandes et al. 1978
3 = Ely Lilly	Brown et al. 1975
4 = CIBA-GEIGY	Staub et al. 1979
5 = CIBA-GEIGY	Urech et al. 1979
6 = DU PONT	Serres and Carraro 1976, Richards and Delp 1976, Denis 1976
7 = RHONE-POULENC	Bertrand et al. 1977
8 = CIBA-GEIGY	Schwinn et al. 1977, Urech et al. 1977
9 = CHEVRON	Lukens et al. 1978
10 = MONTEDISON	Garavaglia et al. 1981

*draft proposal

Table 2 Biological properties of recently developed fungicides (cf. Table 1)

Chemical	Biological Activity*			
	in vitro	preven-tive	curative/ eradicative	Main spectrum of activity
Group 1				
triadimefon	+	+	+	powdery mildews, rusts
bitertanol	+	+	+	scab and other leaf spot pathogens
fenarimol	+	+	+	scab and powdery mildews
etaconazole	+	+	+	leaf spot pathogens, rusts, powdery mildews, scab
propiconazole	+	+	+	leaf spot pathogens, rusts, powdery mildews, scab
Group 2				
cymoxanil	+	±	+	Peronosporales
phosetyl Al	±	+	+	Peronosporales and others
metalaxyl	+	+	+	Peronosporales
milfuram	+	+	+	Peronosporales
benalaxyl	+	+	+	Peronosporales

* + = strong activity, ± = weak activity, - = no activity

Chemical	Behaviour on and in plant		
		Transport	
	penetration	acropetal	basipetal
Group 1			
triadimefon	+	+	-
bitertanol	+	-	-
fenarimol	+	+	-
etaconazole	+	+	-
propiconazole	+	+	-
Group 2			
cymoxanil	+	-	-
phosetyl Al	+	+	+
metalaxyl	+	+	-
milfuram	+	+	-
benalaxyl	+	+	-

Biological activity. *In vitro* studies (Paul and Scheinpflug,1979, Staub et al., 1979) show that these fungicides inhibit mycelial growth at very low concentrations, and that they do not affect spore germination at the normal use rates, but may reduce the length of the germ tubes. *In vivo*, spore germination is hardly affected and germ tubes and appressoria are only slightly reduced (Brandes and Paul, 1979). The main toxic effect on scab is the inhibition of the growth of hyphae in the host tissue; in the case of powdery mildew, secondary haustoria are suppressed. Subsequently initial infections do not develop further; thus, the main site of action of these fungicides occurs inside the host and not at its surface.

Of special interest is the activity of these molecules when applied during on-going pathogenesis, i.e. their curative action. Powdery mildew on cereals for instance can be blocked during all infection stages up to sporulation by triadimefon. Treated spores seem to be less fit than untreated (Paul and Scheinpflug, 1979). The same holds true for powdery mildew on apples. From various sources it is evident that these fungicides stop apple scab development (depending on environmental conditions) up to 120 hrs. after infection (Gilpatrick et al. 1981, Kelley and Jones, 1981). After that time the infection process can still be stopped, but small chlorotic spots occur. These do not sporulate and die out (Hoch and Szkolnik, 1979). Application onto sporulating lesions will result in diminishing sporulation although spores from treated lesions are viable and may cause infections. All products (Table 2, group 1) behave in the same way, but at different concentrations. The degree to which they exhibit curative activity on fruit infections, is not known yet. More information about the reaction of apple scab after treatment with sterol inhibitors may be found in the publication of Kelley and Jones (1981).

Spectrum and level of activity. Whether applied protectively or curatively, most of these fungicides are highly active in the field at dosages much lower than the conventional fungicides. However, the 5 compounds show variation in their activity against different pathogens. Bitertanol is mostly effective against apple scab and other leaf spot diseases, whereas the other compounds also control powdery mildews and rusts. Under certain conditions they seem to be weak in the control of fruit scab (Palm 1981).

Crop tolerance. All products seem to be well tolerated by the three crops in question. However, some of them may, under certain conditions, cause plant growth regulating effects, resulting in greener leaves, shorter internodes and, in severe cases, in smaller size and shape of the fruit. Such effects rarely reach an economic level under normal use conditions.

Risk of resistance. Much work is being done to evaluate the potential for resistance to ergosterol inhibitors. Although little field use data are available from the crops in question, the following can be stated :

- resistant strains can be obtained under laboratory conditions. Some of these strains are pathogenic but their fitness seems to be reduced (Gilpatrick, 1981, pers. comm.).
- Fungal populations differ in their sensitivity to these fungicides. Isolates with reduced sensitivity have been reported at low dosages on cereal powdery mildew from England (Hollomon and Butters, 1981, Fletcher and Griffin, 1981). However, at normal use rates such strains are still controlled easily. However, it might be advisable to establish monitoring systems to detect sensitivity shifts at an early stage and to study their development systematically.

On perennial crops with their large number of treatments per season, it cannot be excluded that the continuous selection for improved fitness and lower sensitivity might eventually lead to resistance to ergosterol inhibitors. It would therefore be wise not to use these products exclusively over an extended period of time but either in mixtures and/or in alternation with fungicides of different biochemical mode of action.

IMPROVEMENT IN CHEMICAL DISEASE CONTROL

For over a hundred years, chemical disease control has been based on disease prevention. The fungicides used for this purpose generally inhibit spore germination, but once the pathogen has penetrated the host tissue, they are no longer able to exert any control. New crop growth as well as heavy rainfall require the renewal of the fungicide layer on the plant surface. By contrast, the new fungicides have, because of the biological properties described above, the potential to partly overcome these shortcomings as the following examples show.

1. Improvements over traditional protective spray schedules in grapes and apples. One of the shortcomings of residual fungicides is the shortlived protection that they give to the crop. The new systemic materials offer clear advantage in this respect. On grapes, downy mildew control can now be achieved with 14-21 day spray intervals using metalaxyl or phosetyl Al, a big advantage over the traditional spray intervals of 7-10 days (Schwinn 1979). This results in a reduction of spray applications and amount of chemical per growing season. A similar saving can be achieved by the use of sterol inhibitors for the control of powdery mildew in grapes (Table 3).

Table 3 Control of *U. necator* on grapes, France 1979
Variety : Cabernet Sauvignon

Treatment g a.i./100 l		Interval	No. of sprays	% attack bunch surface 24.8.79
untreated	-	-	-	74,4
sulfur	1000	according to warning system	7	13,0
fenarimol	1,6	14 days	7	5,0
triadimefon	2,5	"	7	0,7
propiconazole	2,5	"	7	0,3
fenarimol	2,4	21 days	5	5,4
propiconazole	5,0	"	5	0,8

CIBA-GEIGY unpublished data

A further interesting aspect is the fact that some of the sterol inhibitors can control both scab and powdery mildew on apples (tables 2 and 4), a property which is advantageous in areas and on varieties where both diseases occur simultaneously. The use of such compounds also acts as an insurance against damage from both diseases in areas where it is traditional to spray against only one of them. For example, powdery mildew has often increased in relative importance when scab only fungicides, such as captan, were used. This aspect, however, has only local importance because many growers, for various reasons, prefer to change products during the season.

Another advantage of some of the new fungicides is the low amount of product needed over the growing period, as compared to spray programmes with conventional products. This results in a lower load of chemicals in the environment (Table 4).

Finally, a higher level of control is given by the new generation of fungicides. This has a particular significance for the control of the downy mildew diseases, where the explosive epidemiology of these pathogens highlights the shortcomings of surface protective fungicides. Trial work conducted during 1977, the year of the very serious *Plasmopara* epidemic showed how a compound like metalaxyl is able considerably to improve the control of early attack on fruit compared to residual products (Urech and Schwinn 1978, Table 5).

Table 4 Simultaneous control of *Venturia inaequalis* and *Podosphaera leucotricha* on apples, South Africa 1978/79

Variety : Winter Permain
Spray schedule : 8 protective sprays

Treatment	g a.i./100 l	% leaf scab	% fruit scab	% powdery mildew
untreated	-	58,8	68,8	52,4
mancozeb	120,0	8,0	1,8	52,0
etaconazole	1,25	2,1	1,5	1,6

Total amount of fungicide per season and ha (kg a.i.)

mancozeb	14,4
etaconazole	0,15

Water volume/ha : 1500 l (average)

CIBA-GEIGY unpublished data

Table 5 Control of *P. viticola* on grapes in France, 1977
Variety : Merlot
Spray schedule : 7 protective sprays

Treatment g a.i./100 l	% leaf infection 3.8.	 10.9.	% fruit attack 11.8.
untreated	43,2	81,0	98,0
maneb + copper 60 + 102	5,5	19,0	55,0
metalaxyl + copper 30 + 100	1,0	8,0	1,0

CIBA-GEIGY unpublished data

2. Diseases of hops and apples previously not controlled by chemical means. Primary infections of *Pseudoperonospora humuli* on hops. Until recently it was not possible to effectively control primary infections of hop downy mildew. The introduction of phosetyl Al and metalaxyl has changed this situation considerably. Metalaxyl is highly active against primary infections after granular or high volume soil application at low rates. A single application results in at least 9 weeks of control (Smith 1979). Phosetyl Al appears to be weaker when applied to the soil, but its basipetal properties allow its use as a foliar spray. Normally two sprays are necessary for good control (Chalandon et al. 1979).

The use of the systemic products for control of the primary infections also facilitates the control of secondary attack on leaves and cones both by reducing the amount of inoculum and by translocation of the active ingredient into the vines (Smith 1979).

Control of collar rot *(Phytophthora cactorum)* on apples. In the past no effective control method for this disease was available. Cultural measures were usually insufficient and loss of trees could not always be avoided. Fungicides were generally ineffective. Both metalaxyl and phosetyl Al have shown to be effective against soil-borne *Phytophthora spp.* on perennial plants (Urech et al. 1978, Williams et al. 1977, Zentmyer and Chr, 1978, Margot, 1981). Experimental evidence indicates that the same holds true for *P. cactorum* on apples where two to three foliar applications with phosetyl Al for example are needed for effective control (Table 6).

Table 6 Control of *P. cactorum* on young apple trees

Treatment g a.i./100 l	Length of canker (cm)
untreated/uninoculated	0
untreated/inoculated	22,2
phosetyl Al 200 3 treatments; inoculated	2,6
phosetyl Al 200 1 treatment; inoculated	11,1

- artificial inoculation : July 10
- fungicide treatments : June 12 (both treatments)
  July 9, August 14
- evaluation : September 12

RHONE-POULENC unpublished data

3. Curative disease control. Most of the new fungicides have marked curative and eradicant properties, which can be of practical importance as illustrated by the following examples. Primary infections of apple powdery mildew are the source of inoculum in the orchards and therefore should be eliminated. So far this has been done by manual pruning of the attacked terminals. Table 7 shows how the same effect can be achieved by chemical means. Fenarimol partly controls primary infections by inhibiting mycelial growth and sporulation on the shoots, leading to a significant reduction of the inoculum level in the orchard. Moreover, the high degree of activity on secondary mildew assures good disease control throughout the season, resulting in a marked reduction in the number of newly infected overwintering buds. A similar activity is exhibited by triadimefon and etaconazole. It is assumed that these highly effective fungicides with both preventive and eradicative properties will lead within a year or two of their use to a general reduction of the powdery mildew inoculum in orchards so that they can be used at a lower frequency and probably at a lower rate.

Curative control of *Plasmopara viticola* on grapes has been described by Urech and Schwinn (1978). These data showed the following : whilst a residual fungicide failed almost completely to control an epidemic once it had started, the systemic fungicide was effective. Curative properties against this disease have been reported also for cymoxanil and to a lesser extent for phosetyl Al. Whilst these results are striking, it must be pointed out that curative applications on grapes have their limitations. They should not be considered during the period of flowering and early fruit set, because once infection has occurred, the damage in terms of crop loss is already done. Curative properties, however, enable these products to be used in forecasting systems, a topic which is dealt with below.

Table 7 Control of *P. leucotricha* on apples in Switzerland 1980

Variety : Jonathan
Spray schedule 13 protective sprays

Treatment g a.i./100 l		% control of powdery mildew		% terminal buds infected
		primary	secondary	
		1.7.	6.8.	5.12.
untreated	(0-5)	(2,9)	(4,2)	46
dinocap/ sulfur	30/ 240	0	65	26
fenarimol	2,4	45	92	4

CIBA-GEIGY unpublished data

The curative properties of the sterol inhibitors have brought a new element into the scab control practice. Kelley and Jones (1981) showed the after-infection or curative properties of bitertanol and etaconazole on apple scab. Both products inhibit scab development when applied 3 days after start of the infection. Application 2 days before expected occurrence of the symptoms and again one week later resulted in chlorotic, abnormal lesions which did not sporulate.

4. Disease control using disease prediction. Disease prediction systems exist on a large scale in grape-growing areas and also in apple-growing areas, especially for scab. Residual fungicides, because of their limited flexibility, are of limited use in spray programmes based on disease forecasting. Systemic fungicides with their curative properties show a real advance in this context. The most promising results are available for apple scab.

Gilpatrick et al. (1981) used an automatic electronic device to monitor and calculate apple scab primary infection periods and to determine the timing of sprays of curative scab fungicides. These workers demonstrated that a sterol inhibitor provided outstanding disease control without symptoms on leaves or fruit when applied curatively at about 72 hours after the beginning of infection periods. Their study indicated that such techniques may lead to a reduction in the number of sprays compared with a conventional protective programme. The degree of reduction will no doubt depend on prevailing weather and other factors.

Unfortunately, from a perusal of the literature, there appears to be a dearth of similar work on the control of downy mildews in grapes in spite of the fact that effective compounds are now available which would permit practical use of disease forecasting methods.

IMPLEMENTATION OF NEW APPROACHES FOR CHEMICAL DISEASE CONTROL

In all the three crops which are dealt with in this paper, there is a long history of chemical disease control. For many years preventive sprays have been carried out, either routinely or in accordance with the recommendations of the warning services. As has been described above, there are now fungicides available or in the development stage that offer the possibility of further improving on the current methods for disease control.

Therefore we should now turn our attention to the question of how these fungicides have changed the practical methods of disease control to date. If one looks at the date of discovery of the new fungicides, the answer regarding sterol inhibitors must be less complete than that for the new Oomycete fungicides.

Hop growers appreciate the new possibility of controlling primary infections of downy mildew, therefore they use the new products widely for this purpose. This offers them a convenient solution for a problem which was previously hard and laborious to solve satisfactorily. These new fungicides are also used to a certain extent as foliar sprays for the control of secondary infections on leaves and cones in intervals that are longer than those recommended for conventional fungicides.

In some apple growing areas sterol inhibitors are already used for scab and powdery mildew control. So far no changes in the approaches to scab control are evident; it appears that these new materials are being used just like conventional fungicides.

In grapes where the new downy mildewicides have been used for about 3-4 years, one might expect most changes in disease control to have come about. In fact the only noticeable progress is in the use of the new fungicides (both downy mildewicides and sterol inhibitors) at longer intervals. Special recommendations based on forecasting have not yet been made for the new fungicides and their curative activity only serves as an additional sales argument.

Overall, the new products have mainly been used in conventional spray schedules - their unique properties and their potential to improve disease control methods have not yet been exploited.

In order to discover why the advantages of the new products have not been better exploited, one must look at the various social groups involved in plant disease control and their interest and motivation to change well established methods.

The primary needs of the farmer are reliable efficacy at minimum costs, and in many cases a planned programme of chemical control measures. The farmer likes to carry out his plant protection programme in accordance with clear and simple recommendations. Generally he has little interest in experimenting which naturally creates a risk for him.

The consultant, the advisory and extension service as well as the scientific institutions are the intermediaries between the producer and the user of agrochemicals and frequently find themselves involved in the conflict of interests between the two parties. Therefore they cannot be blamed if their recommendations are often conservative. Sometimes also, they know too little about the properties of new products and the results of trials to judge on the usefulness of a new approach.

The final group are the manufacturers. They invest increasing sums in research and development for new products. The time-span between synthesis and first marketing of new products amounts now up to 6-8 years. Therefore it is understandable that market introduction of new products takes place as early as feasible without awaiting the development of highly sophisticated use methods.

The main solutions to this problem are : better education and knowledge of the problems of disease control on the part of all those involved, better knowledge of the products, more closely directed research and better information supplied to the users and consultants, etc. However, since this cannot be done at short notice, the results have so far been poor.

One area of progress, however, is in Integrated Pest Management (IPM). "IPM is a combined use of chemical cultural, genetic, and biological methods for effective, economic pest suppression with a minimum effect on nontarget organisms and the environment. It is based on understanding the biology and ecology of the plant or animal to be protected (Kuhr 1979)".

This approach implies that all aspects of crop management and production are under investigation and that disease control is only one aspect. Every improvement in disease control technology can be considered as part of an IPM system, whether it be lower rates, safer chemicals, longer intervals, less frequent sprays, antiresistance strategies, etc. And, of course, disease prediction, which allows the farmer to apply the right product at the right time.

IPM systems in Europe are still in their infancy except in certain fruit growing regions. The only important factor in this connection is disease prediction, which is practiced in some countries and crops combined with spray recommendations. The information systems, however, are mostly not adequate and certainly do not enable the farmer to act quickly enough to make use of the new fungicides. Our colleagues in USA are doing better in this respect; not only do they actively work out and promote IPM programs and afterwards check the results, but they also try to fit the new generation of fungicides into such systems.

The situation as it stands at present is far from satisfactory. The chemical industry which is willing and able to cooperate in finding better and more intelligent solutions (Geissbühler 1979), has developed a number of promising and exciting fungicides. They need to be used correctly in order to contribute to the objectives described above.

CONCLUSIONS

The new generation of systemic fungicides described in this paper interfere in several ways with the host-parasite interphase. Because of their systemic movement the fungicides offer a longer protection of the crop including the new plant growth. Once they have penetrated the plant they are independent of weather conditions. They are highly toxic to the pathogens and are able not only to increase the level of disease control but also to slow down the epidemic spread of pathogens. Finally they act on already established infections. In view of these advantages of the new fungicides over the conventional products, one can anticipate improved chemical disease control in the future. The following important changes may be seen during the next decade :

- Less sprays will be needed to get adequate or superior disease control due to the longer persistence of effect of some of the chemicals and the possibility of using them successfully according to disease forecasting. The amount of chemical needed for good disease control per surface unit and growing period will drop sharply when these highly active molecules are used.

- Disease control will become more reliable in different ways : curative applications will be made if a residual spray was missed or failed; higher levels of disease control will be achieved; new growth foliage and rapidly growing parts such as flowers and young fruits will be protected.

- A number of systemic or soil-borne diseases are for the first time now subject to chemical control on a wide scale.

- The farmer can use the new chemicals with more flexibility, an aspect which is of great interest for example in the control of apple scab because growers will not need to spray during rainy or windy periods as is often the case with protectants. They will be able to wait for more favourable weather conditions and still get good control. The same holds true for grapes where inaccessibility of vineyards due to weather conditions often prevents proper timing of applications with residual fungicides.

The implementation of the new chemicals into practice is currently rather slow. A common understanding and a tight collaboration between all social groups involved in plant protection is needed in order to achieve improved implementation.

Some of these new fungicides are prone to resistance, a fact which can reduce their value. They should therefore be used in such a way that occurrence of resistance is prevented or slowed down. It seems that in most cases mixtures with residual fungicides are the most promising way to achieve this aim. Only an intelligent and precise use will help to safeguard these chemicals such that we have not to conclude in a few years that they were discovered ahead of their time.

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SESSION 9

PESTICIDE RESISTANCE— ITS IMPACT ON PEST AND DISEASE CONTROL

Proceedings 1981 British Crop Protection Conference - Pests and Diseases

INSECTICIDE RESISTANCE – HOW CAN INDUSTRY MEET THE CHALLENGE?

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Summary Industry is one institution amongst many which actively participates in the fight against pest resistance (R). A large number of chemicals synthesized by each major company in the Agrochemical Business provides the chemical means which may lead to insecticides of entirely new structure, or to ones belonging to a known group but with the ability to control R-insects well.

Combination effects, such as potentiation between traditional insecticides and more recent types like the pyrethroids often reveal activity which can be exploited in combatting R-insects.

The search for, and development of, highly effective chemicals to suppress known R mechanisms will be a major future task of the organic chemist and the screening biologist in industry. New lines of chemical research will be open for the chemist to follow.

Biological research in industry will continue to provide the basis for successful plant protection on a large scale by monitoring R levels in target pests. Basic research on R-mechanisms will be continued from which our insight into the R phases in lepidopterous development has come.

The adaptation of results from basic research must be further developed into Integrated Pest Management Programmes by which R insects can be controlled. The demonstration of commercial control of bollworms by taking the sensitive imago as the target is an example of industrial field and basic research converging into a new control principle. Our efforts must be concentrated on continuing in this direction.

INTRODUCTION

The basic assumption I make for the future control of insect pests is that it will be carried out largely according to the principles of Integrated Pest Management. It is generally assumed that chemical control of pests by suitable insecticides will play an important part in the crop protection of the future, since obviously no viable substitutes for chemicals exist under conditions of strong insect pressure in numerous monocultures. In many instances chemical control was, and will be, the sole pillar on which rested and will rest the chances of raising a healthy crop. Therefore, the evolutionary process of selection for resistance (R) will continue more or less intensively, and we will have to put up with the fact that the R problem will stay with us in future.

What does that mean for the chemical industry with its strong engagement in various fields of modern agriculture? First, I believe, it is industry's problem to realize that R will be a decisive factor in its future activities. At the present, according to my experience, this prospect is only very reluctantly accepted and suitable contermeasures are slow in coming. This is easy to understand because a new type of pest, new in the sense of its not being controlled by traditional means, represents an unusual challenge to the traditional type of plant protection as well as to the cultures which remain without the effective cover under which they were raised in the past. This is why the phenomenon of R is an irritant to all who developed effective plant protection in the past 40 years. And yet the future of chemical plant protection now as in the past heavily depends on the success of the organic chemist whose responsibility is to provide the new means to control the "new insects", the resistant insects.

INDUSTRY'S EFFORTS TO PROVIDE CHEMICAL MEANS TO COUNTERACT RESISTANCE DEVELOPMENT

It is common knowledge that the fight for efficient control of R pests is multi-institutional. How does industry contribute in this? I believe its most important contribution is the large number of compounds it provides. Each of the traditional producers of agrochemicals synthesizes new molecules which are expected to have activity in the various fields of agricultural technique. Amongst them new insecticides are conceived which might be able to control resistant pests, even though the number of those which could be successfully developed has declined in recent years. To detect and develop such compounds, is industry's main purpose now as it was in the past, no matter whether they are of new or traditional structure. Amongst the structurally new compounds such types as the formamidines, the benzoylureas, and the pyrethroids may be counted. I call traditional organophosphates, carbamates, and others which despite their general structure are doing well in controlling insects which have developed strong R towards the respective chemical group to which they belong.

New insecticides developed in recent years to control R-insects

An example for a traditional insecticide which has been successful in controlling R insects is profenofos, an OP of the mixed ester type. It was regularly applied to control Egyptian Spodoptera littoralis, an insect highly R to carbamates, OPs, and chlorinated hydrocarbons. Toxicological tests of various field strains showed that its type of R offered efficient protection from monocrotophos poisoning, but none against profenofos action. The most important R-mechanism in these strains is metabolism on the basis of MFOs. Apparently oxidative degradation of profenofos is not possible or at least very difficult.

Tab. 1

Resistance ratios of monocrotophos and profenofos in field strains of Spodoptera littoralis from Egypt

Strain	R/S 1)	
	monocrotophos	profenofos
Behera	107.3	5.7
Gharbia	123.6	4.0
Dakahlia	109.0	4.7
Sharkia	87.0	3.7
Kalioubia	50.0	4.4
Basel-R	136.9	6.1

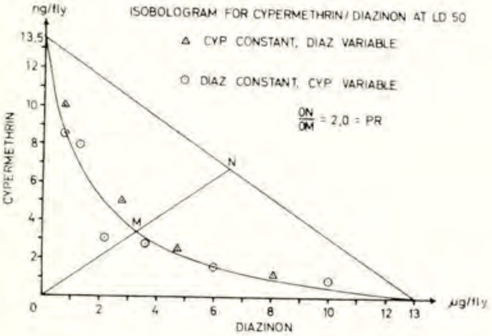
1) larval LD_{50}s of field strains referred to S laboratory standard.

Potentiation between known insecticides to control R insects

Another approach to stay abreast of the development of R is to make use of different modes of action of known insecticides and to establish combinations which potentiate each other and thus compensate for the R-effect. The advantage of such a combination as diazinon and cypermethrin is in keeping a valuable OP fully active and an expensive pyrethroid at low dosages. An additional bonus may be an extension of the spectrum of control which such combinations often also imply. My example demonstrates the technique by which potentiation is established. An isobole, a curve of equal toxicity represented by, for example, LD_{50}s of various component mixtures, indicates potentiation, if its vertex is turned towards the O point of the coordinate system. The potency ratio PR as defined by ON/OM, where M represents the point on the isobole which is farthest from the line of additive effects, indicates potentiation if it is >1. Being a measurable parameter PR is a welcome means to define the extent of interaction between 2 active materials.

Fig. 1

Isobole technique to demonstrate potentiation between insecticides



Such comparative toxicity is shown in Tab. 2 where PRs for combinations of various OPs with cypermethrin are tabulated. Definite potentiation occurs between profenofos, diazinon, and cypermethrin. Monocrotophos and methidathion are not potentiating partners for cypermethrin using houseflies of the multiple-R strain R 300.

Tab. 2

Potentiation between cypermethrin and various OPs, tested on multiple-resistant houseflies

R 300 strain

	potency ratio (PR)
Cypermethrin +	
monocrotophos	1.1
methidathion	1.2
profenofos	1.9
diazinon	2.0

Another example of how to achieve new effects against R insects by combining known insecticides is presented in Tab. 3. The Egyptian cotton leafworm, Spodoptera littoralis, is notorious for its multiple R towards OPs, carbamates, and to a growing extent, pyrethroids. Chlordimeform has been shown by Plapp (1979) to synergize various pyrethroids in R and also in S Heliothis species. Our example in Tab. 3 demonstrates synergistic action between the pyrethroid resmethrin and chlordimeform in both R and S races of S. littoralis. In this case synergism is not explained by MFO-inhibition by the synergizing agent as was shown by joint application with MFO-inhibitors.

Tab. 3

Synergism between resmethrin and chlordimeform (Cdf) in R and S Spodoptera littoralis [1] after feeding on treated Malva silvestris

Insecticide or mixture	LD_{50} ng/cm^2	slope	synergistic ratio	LD_{50} ng/cm^2	slope	synergistic ratio
	R_{OP}			S		
resmethrin	205	1.1	-	108	1.8	-
resmethrin + Cdf 1:8	29.8	3.2	6.9	28.9	2.1	3.7

[1] L_4, average weight 26.3 ± 3.7 mg.

Synergists to inhibit known R-mechanisms

Besides the possibilities of combining known insecticides and taking advantage of potentiation in R insects, the approach of actively searching for new types of synergists which could overcome existing R-mechanisms is a major possibility for industry to combat R. In my view this is the most promising future strategy to counteract R-development. A positive feature of this concept is that the chemist may embark on developing entirely new chemistry in step with our expanding knowledge on the occurrence and importance of different R-mechanisms in pest populations appearing in the field.

In Tab. 4 I tabulated a few recent additions of typical synergists to the available arsenal which might be the forerunners of the development which I expect. The propynylcarbanilid CGA 84708 shown on top of Tab. 4 is a typical MFO-inhibitor which exceeds piperonylbutoxide several-fold in its synergizing potency. It has been a longtime standard in our laboratories.

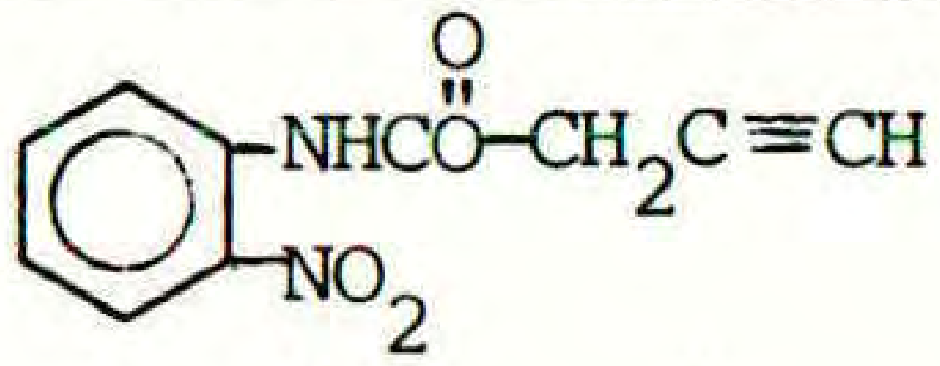
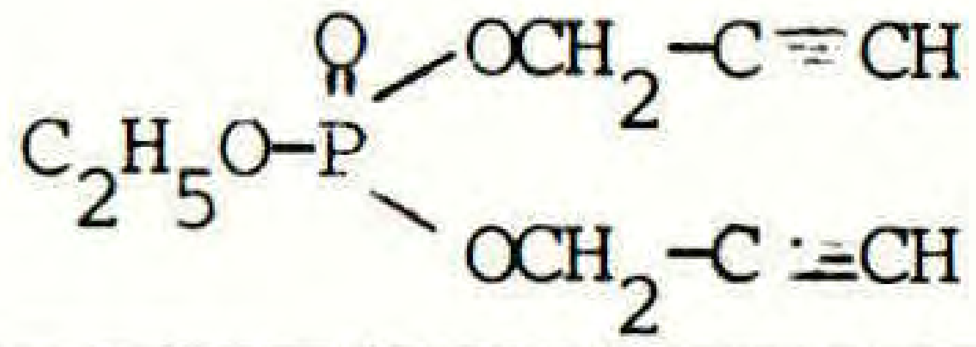
The propynylphosphate phospargyl also shown in Tab. 4 is a recent Bayer development in this field and also an efficient MFO-inhibitor.

Negatively correlated insecticides and potentiation combined

My third example for a newly developed principle to counteract resistance implies 2 pricinples: that of negatively correlated insecticidal action in S and R insects and potentiation. It was reported by Yamamoto et al. (1976) for Mitsubishi Chemical Industries (Tab. 5).

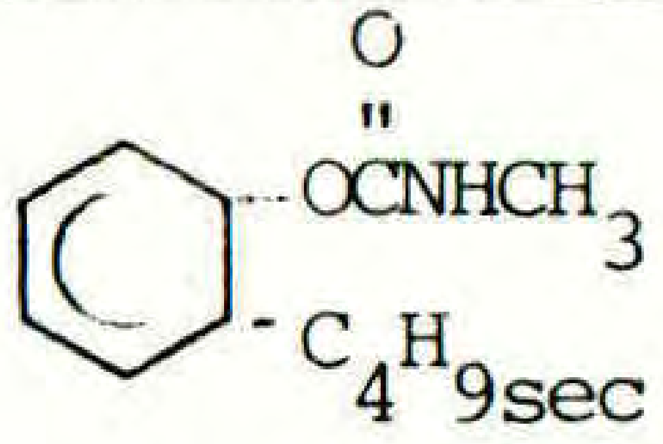
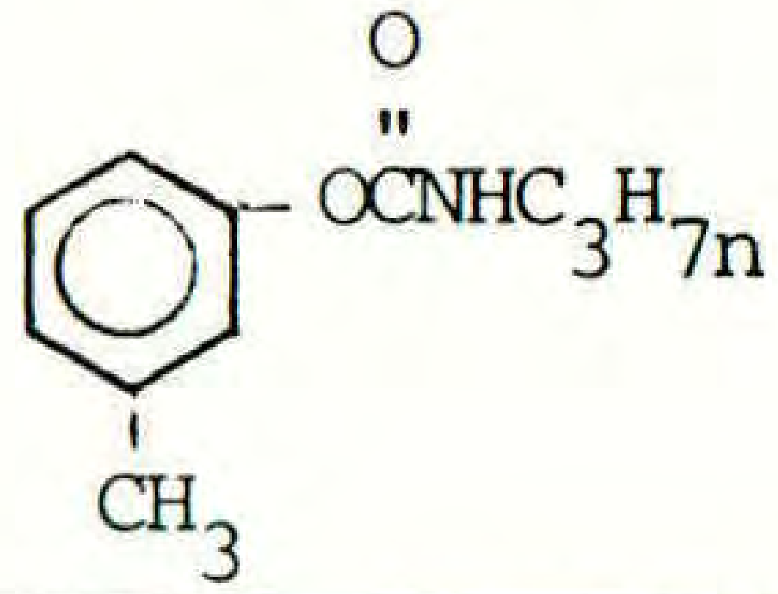
Tab. 4

Restoration of insecticide efficacy in resistant insects by modern synergists

Insect	R-mechanisms present and affected	insecticide	synergist	LD_{50} in µg/g			SR
				S	R	R_{syn}	
Musca domestica	MFO, $AChE_{(i)}$	monocrotophos		3.91	6570	22.6	290
Spodoptera littoralis	MFO, $AChE_{(i)}$	monocrotophos	" "	12.20	1670	91.5	18.3
Musca domestica	MFO, $AChE_{(i)}$	monocrotophos		3.91	4200	13.9	302

Tab. 5

Combination of a negatively correlated effect of two carbamates on AChE of R and S Nephotettix cincticeps plus potentiation between both insecticides

Insect	R-mechanisms present and affected	insecticide	$LD_{50}S$	$LD_{50}R$	$LD_{50}R_{syn}$ 1 : 1	co-toxicity coefficient
Nephotettix cincticeps	$AChE_{(i)}$		2.7	76.6	14.8	4.3
			81.8	51.2		

Nephotettix cincticeps, the green rice leafhopper, has developed R against standard methylcarbamates such as the o-butyl-phenyl methylcarbamate in Tab. 5. This R is based on an altered AChE which has greater affinity to the n-propyl-carbamates as determined by enzyme inhibition studies. The toxicity data of Tab. 5 also show a corresponding trend. Thus in relation to the target enzyme of the R and S type both carbamates are negatively correlated toxicants. But they show also a substantial potentiation effect when used in a 1:1 mixture, as the cotoxicity coefficient of 4.3 demonstrates.

INDUSTRY'S EFFORTS TO COUNTERACT RESISTANCE BY BIOLOGICAL RESEARCH

If in the foregoing chapters the stress was on the traditional chemical means by which industry is engaged in counteracting R, we should now turn our attention to its efforts in the field of biological sciences. As yet these efforts are on a smaller scale than those of chemistry, but their importance increases steadily. R-diagnoses of field populations provide important basic information for large scale control efforts. Basic studies on R in the different development phases of the lepidoptera, and finally field experiments can demonstrate that the insight into R specific to certain periods of insect life could be used to develop a new principle of control.

Diagnoses of R in field populations of pest insects

Houseflies are notorious for their capability of developing R against all possible types of insecticides. When such an insect is controlled on a large scale it is necessary to keep track of the R-development by constantly monitoring the treated pest. If the cross-R patterns are checked possible alternative insecticides may be identified which can supplant the compound in current use when it is affected by increasing R.

In Saudi-Arabia such analyses were made at different locations, and the R-development towards diazinon was checked against R and S laboratory standards (Tab. 6). While diazinon-R was increasing and DDT-R was very high due to a long history of DDT-control in these fly strains,there was no cross-R to the pyrethroid resmethrin as the comparison with the sensitive WHO-S strain indicated. DDT-R was metabolic and based on the presence of the enzyme dehydrochlorinase as the combined application of DDT and F-DMC revealed. DDT-R based on the kdr gene could not be found, and the pyrethroid resmethrin was fully active on these flies.

Tab. 6

Resistance patterns in field strains of Musca domestica from Saudi Arabia

Insecticide	resmethrin		diazinon		DDT	
Strains	LD_{50} 1)	R/S 2)	LD_{50}	R/S	LD_{50}	R/S
WHO-S	0.058	-	0.05	-	0.13	-
R_{lab}	0.084	1.45	2.67	52	>100	>1000
Riyadh	0.020	0.34	0.46	9	>10	>100
Jeddah	0.034	0.59	1.34	26	>10	>100
Mecca	0.018	0.31	0.97	19	>10	>100
Dammam	0.019	0.33	0.75	15	>10	>100
Quatif	0.019	0.33	0.96	19	>10	>100

1) µg/♀; 2) referred to WHO-S.

Another effort to diagnose R levels of field populations has already been touched on when the OP profenofos and its action on R S.littoralis field strains from Egypt was mentioned. In 5 strains the reaction pattern was quite uniform despite their origin from locations more than 120 km apart from each other. Dosage mortality lines of field strains were not significantly different which pointed to a generalized type of R towards monocrotophos. Also towards profenofos the reaction was very uniform, but in a range that must be called sensitive. We attribute this uniformity of a variety of field strains in their reaction to both toxicants to the generalized application of monocrotophos over a large area and the relative mobility of the moths carrying the R-genes.

Basic research on R-mechanisms

In our efforts to define R-mechanisms during the development of S.littoralis we showed that R in this lepidopterous species is present in the larval phase, and not the egg stage or the imago. Joint application of MFO inhibitors with monocrotophos resulted in insignificantly increased toxicity when applied to eggs and imagines in R, as shown in Tab. 7. The larvae, by contrast, showed a synergistic ratio of 20 if monocrotophos plus CGA 84708 were jointly applied. Thus, if by means of timing and application eggs and imagines could be made the prime targets of insecticide application, the most effective R-mechanism, the MFOs in larvae, could be avoided and control achieved even under conditions of high R.

Tab. 7

Stage-specific resistance in Spodoptera littoralis. LD_{50} µg/ insect. Eggs LC_{50}s in ppm

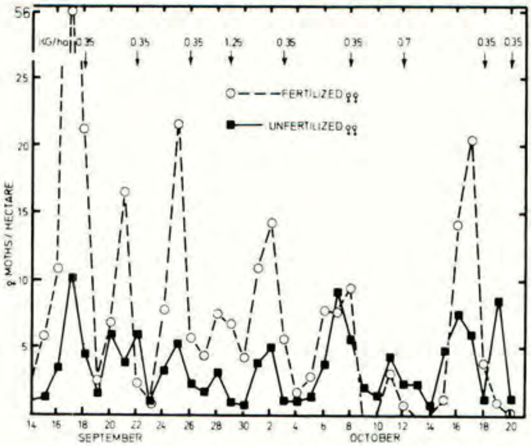
Eggs	R	S	R/S
monocrotophos	565	3.8	32
monocrotophos + PBO	404	7.9	
synergistic ratio	1.4	0.5	
Larvae			
monocrotophos	43.8	0.32	137
monocrotophos+CGA 84708	2.2	0.98	
synergistic ratio	20	0.33	
Imagines			
monocrotophos	4.7	5.0	1
monocrotophos+CGA 84708	2.8	7.0	
synergistic ratio	1.7	0.7	

Basic and field research to develop new principles of field control

That such reasoning is a definite possibility has been shown by Ciba-Geigy researchers mainly concerned with application problems. Topper and Lawson (1981) synchronized aerial application of monocorophos with the appearance of certain critical numbers of moths of Heliothis armigera in the Sudan Gezira. In doing so commercial control over a large area was achieved. It should be mentioned that other facts apart from high sensitivity of the moths such as irritation effects by insecticide residues and aircraft noise may also have contributed to the success of this attempt. However, it remains a fact that basic and field researchers saw their respective results and reasoning confirmed in a successful field experiment. The result obtained may offer a possibility of reducing the dosage of insecticide applied and prevent R-development by controlling a phase in the pest's life cycle which is not protected by, and possibly cannot develop, a powerful resistance mechanism.

Fig. 2

Management of Heliothis armigera in the Sudan by sprays directed against adults



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PRESENT TRENDS AND FUTURE NEEDS IN MODELLING FOR THE MANAGEMENT OF INSECTICIDE RESISTANCE

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Summary Mathematical models may be valuable in formulating strategies to prevent the development of insecticide resistance by pests, but present examples are much too generalised to be applied directly to practical situations. Although a number of tactical options have been proposed to delay resistance, little confidence can be placed in these predictions until the descriptive properties of models have been tested using empirical data.

The construction of realistic models of resistance requires accurate input from a broad range of disciplines, including biochemistry, genetics and ecology. A multidisciplinary approach is being used at Rothamsted Experimental Station to study the development of resistance to pyrethroids in local housefly populations.

Detailed studies of this kind should permit the construction of purpose-built models which are nonetheless sufficiently versatile to be tested against other pest species.

INTRODUCTION

Insecticide resistance now poses a serious threat to our ability to contain many pests of agricultural, medical and veterinary importance. Fewer new insecticides are being introduced to replace those to which resistance has developed, and the number of species with resistant strains continues to rise. It is therefore essential to take steps to conserve the effectiveness of existing compounds and prevent the rapid obsolescence of newer ones.

The 7th Report of the Royal Commission on Environmental Pollution (Anon., 1979) recommended increased research into several areas of pesticide development and application. Amongst these it stressed the need to develop control strategies designed to prevent or delay the onset of resistance in pest populations. The formulation of effective strategies is however difficult because resistance is a complex phenomenon. We still know too little about how resistance develops under field conditions and this is probably why so far relatively little has been done to develop practicable strategies to prevent its occurrence.

The success of resistance-countering strategies relies upon our ability to anticipate their effect on the genetic structure of a target pest population. Our present limited knowledge of the extent to which various genetic and ecological parameters influence the development of resistance is derived from computer simulations using mathematical models. Although this work has indicated some of the options available to delay resistance (Comins 1977a,b; Georghiou and Taylor 1977b,c; Curtis et al 1978; Plapp et al, 1979; Taylor and Georghiou 1979; Wood and Mani, in press), these models are too generalised and insufficiently realistic to be directly applicable to practical situations. Specific studies of resistance for which well-documented evidence is available have already revealed complications which these models cannot describe adequately; for instance, present day models cannot anticipate the modes of polyfactorial and multiple resistances which may result from the sequential use of several different insecticides (Sawicki, 1975). Further investigations will no doubt expose other shortcomings of these existing models. This paper reviews the work that has been done and considers what further research is necessary before models can usefully be applied to aid the construction of successful control strategies.

The role of mathematical models   Insecticide resistance is, as Georghiou and Taylor (1977a) noted, an evolutionary phenomenon. It is therefore amenable to study using well-established population genetics theory (eg. Hartl, 1980). Given a set of initial assumptions and parameters which influence changes in gene frequency, this theory enables us to predict the likely course of selection in populations over successive generations. These equations can be incorporated into deterministic or stochastic mathematical models which investigate the effect of varying some or all of these parameters on the final result. Most models in population genetics are deterministic in that only one outcome is possible under any prescribed set of conditions. In contrast, stochastic models allow chance effects to operate during mating and selection, and predict the probability that gene frequencies in any generation have one of several possible values. Such chance effects are an important component of evolutionary phenomena. Although the stochastic theory of population genetics is well developed (Goel and Richter-Dyn, 1974), no attempt has yet been made to incorporate it into models of resistance.

Models are employed primarily to simplify an inherently complex situation. They permit the identification of its most important components and the elimination of unnecessary detail (discussed by Levins, 1966). Useful models of insecticide resistance will have to satisfy several major requirements. Firstly, because biological systems are extremely complex, any attempt to simulate all the quantitative relationships between parameters leads to intractable equations. The models must therefore remain mathematically manageable. Equally, an oversimplified model which ignores too many parameters is likely to be so vague as to be useless. A useful model must compromise between realism and manageability.

Secondly, realistic strategies are bound by operational and economic constraints. It is of little value to explore options which cannot feasibly be applied in practice, and theoreticians must appreciate these restrictions when building models.

Finally the descriptive properties of a model must not only be verifiable but also verified using empirical data. Only when a model is capable of describing changes in susceptibility actually observed in the field can we place any confidence in the predictions which arise from it. This is by far the most formidable aspect of modelling because of the difficulties involved in quantifying parameters such as migration rates and the relative fitness of resistance genotypes for natural populations. The collection of such experimental data is nonetheless an essential step both to verify existing models and to indicate the theoretical refinements needed for future more realistic ones.

Present trends in modelling for resistance   Mathematical models currently available to describe resistance clearly do not satisfy these requirements. With very few exceptions (Comins, 1977b; Hueth and Reger, 1974) they do not consider whether the resulting proposals for delaying resistance are operationally and economically feasible. In only one case, to be described later, has an attempt been made to verify a model using field-collected data (Curtis and Rawlings, 1980). In spite of these shortcomings the models developed so far have identified some of the important parameters and their major findings can be summarised under four headings: 1) the effective dominance of resistance (R) genes; 2) the effect of refugia; 3) the effect of migration; and 4) the timing of insecticidal application.

i) The effective dominance of R genes

Most of the resistance mechanisms which have been identified are controlled by incompletely dominant genes. In theory it is possible to make such genes effectively recessive by applying a dose sufficiently high to kill individuals both homozygous and heterozygous for the R gene. Wood and Mani (in press) have shown that this strategy can significantly retard the spread of resistance through a population if the R gene is initially very rare (Figure 1). Once the gene becomes more common, however, this tactic can have the opposite effect by accelerating an increase in the frequency of the R gene. The proposal also assumes that it is possible to administer a prescribed uniform dose to each individual in a population (Comins, 1979) - an assumption most unlikely to hold in practice. Furthermore, when resistance is polyfactorial the application of high doses can select preferentially those mechanisms which confer singly the highest levels of resistance, or which interact to give the same result. Thus although manipulation of dominance is theoretically possible, it is likely to be of restricted practical value.

ii) Effect of refugia

'Refugia' - a term of Georghiou and Taylor (1977b) refers to parts of a sprayed area, such as the underside of leaves, in or on which insects are protected and able to escape treatment. Provided the probability of escape is independent of the R genotype, the effect of refugia is to conserve susceptible (S) genes in a population and thus retard the onset of resistance (Figure 2). Although we have little control over the number of individuals which escape in this way, refugia can be artificially created by leaving sections of a treated area unsprayed. The extent to which this can be done is subject to major economic constraints and highly specific to the pest species being considered.

iii) Effect of migration

The feasibility of leaving areas unsprayed also depends on another parameter, the ability of individuals to move between treated and untreated sections of the control area. On a larger scale, the extent to which migration results in gene flow between populations may have important consequences for the development of resistance (Comins, 1977a; Curtis et al, 1978; Taylor and Georghiou, 1979). Theoretical studies suggest that the immigration of S individuals from an untreated into a treated area can greatly influence the development of resistance in the latter. This type of immigration can be simulated to an extent by releasing susceptible insects into a treated population. However for most pests strategies which involve such releases are likely to be hard to implement and probably economically unsound.

iv) Timing of insecticide application

In many cases this may be the most important parameter being directly under an applicators' control. Not even pest populations can increase in size indefinitely, and density-dependent mortality factors will operate at some stage of their life-cycle to keep numbers in check. If treatment is applied before this critical stage is reached, the resulting reduction in population size may simply be compensated for by a proportionate decrease in density-dependent mortality. Because these regulatory factors operate principally on immature stages the use of ovicides and larvicides should be avoided wherever possible. It is however difficult to visualise how this can be done for example in preventing damage to cotton by noctuids since only the larvae can be treated with any degree of effectiveness. The correct timing of treatment of adults in relation to immigration and the period between emergence or maturity and mating is also important, as is shown schematically in Figure 3. This figure shows five possible occasions during the life-cycle of a pest with discontinuous generations at which insecticides might be applied. To control adults, treatment at (3) is preferable to (1) and (2) as it gives susceptible migrants the opportunity to mate with individuals in the as yet untreated population. If immatures have to be controlled, treatment at (5)

Figure 1. The rate of increase of a resistance gene in a population when the gene is dominant, recessive or of intermediate dominance (half the heterozygotes RS survive exposure). The gene is initially present at a frequency of 0.00001. In this case 0.02% of the population (irrespective of R genotype) escapes exposure (After Wood and Mani, in press).
D - Dominant   R - Recessive   I - Intermediate dominance

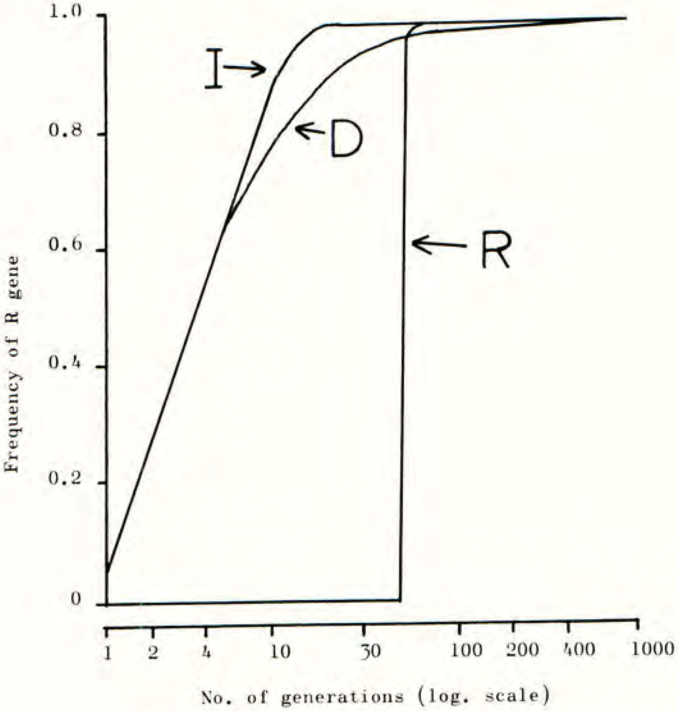


Figure 2. The rate of increase of a resistance gene in a population when the proportion of individuals which escape exposure (E) varies from 0 to 0.5. The gene is of intermediate dominance and is initially present at a frequency of 0.0001 (After Georghiou and Taylor, 1977b).

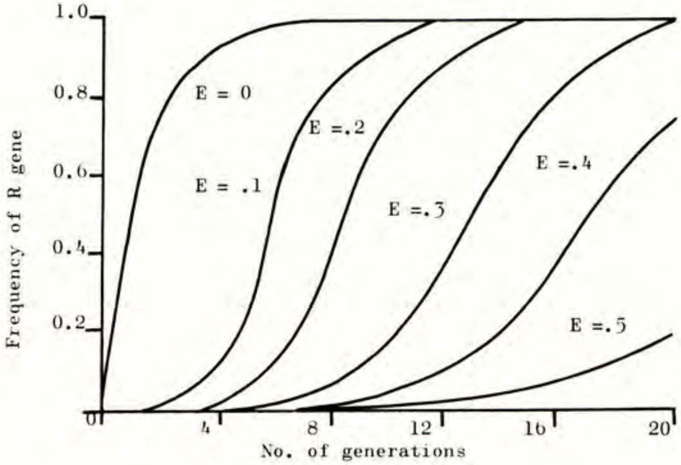
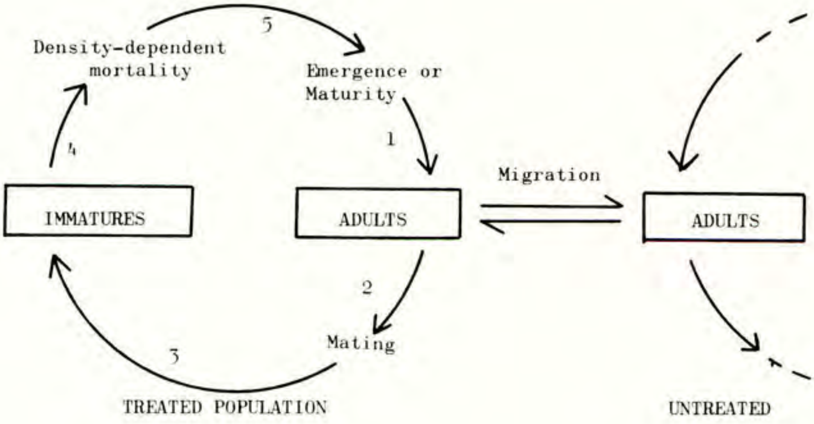


Figure 3. A schematic representation of the life-cycle of a pest with discontinuous generations. The migration of adults results in gene flow between treated and untreated populations. Five stages at which insecticides might be applied are identified (see text for details).



following density-dependent regulation is preferable to (4). Unfortunately this type of precise timing is of little benefit against populations which contain immatures and adults at all stages of development.

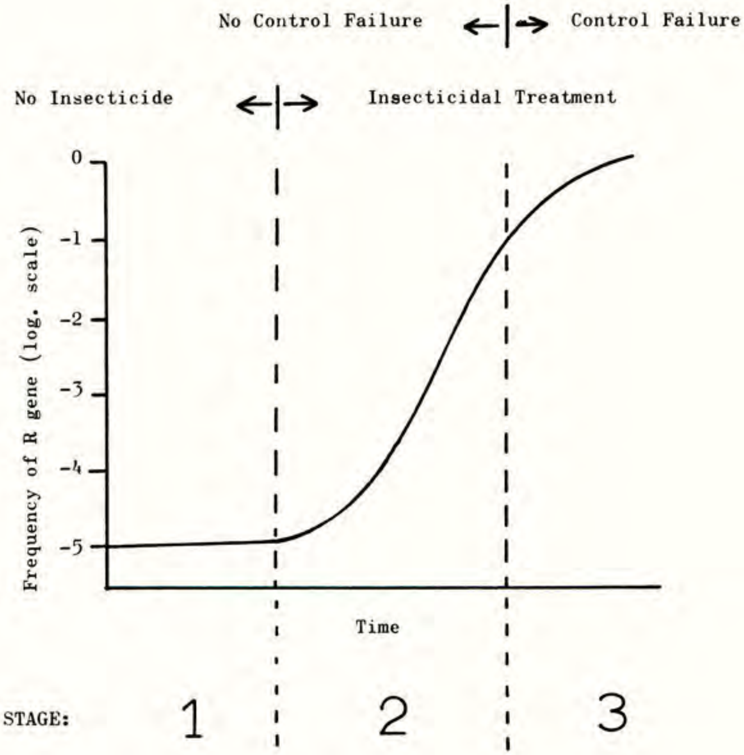
These then are the main areas on which attention has so far been focussed. We cannot as yet assess how important these options will prove in the formulation of resistance-countering strategies because they have not been tested under field conditions. One notable exception is the work done by C.F. Curtis and his co-workers to test the feasibility of applying their theoretical model (Curtis et al, 1978) to suppress the development of resistance in anopheline mosquitoes. This model suggested that a strategy which involved spraying adjacent sectors of a grid with unrelated chemicals could utilise the migration of adult mosquitoes between sectors for preventing resistance to either compound. Preliminary field studies in Sri Lanka were directed towards quantifying these migration rates and determining what size these sectors should be (Curtis and Rawlings, 1980). However after further theoretical work, Curtis (in Wood, 1981) now doubts that this strategy can be effective in delaying resistance and other options are being considered.

Future needs Mathematical models of resistance have to make certain assumptions regarding the status of R genes prior to exposure to a selecting agent. Figure 4 is a schematic representation of three stages in the development of an R gene in a pest population. The first of these stages refers to the period before treatment, in which it is generally assumed that the R gene is already present at an extremely low frequency. Its rarity at this stage may be due to the disadvantageous properties of R genes in the absence of selection with insecticides so that only the rate of mutation of S to R (occurring perhaps once in 10^5 or 10^6 individuals) maintains them in a population. Unfortunately, at present we are unable to verify these assumptions because it is impossible to detect and monitor genes at such low frequencies. Since the subsequent response of a population depends on the initial presence and frequency of these genes, modelling would greatly benefit from the development of sensitive screening techniques to assess the resistance potential of untreated populations. R genes may be much more common in these populations than is usually supposed but still be undetectable by current techniques.

During stage 2 the R gene increases in frequency to the point at which control failure becomes apparent. It is this process that mathematical models have attempted to describe. However, realistic models to describe this second stage development cannot be formulated until we have a much better understanding of complications likely to arise in the field. It now appears that existing data for specific cases of resistance will be of little help in this respect. The long-term study by J. Keiding on the development of multiple resistance by Danish houseflies, undoubtedly the most comprehensive of its kind ever performed, was inadequate for producing a model to describe the spread of resistance to dimethoate on animal farms because information on essential ecological parameters was missing (Gibson, in press.) This work has nonetheless served to emphasise the difficulties involved in interpreting observed changes in susceptibility even when such well-documented evidence is available.

Modelling for resistance therefore needs a different approach i.e. the examination of the situation in the field coupled with detailed research into its development and nature in the laboratory. Because of the complexity of the problem, initial work must be directed towards the construction of a satisfactory model for one pest and one group of insecticides. This requires the collaboration of many disciplines such as genetics, biochemistry and ecology to generate the large and diverse input necessary for such a model.

Figure 4. Three stages in the development of a resistance gene in a pest population under insecticidal treatment (see text for details).



At Rothamsted Experimental Station we are using this multidisciplinary approach to study the development of resistance to pyrethroids in the housefly (Musca domestica L.). The recent introduction of photostable synthetic compounds to control flies on animal farms in the U.K. has provided us with an opportunity to monitor changes in susceptibility which results from their use, and to construct a model to describe the spread of resistance within farm populations and over the Harpenden area as a whole. Many of the important ecological parameters are now being determined for field and laboratory populations. Simultaneously, we are investigating the genetics of the polyfactorial resistance to pyrethroids in houseflies and are identifying the biochemical nature of the resistance mechanisms. This work should enable us to construct a purpose-built model, and we hope that this will be sufficiently versatile and robust to be tested against other species and that it can form the basis for the formulation of successful strategies to counter the development of resistance.

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IMPACT OF FUNGICIDE RESISTANCE ON DISEASE CONTROL

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Summary The risk of disease control failure due to development of fungicide resistance is considered in relation to properties of the fungicide, especially systemic, selective and specific action. Attention is paid to the consequences of fungicide resistance for the farmer, the manufacturer, the consumer, the extension service and the regulatory authorities. Future problems and the prospects for development of fungicides with low resistance risk are discussed.

INTRODUCTION

Failure of disease control due to development of fungicide resistance in plant pathogens has, in recent years, become a frequent phenomenon in agriculture. It may have a significant impact on disease control in field crops as well as in the harvested product both in the developed countries and in the tropics. Development of fungicide resistance may cause yield losses for the grower, endanger the financial returns for the manufacturer and thwart the advice of the extension officer. It affects agriculture at the level of both economic farm management and of world food production, and it should further be a matter of consideration for national regulatory authorities.

Some of the new fungicides seem to be less risky with respect to the occurrence of fungicide resistance than others. The fungicide resistance hazard appears to vary also for different types of disease. In view of this, those factors which may play a role with respect to the build-up of a resistant pathogen population will be discussed. Attention will be paid to the selective and specific action of the fungicide, its systemic properties, the fitness of resistant strains, the nature of the pathogen and the type of disease. Finally, the situation with respect to chemical disease control in the future and the prospects for development of adequate fungicides with a low risk for resistance will be discussed.

THE CONCEPT 'RESISTANCE'

When in a pathogen population, which as a whole is sensitive to low or moderate concentrations of a fungicide, forms are present or emerge by mutation or otherwise with a significantly decreased sensitivity to this fungicide, one speaks about 'resistance'. It has been recommended by the Food and Agriculture Organization of the United Nations to reserve this term for a stable, genetically based decrease of sensitivity, and not to use the word 'tolerance', as it is ambiguous (Anon., 1979). The word 'insensitivity' is less adequate, since it suggest a complete lack of sensitivity, which will seldom be the case.

When dealing with a plant pathogen, the occurrence of fungicide resistance may be investigated in various ways. It may be studied *in vitro*, either with or without use of mutagenic agents, or *in vivo* by testing isolates from the greenhouse or the field with respect to sensitivity to the fungicide. Less sensitive isolates falling outside the normal distribution curve of sensitivity to the fungicide are called 'resistant'. Comparison with base line data is needed to establish this. When resistant strains are found *in vitro* or *in vivo* it does not necessarily follow that problems will arise in practice. However, the suggestion that one should not speak about resistance until there has been a failure of disease control is not justified. Disease control failures occur only after a considerable proportion of the pathogen population has become resistant. The build-up of resistant strains is dependent on various factors and hence the concept 'resistance' would become rather vague and dependent on variable circumstances.

When speaking about resistance, it should further be mentioned how the resistant strains were obtained, and data should be provided about the level of resistance and the properties of the resistant strains. In this way, unnecessary alarm for the growers may be avoided.

RESISTANCE HAZARD AND TYPE OF FUNGICIDE

Systemic, selective and specific action

Fungicides such as copper compounds and dithiocarbamates are usually called 'conventional fungicides', since they control disease in the conventional way by protection of the plant at its surface against attack by parasites. Such compounds have in common that they are not systemic and not very selective, affecting a wide variety of pathogens. Most of these compounds do not exert a specific action, as they interfere with the fungal metabolism at many sites.

Many of the newer compounds, however, are systemic, i.e. they are taken up by the plant and transported in the plant system. Since multi-site inhibitors would be too reactive with plant constituents, and hence not be transported, it must be assumed that all systemic fungicides are specific-site inhibitors. This is supported by studies on the mechanism of action of these compounds, carried out so far. The reverse, however, is not necessarily true. Several specific-site inhibitors appear to be non-systemic, e.g. some dicarboximides, organic tin compounds and several aromatic hydrocarbon fungicides.

Within the group of specific-site inhibitors, there is a wide variation with respect to selective action. Some of them act only against fungi belonging to one genus (e.g. the antibiotic validamycin against Rhizoctonia spp.), others against fungi belonging to one order (e.g. the hydroxypyrimidines against powdery mildews) and again others to fungi belonging to one class (e.g. the acylalanines against the Oomycetes). Finally there are systemic fungicides, which have a still wider spectrum of activity, such as the benzimidazoles. But even in the latter case the spectrum of activity is smaller than that of the above mentioned conventional fungicides; benzimidazoles are inactive against Oomycetes and certain other groups of fungi.

The question will be considered whether and to what extent a relation exists between the above mentioned properties (i.e. systemic, selective and specific action) and the development of fungicide resistance. In Table 1, a number of fungicides are listed on the basis of their mode of action (specific, systemic), the occurrence of resistant strains in vitro or on the plant and the estimated risk for failure of disease control. The data from this table give the following indications:

1. The chance to obtains mutants, in vitro or in vivo, which are resistant to conventional, multi-site inhibitors, seems to be absent or very low. The risk for failure of disease control therefore is low for these compounds. One of the few exceptions is the development of resistance to organic mercury in the oat leaf spot pathogen, Pyrenophora graminea (Noble et al., 1966). In such a case decreased sensitivity may be due to detoxification or reduced permeability.

2. In experiments in vitro with specific-site inhibitors, resistant mutants may be obtained in virtually all cases. This holds for systemic as well as for non-systemic specific-site inhibitors.

3. Not all systemic fungicides do encounter resistance problems in the field, in spite of the fact that in many cases resistant mutants were easily obtained in laboratory experiments. The estimated risk for failure of disease control varies from high to very low for different groups of fungicides. The risk estimation, however, is rather crude, as the build up of a resistant pathogen population does not only depend upon the type of fungicide, but also on various other factors.

Table 1

Specific and systemic action of a number of fungicides in relation to emergence of fungicide resistance

Fungicide or fungicide group	Mode of action:		Occurrence of resistant strains:		Risks[3] for failure of disease control
	specific	systemic	in vitro	on plants:	
Copper compounds	-	-	-	-	very low
Dithiocarbamates	-	-	-	-	very low
Chlorothalonil	-	-	-	-	very low
Phthalimides	-	-	-	-	very low
Organic Hg compounds	-	-	+	+	low
Aromatic hydrocarbons	+	-[1]	+	+	high
sec Butylamine	+	-	+	+	high
Dicarboximides	+	-[1]	+	+	moderate to high
Dodine	+	-	+	+	moderate
Organic tin compounds	+	-	+	+	moderate
Acylalanines	+	+	+	+	high
Benzimidazoles	+	+	+	+	high
Dimethirimol	+	+	0[2]	+	high
Ethirimol	+	+	0[2]	+	moderate
Organic P compounds	+	+	+	+	moderate
Carboxanilides	+	+	+	+	moderate to low
Fenarimol, nuarimol	+	+	+	-	low
Imidazoles	+	+	+	-	low
Morpholines	+	+	+	-[4]	low
Triazoles	+	+	+	-[4]	low
Triforine	+	+	+	-	very low

+ with the property; - without the property.

[1] Chloroneb and procymidone have systemic properties.

[2] Concerns obligate parasites.

[3] The risk for failure of disease control is a rough estimation, as it also depends on other factors (type of disease, strategy of fungicide application, etc.).

[4] Occurrence of strains with decreased sensitivity to some of these compounds has been reported.

Fitness of resistant strains

Whether or not a resistant pathogen population will build up in the field from rare resistant cells depends in part on the fitness of the resistant strains in comparison to that of the sensitive wild type pathogen. In many cases, resistant mutants are found which in the absence of the fungicide are less fit than the wild type. It is of crucial importance to know whether such a reduction in fitness applies just to some strains or to all strains which are resistant to the particular fungicide. In the former case, application of the fungicide will select for those resistant mutants which are most fit, whereupon a problem may arise. In the latter case, where resistance is always accompanied by reduced fitness due to a genetic-biochemical link, the build-up of a resistant pathogen population will be hampered or may even be impossible. Such a link has been reported to be probable for the antibiotic pimaricin

(Dekker and Gielink, 1979), and possibly also for some other systemic fungicides. Beever and Byrde (1981) report that strains of Botrytis cinerea with a relatively high level of resistance towards dicarboximides had a higher osmotic sensitivity than normal wild type strains. Growth of these resistant variants was strongly inhibited on an agar medium supplemented with 4% NaCl or with strawberry juice, which reflects lower fitness.

Persistence of the fungicide

A fungicide which is very persistent on or in the plant exerts a continuous selection pressure for resistance on the pathogen population. A fungicide with less persistence may show less hazards in this respect. Interactions between the duration of the selection process and the length of the life cycle of the pathogen have been discussed by Wolfe (1975). He suggests that, if the life cycle is longer than the period that the minimal effective dose is present, a considerable selective advantage for resistance may exist, since the selected organism will presumably be well-fitted to environments both with and without the fungicide. If the life cycle is shorter, individuals selected for resistance may be unsuited to the environment after the disappearance of the fungicide.

RESISTANCE HAZARD AND TYPE OF DISEASE

Failure of disease control may occur when the majority of a pathogen population has become resistant. In addition to the type of fungicide, the nature of the pathogen and the type of disease may have an influence. Fungicide resistance will build up more rapidly in a pathogen which sporulates abundantly than in a pathogen which sporulates scarcely or produces spores which do not spread easily, as is the case with several soilborne, root or stem base pathogens. For instance, development of resistance to benzimidazole fungicides has occurred rapidly with various powdery mildews and Botrytis diseases, but until now not with eyespot (Pseudocercosporella herpotrichoides) in cereals (Horsten and Fehrmann, 1980). In the latter case the infection threshold, the minimum amount of inoculum for successful infection, is high so that the appearance of single mutant cells will rarely result in infection by resistant strains and thus the resistance risk will be low.

Another example is the rapid development of resistance to metalaxyl (Ridomil) in late blight (Phytophthora infestans) of potato in 1980 in The Netherlands (Davidse et al., 1981). This is a pathogen which, under suitable weather conditions, may spread explosively from very few foci. Thus a resistant pathogen population may be formed rapidly from only a few mutant cells under selection pressure by the fungicide. On the other hand, control of sunflower downy mildew with metalaxyl by treatment of the seeds has not yet met with resistance problems; in this disease systemic infection takes place by spores remaining in the soil and the vegetative summer cycle of this pathogen does not play an important role.

The pathogen which causes cedar apple rust, Gymnosporangium juniperi-virginianae, even lacks a repetitive summer cycle on the apple host, where it forms only spermagonia and aecidia. Control failure due to resistance of this pathogen to benzimidazoles has not yet been observed, whilst Venturia inaequalis on the same fruit trees has become resistant (Gilpatrick, 1981).

It is further striking that no resistance problems have occurred after treatment of wheat, barley or maize seed with carboxin against smut, even though resistant mutants could be obtained easily in vitro and did not show reduced fitness (Georgopoulos et al., 1975). It has been suggested that this might be attributed to the low apparent infection rate of smut pathogens (Georgopoulos, pers. comm.).

It will also be clear that the degree of selection pressure by the fungicide, needed for control of a particular type of disease, will play an important role.

IMPACT OF FUNGICIDE RESISTANCE

The farmer

In several cases, disease control failure due to development of fungicide resistance has occurred after only a short period of use of the fungicide involved, and in other cases after a more or less prolonged period of time. In almost all cases, however, failure of control came as a surprise, and the cause was mostly not recognized. Often farmers reacted by more frequent applications and higher doses of the same fungicide. When it became clear that fungicide resistance was involved, the damage had already occurred. In such cases the farmer is confronted with unexpected crop losses. Examples are the development of resistance to dimethirimol in powdery mildew on greenhouse grown cucumbers in 1970 in The Netherlands, to kasugamycin in *Pyricularia oryzae* on rice in Japan in 1971, to benomyl in *Cercospora beticola* on sugar beet in Greece in 1972 and in *Venturia inaequalis* on apples in Northern Germany in 1974 and resistance to metalaxyl in *Phytophthora infestans* on potatoes in The Netherlands and in the Republic of Ireland in 1980. In the last case, the damage to the crop in The Netherlands was in the order of magnitude of several million guilders. In some of these cases farmers have sought loss compensation from the manufacturers via the court.

There is a second point of importance to the farmer; by the sudden development of resistance he may lose the use of an excellent compound upon which he has become dependent for efficient control. In the case of metalaxyl resistance in The Netherlands and Ireland, the manufacturer withdrew 'Ridomil' from the market. When in the next year, 1981, a heavy blight epidemic occurred in the Netherlands, officially no "Ridomil' was available, not even in areas where no resistance occurred in the previous year, and where it could have saved the crop. The compound made, however, a good price on the black market.

Finally, the development of resistance may confuse the farmer, when careful application of the fungicide, according to the recommendations given by the manufacturer and the extension service, does not lead to satisfactory disease control.

The agrochemical industry

The failure of a fungicide may have several consequences, not only for the manufacturer of the product, but also for the agrochemical industry as a whole. If it leads to reduced sales, the financial returns of the compound, which has been developed by the company at high cost, may be endangered. Moreover, as has happened already in several cases, farmers may file a law suit against the manufacturer, claiming compensation for losses due to inadequate disease control. This will prompt the manufacturer to carry out experiments in order to estimate the resistance hazard of a new product; it seems, however, not yet possible to provide a prediction with certainty (Dekker, 1981). These events increase the risks undertaken by a manufacturer, and it may make the chemical industries more hesistant in developing new fungicides (Schwinn, 1981). This, in its turn, may be unfavourable for the farmer, who needs a variety of chemicals for efficient crop protection.

The extension officer

Development of resistance may thwart the advice given by the extension service, and farmers may lose confidence. It is therefore necessary that farm advisers keep abreast of new developments with respect to the fungicide resistance problem, and that they know how to reduce the risks and what should be done when resistance is observed.

Regulatory authorities

In addition to data about the effectiveness of a new compound and its toxicological effects, the potential risk of resistance may be a point of consideration. In addition, knowledge of the potential risk should encourage the regulatory authorities to be cautious with respect to classical fungicides, which should not be abandoned upon the introduction of newer fungicides. They may be needed as companion or alternative product to fungicides 'at risk' (Schwinn, 1981).

The consumer

The consumer may be effected when due to severe losses by resistant pathogens the cost of agricultural produce would increase, or when some produce would locally and temporarily not be available. This will not happen very readily, at least not in the developed countries. However, if it did occur in a staple crop or in a high value export crop in a developing country, it might have a serious impact on the population and on the economy (Schwinn, 1981).

PROSPECTS

It has to be expected that with the development of more selective and more efficient new fungicides, the danger of development of fungicide resistance will increase in the future. This holds especially for the developing countries, where selective fungicides are expected to be used to a considerable extent in the future.

In addition to the development of strategies to avoid fungicide resistance, when dealing with compounds at risk, efforts should be continued to find fungicides with a low risk for resistance. The fact that a wide variation exists with respect to the hazard of fungicide resistance even within the group of specific-site inhibitors is encouraging. Some compounds, where resistance is linked to decreased fitness, are less hazardous in this respect. It would be of interest to know whether cases could be found, where mutations for resistance would be all lethal, thus precluding the emergence of resistance.

Until the present, several compounds have been developed which are not or only slightly fungitoxic in vitro, but still provide effective disease control in the field. So far, no breakdown of disease control has been observed with these compounds. In an experiment over a prolonged period of time with tetrachlorophthalide, active against rice blast, Uesugi (1981) did not observe a decrease in effectiveness of this compound. It should be explored whether artificially induced resistance in the host by such chemicals can be broken by the pathogen.

Finally, the use of chemicals might be considered which provide disease control by selectively favouring antagonists of the pathogen (Dekker and Langerak, 1979). As a means of biocontrol, some authors even consider the introduction of antagonists which have been deliberately produced by laboratory manipulation for their resistance to the fungicide (Papavizas et al., 1981).

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STRATEGIES FOR DEALING WITH FUNGICIDE RESISTANCE PROBLEMS

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Summary Resistance to fungicides, a serious problem, can be delayed or prevented by early use of spray programmes designed to preclude long-term exposure of a pathogen to a single fungicide. This is done by the use of a companion fungicide with a different mode of action in mixtures and/or rotation schedules. Examples of strategies in use for different groups of fungicides are discussed and recommendations for future action are presented.

Résumé La résistance aux fongicides est un problème grave qui peut être évité ou retardé par l'usage opportun de programmes de traitement ayant pour but d'éviter d'exposer regulièrement un champignon pathogène a un seul même fongicide. Ceci est effectué grâce à un fongicide annexe ayant un mode d'action différent, en application mélangée et/ou en rotation. Des exemples de stratégies utilisées pour différents groupes de fongicides sont présentées et des recommendations visant de futurs programmes sont formulées.

INTRODUCTION

It is quite evident from Professor Dekker's presentation that many of the most effective fungicides have a propensity for resistance. Therefore, it is in the best interests of all concerned with the control of plant diseases to prolong the effective life of fungicides by using them in such a way that resistance problems are avoided. Not only is the strategy for use very critical but so is the need to start soon after introduction, before subjecting the wild population of the pathogen to excessive selective pressure. A most hazardous situation occurs when many fungicides with a similar mode of action and cross-resistance are developed and marketed by different companies (e.g. sterol inhibitors). This calls for increased care and responsibility to avoid abuse by one which can create resistance problems for the others. Fortunately, there are ways to delay and avoid resistance problems. But it will take study and discipline to use them effectively.

SUMMARY OF STRATEGIES

Resistance can be mitigated or prevented by early use of spray programmes designed to preclude long-term exposure of the pathogen to a single fungicide. The reality is that coping strategies range from abstinence to exclusive use until there is evidence of a resistance problem. There are situations where the risk of resistance appears too great to justify development of a fungicide. Also, the tedious governmental registration processes frequently restrict desirable options for recommendations to prevent resistance. It can be difficult, in some countries impossible, to register mixtures for this purpose. The logic and effectiveness of starting coping strategies immediately with the introduction of a new product can be overridden by these economic or registration restraints.

The use of a companion fungicide with a different mode of action is a basic tool in many effective strategies. Emerging resistant strains can be eliminated or held at insignificant levels by the companion. Either multisite or specific-site agents may serve as an effective companion. Of course, the multisite companion with little likelihood of resistance further reduces the risk of crop failure. There should be no significant amount of resistance to either companion because combinations have been effective only when used before resistant strains begin to dominate a population.

The rates of the components of these mixtures may vary for many reasons including relative effectiveness, residual qualities, economics, etc. A most important factor is the relative pressure on resistant strains. If the companion is weak, it may need to be used at full strength. Where disease control objectives permit, the fungicide with a propensity for resistance should be used at a reduced rate to decrease selective pressure. So far, there is little evidence for development of fungicide resistance in the field from a gradual adaptation to sublethal levels of fungicides. Until this effect is documented with fungicides, it makes sense to use lower rates to reduce selection pressure.

Rotation of agents with different modes of action is another strategy to reduce the exposure of the pathogen to one fungicide. There are many possible variations in rotation schedules.

As a preventive strategy, the specific-site component should not be used repeatedly alone. But it is possible to use a fungicide until it loses some effect then repeat it's use after a rotation period with an alternative fungicide. Re-entry is possible where the resistant strains are poorly fitted and drop out of the population rapidly. This must be done carefully, of course, because the use of agents alone can be risky where resistance once caused product failure. Consideration can be given to re-entering a spray programme even where resistant strains appear well fitted for survival. This is because some unexpected factor can put a selective action against the resistant strains leaving mostly sensitive strains. These situations can be detected with monitoring programmes or by field trials. Re-entry must be done with caution and, to reduce risk, with mixtures.

There are special situations where a fungicide or fungicide mixture will provide unique advantages as a critical treatment or two. For instance, it is tempting to reserve some agents with curative effects for times when disease has "gotten away". This may be a most undesirable strategy, however, because it uses the compound during a high sporulation and reproductive time which can result in maximum resistance selection. In addition, the use must be sufficient for the company to justify continuation in the market.

Schematic presentation of strategies:

S = specific-site agent with high propensity for resistance
M = multisite agent with little chance of resistance problem

	Exclusive	
S → S → S → S		Greatest chance for selection
	Mixtures	
S+M → S+M → S+M → S+M		Reduced selection if started soon M should be strong
S+S' → S+S' → S+S' → S+S'		S and S' have different modes of action Start when no resistance to S or S'
	Rotations	
M → S → M → S		S for critical use in schedule
M → S → M → M		More effective if S has short residual
M → S+M → M → M		Most effective in high risk situations

THEORETICAL AND MATHEMATICAL MODELS

There are a complex of interactions of factors which impact on the population dynamics of fungicide resistant strains. Unfortunately, solid data are lacking for many components of the models and assumptions have to be used. Even with these shortcomings, models help define those factors which seem to have an impact on resistance.

At Du Pont, models helped us to formulate a primary strategy with benomyl based on using mixtures with strong, unrelated companions as soon as possible. Using a completely different model, Kable and Jeffery (1980) verified that mixtures are more effective than alternating programmes except in the almost impossible situations where application methods attain complete coverage of the target. Also, Skylakakis (1981) developed equations to predict the direction and sometimes the speed of change of the proportion between fungicide resistant and sensitive populations. Factors that affect the speed of resistance build-up are measured by a new parameter called "standard selection time". A general conclusion from preliminary studies with this model was that mixtures were the best strategy under conditions where the pathogens have slow infection rates and low fitness. On the other hand, rotation programmes designed to limit the total time the population is exposed to selective pressure may be the best strategy when resistant strains have high infection rates and fitness.

CURRENT EXPERIENCES

Various ways that some resistance problems are being handled are summarized by related agents in alphabetical order.

Acylalanines, those highly active systemic agents for the control of Oomycetes, gained broad acceptance and high market penetration because of their curative and residual qualities. Unfortunately, in 1980, there were cases of non-performance of metalaxyl due to resistant strains of cucumber downy mildew *(Pseudoperonospora cubensis)*, potato late blight *(Phytophthora infestans)*, and tobacco blue mold *(Peronospora tabacina.)* Recently, resistance has been found in *Plasmopara viticola* in South Africa.

Resistance has occurred under high infection pressure, on susceptible cultivars and when the product was used alone and exclusively on a curative or extended interval between sprays. The Ciba-Geigy strategy is to use mixtures with residual fungicides against foliar pathogens, and so far there are no resistance problems where mixtures have been used from the beginning. Since many growers tend to ignore recommendations of tank mixing, they are marketing pre-pack mixtures where possible. It is important that the related acylalanines be used in ways to avoid resistance because cross-resistance will make all of these acylalanines ineffective.

Benzimidazole-resistant strains selected out of a broad spectrum of fungal populations are cross-resistant to benomyl, carbendazim, thiophanate methyl and thiabendazole, but they usually retain sensitivity to unrelated fungicides. Therefore, strategies for avoiding resistance include the use of unrelated fungicides. The reduction of selective pressure by reducing treatment number and rate and the control of emerging resistant strains by mixtures with unrelated companion fungicides has delayed and prevented resistance problems (Delp, 1980).

Many benzimidazole-resistant strains are fit for survival and may stay as a part of the pathogen population for several seasons. Typical examples are *Venturia* and *Botrytis* spp. On the other hand, some resistant populations of *Cercospora, Mycosphaerella, Erysiphe and Penicillium spp* have dropped to manageable levels so benzimidazole fungicides are effective again. Of course, re-entry into an area that previously had a resistance problem must be done with caution because there is a higher risk of failure. Levels and percentage of resistance in a population may be determined by monitoring techniques, but the relationship of these data to loss of disease control is often not clear.

Some of the effective strategies recommended by Du Pont Co. are:

- The use of benomyl (sometimes at reduced rates) is recommended in combination with a strong unrelated fungicide. This is especially effective to avoid resistance problems when started before exclusive use of benomyl, such as against peanut Cercospora, strawberry Botrytis, and stone fruit Monilinia.

- The use of benomyl is also recommended in one or two critical sprays in addition to full-season fungicide programmes in situations where the traditional programme is inadequate. This provides economic yield boosts in coffee *(Colletotrichum coffeanum)*, banana *(Mycosphaerella spp)*, apples and other crops.

- Under conditions where no companion is available, benomyl has been used alone. Resistance is not a problem yet where exclusive use has been limited to once or twice each season for control of soybean and cereal diseases. On the other hand, citrus *Mycosphaerella citri* subjected to a single treatment each year is a resistance problem in Florida.

Dicarboximide-resistant strains of *Monilinia* and *Botrytis spp* are easily developed in laboratory cultures and are occasionally selected from the field. So far, most cases have not developed into serious field problems, apparently because the resistant strains are less fit for survival. The companies marketing iprodione, procymidone and vinclozolin are carrying out trials with mixtures in order to develop programmes to avoid resistance problems. They also have studies with resistant strains and are on the lookout for the emergence of persistent field problems. When the problems do emerge it could be too late to make the most effective use of preventive strategies. Therefore, mixtures or rotations are being recommended by many investigators and distributors.

Kasugamycin-resistant *Pyricularia oryzae* strains are less fit than the wild strains and will drop out of a population when the selective pressure of this antibiotic is removed. But it is necessary to use mixtures and alternating programmes to avoid failure of kasugamycin in areas where this popular rice blast fungicide was used exclusively (Uesugi, 1979). A combination product of a reduced rate of kasugamycin plus phthalide is used in rotation with phthalide and probenazole which have different modes of action. Hokko Co. recommends the use of this mixture in rotation with different fungicides for the successful prevention of resistance in Japan.

Pyrimidine fungicides illustrate the complexity of interactions even in closely related compounds and pathogens. No resistant apple powdery mildew has yet resulted in a failure of bupirimate. On the other hand, cucumber powdery mildew soon overcame intensive use of dimethirimol as a soil-applied systemic in glasshouses. The product was withdrawn for a few seasons and re-introduced with a restriction of only one application per season, but resistance recurred and dominated in a short time. Under less intensive use in the field, dimethirimol continues to perform satisfactorily against cucumber powdery mildew in many places.

On barley, with widespread and successful use of ethirimol as a seed treatment, there was early evidence of a shift in sensitivity of barley mildew in the United Kingdom. In the absence of ethirimol, the mildew population rapidly regained sensitivity, and a strategy was developed to withdraw use on winter barley so that it would have maximum effect on the more critical spring crop. Now the treatment of the winter crop has been successfully re-introduced because of changing crop practices and the broad use of unrelated fungicides.

Organic tins are contact fungicides with what appear to be multiple modes of action, but after several years of exclusive use and by the end of each treatment season, the control of *Cercospora beticola* by triphenyl tin acetate is unsatisfactory on sugar beet in Greece. The selective pressure from one season has not carried over to the next so the strategy is to start the season with fentin and switch to an alternative fungicide when effectiveness is lost about mid season.

Sterol inhibitors are a formidable group of fungicides with potential for broad use and complex resistance problems. There are so many highly active compounds, all with cross-resistance because they all stop fungi by the inhibition of ergosterol biosynthesis. Fully pathogenic resistant strains are easy to select in the laboratory. So far, field resistance has been rare but shortly after the introduction of imazalil for citrus treatment, resistance became a problem with *Penicillium spp.* Most other uses have been of a relatively low exposure so far, but intensive use will soon be common. There is much hope and some serious scientific speculation that all resistant strains will be unfit for survival and, therefore, will not be a problem. Unfortunately, much of the recommended use is based on this hope. But scientists around the world are watching for fit resistant strains to dominate pathogenic populations. There is a lot of speculation as to the best strategies to use to cope with these potential problems. Some scientists are using lessons from the experiences with other fungicides and are recommending various preventive measures. In some cases reduced rates of the sterol inhibiting fungicide are combined with other agents, even systemic fungicides, with different modes of action.

RECOMMENDATIONS

There are many actions necessary to cope with resistance problems. Many will require cooperative efforts between the various segments of our society promoting the use of fungicides. Specific recommendations for each segment are outlined below:

Industry

- Keep old reliable fungicides available.
- Discover new fungicides with different modes of action.
- Establish cooperative action to cope with resistance.
- Test strategies, monitoring and population dynamics.
- Promote best strategies.

Government and Academic Institutions

- Keep large arsenal of potential products.
- Test strategies.
- Educate industry, regulating agencies and growers.
- Cooperate with industry and advisors on resistance research and communications.

Regulatory Agencies

- Keep old reliable fungicides available
- Consider need for keeping all products free of resistance problems.
- Register effective strategies before serious field problems occur.
- Register mixtures aimed at reducing the risk of resistance.

Growers and Advisors

- Be aware of reasons for complicated disease control programmes.
- Give long-term consideration to product use (don't abuse and lose).

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SESSION 10

ROLE OF APPLICATION TECHNOLOGY IN PEST MANAGEMENT

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SOME FACTORS AFFECTING THE EFFICIENCY OF SMALL PESTICIDE DROPLETS

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Summary The relationships between droplet numbers, droplet size and chemical concentration on the effectiveness of pesticide sprays are as yet little understood. Reductions in droplet size on the leaf dramatically reduce the amount of chemical required to kill a pest. Chemical concentration is an important factor in improving efficiency against static targets, while leaf surfaces can alter pesticide performance.

Limited tests have shown that formulation can also dramatically affect pesticide efficiency. LD_{50} values for second instar whiteflies Trialeurodes vaporariorum using 10% permethrin formulated in five ways varied from .41 µg/cm^2 to 3.18 µg /cm^2 using 50 µm diameter droplets.

During the last few years the glasshouse industry, in common with other branches of agriculture and horticulture, has been under economic pressures to streamline production and maintain profitability. These changes have changed crop protection practices, with integrated pest management being more widely used each year. New ULV pesticide application techniques are in use, involving thermal fogging and spinning disc equipment.

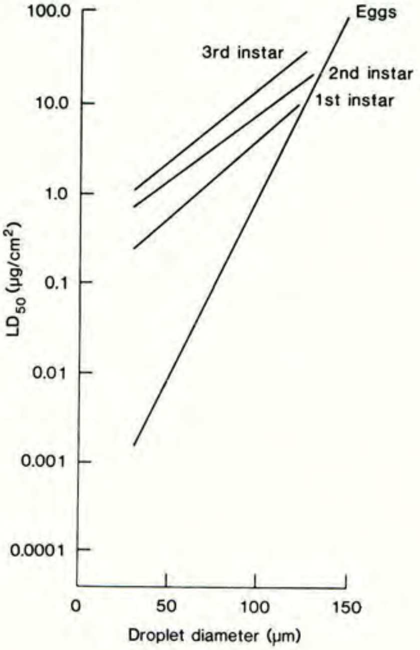
Jarrett, Burges and Matthews (1978) reported on the deposition of Bacillus thuringiensis spores on densely planted chrysanthemums using a CDA and spinning equipment and compared results with a HV spray. Although CDA and fogging wasted less spray this economy was nullified by uneven distribution of the deposits. There was no underleaf cover with thermal fogs while, with CDA, deposits ranged between 0.1 and 204 bacterial spores per sq cm on more or less accessible underleaf surfaces. This study poses the question, if insecticides were being used how many droplets per unit area would provide effective control of a particular pest? Mboob (1975) in his study of two application machines (Turbair Tot and Microgen) against whiteflies showed that, although each droplet produced by the Turbair contained 80 times more chemical than those produced by the Microgen, the latter sprayer needed to deposit some 15 times as many droplets to achieve a similar efficiency. This study poses a number of questions concerning the relationships between drop sizes and chemical concentration.

At the GCRI answers to a number of apparently simple questions are being sought. What are the inter-relationships between droplet numbers, droplet size and chemical concentration and formulation with respect to biological efficiency of sprays? Such studies have only been concerned with droplets after they have impacted on the leaf surface.

The data from a large number of bioassays involving tens of thousands of whiteflies (Fig. 2), clearly shows that reducing droplet diameters considerably reduced the amount of permethrin required to kill whiteflies of any instar. Similar trends have been shown with dicofol against spider mites (Tetranychus urticae). By defining the amounts of chemical required to kill (LD_{50}) a particular whitefly stage, the data (Fig. 2) indicate that eggs are extremely susceptible to the pesticide relative to other stages. As much as 100x more chemical would be needed to kill first instar larvae. In practice, therefore, the best target to kill would be eggs which tend to be laid on the undersides of young leaves, a clearly defined habit within the plant canopy.

Figure 2

Relationships between droplet diameter and LD_{50} using 30% permethrin against various developmental stages of T. vaporariorum

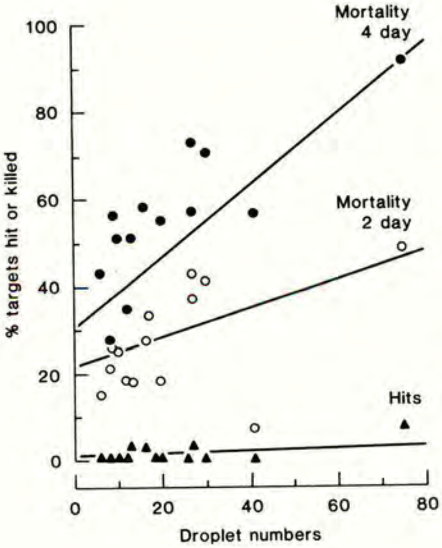


A thorough study (Munthali, 1981) using dicofol against red spider mites (Tetranychus urticae) clearly illustrates the importance of some parameters, while indicating the complexity of the subject, and how little is known about the behaviour of pesticide droplets on leaf surfaces. The same bioassay techniques (Munthali and Scopes, 1981) are being used to study the effects of permethrin against whiteflies (Trialeurodes vaporariorum).

To stimulate further thought and discussion on these problems I would like to illustrate in very simple terms some of the results of bioassays using mono-sized droplets applied through a microtip nozzle (Uk, 1978).

Figure 1

Bioassay of T. vaporariorum eggs sprayed with 36 µm droplets of 10% permethrin

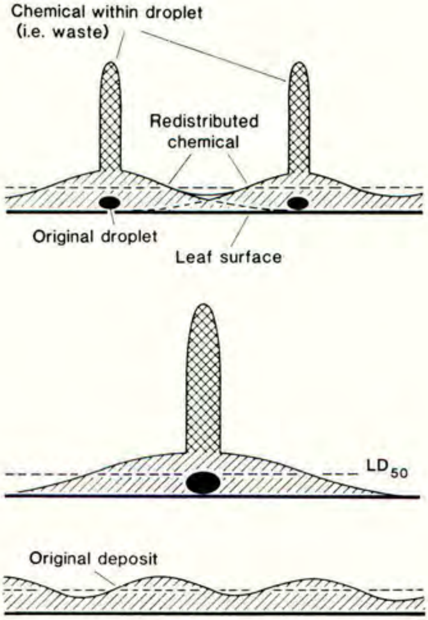


Although 77 droplets per sq cm were applied in one leaf disc, a typical bioassay using permethrin against whiteflies (Fig. 1) showed how few targets (less than 10%) were actually hit by the spray. Mortality increased during the four days that the bioassay was conducted, suggesting that the permethrin spread across the leaf from the points of impact of the droplets.

Why are large droplets less efficient? Is the ideal spray a thin, but continuous, deposit of chemical (Fig. 3)? The wastage of pesticide by applying large droplets is clear (middle diagram). Perhaps an important criterion is the droplet circumference in relation to volume, and bearing in mind that the amount of chemical may decline rapidly as the distance from the point of impact increases, larger numbers of small droplets would appear to be preferable. The continuous deposit obtained with HV spraying is achieved by the efficiency of the operator while efficiency of an LV application relies, in part, on the spread of the chemical once the droplet has reached the leaf. This may, perhaps, be improved by applying larger numbers of small droplets or by formulation. It is also easy to imagine that highly charged droplets, as produced by an electrostatic sprayer, would shatter on impacting on a leaf so producing large numbers of even smaller droplets, thereby improving effectiveness. The production of small droplets with electrostatic charges should not cause human hazards by drift so that such techniques could prove invaluable. Extrapolating the data so far obtained at the GCRI, the minimal amount of chemical required to kill target pests would be delivered with a very small droplets, perhaps less than 10 µg diameter. Electrostatic spraying is obviously a desirable method of impacting small droplets on surfaces.

Figure 3

Hypothetical distribution of pesticides from HV application (bottom) compared with large (middle) and small (top) discrete droplets

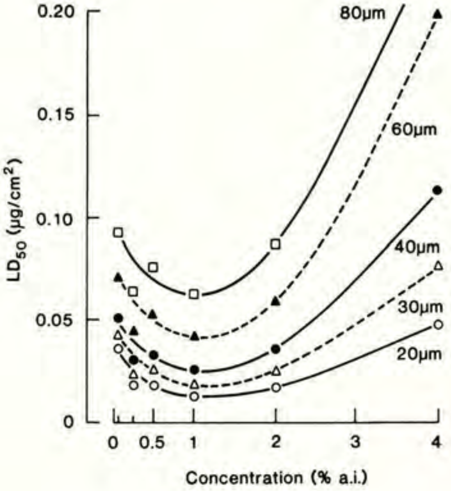


Now that assay techniques are available for small numbers of mono-sized droplets, many parameters can be tested.

Concentration of the pesticide appears to have an important effect on efficiency regardless of droplet size. Fig. 4 (Munthali, 1981) shows not only the amounts of dicofol needed to kill T. urticae eggs using various droplet sizes, but also that a 1% solution of the pesticide is most efficient, more chemical being needed as higher or lower concentrations are used. (As might be expected, this efficiency increases with decreasing droplet size.) These data apply to one chemical and similar data for other chemical-pest systems could define the requirements of a target when one of three parameters, droplet size, numbers, or chemical concentration, is now known.

Figure 4

Relationships at constant droplet diameters between dicofol concentration and mortality of T. urticae eggs



The results clearly suggest that, after application, pesticide from the droplets is redistributed across the leaf. Fig. 1 (egg data) suggests that minute amounts can cover large areas, but our experience with the scanning electron microscope does not indicate such movement. Other studies in progress, however, do show that droplets spread. Obviously formulation has a very important role in efficiency. In Table 1, 10% permethrin was formulated in 5 different solutions and sprayed onto second instar whiteflies. Marked differences in LD_{50} values resulted. This data emphasises the need to understand the role of formulating chemicals on biological efficiency.

Table 1

LD_{50} values of whitefly eggs after spraying with 10% permethrin formulated in different solvents

Formulation and ingredient (mixtures)		LD_{50} values ($\mu g/cm^2$)	
		50 µm	80 µm
JF 8130	low volatile chlorinated + paraffinic solvents	1.05	3.72
JF 8131	volatile polar solvent + volatile paraffin	3.18	4.03
JF 8132	volatile polar solvent + low volatile paraffin	.97	4.72
JF 8133	volatile polar solvent + low volatile paraffin + very low volatile paraffin	.84	4.72
VK1	very low volatile polar solvent + low volatile paraffin	.41	1.33

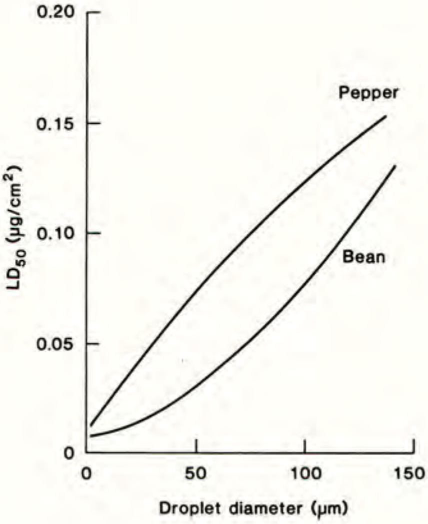
Other variables, such as leaf surface, may also influence biological efficiency (Fig. 5) (Munthali, 1981) and so it may be possible to select varietal characteristics to help in chemical pest control.

Although the data discussed are illuminating they merely stress how little we know about the performance of pesticides on leaves - an aspect that increases in importance as we change from HV to the use of discrete droplets at ULV rates of application. Future improvements in chemical pest control may come, not so much from chemicals, as from the methods of application.

The subject is complex, but a better understanding of the basic parameters may go a long way to improving crop protection.

Figure 5

Relationship between droplet diameter and mortality of T. urticae eggs with 1% dicofol sprayed on bean (Vicia faba) and sweet pepper (Capsicum anuum) leaves



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Recent Developments in Electrodynamic Spraying

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Summary During the past two years ICI have progressed the development of electrodynamic spraying technology and have produced a novel 'closed system' for the hand-held sprayer. This technique is now being researched for eventual incorporation into a vehicle-mounted Electrodyn sprayer. A swath modifying electrode - the 'Deflectrode' - has been developed for the hand-held sprayer. Work is also in progress to determine the lower limits of volume median diameters for the electrodynamic system.

INTRODUCTION

Since November 1979 when first details of the electrodynamic spraying process were announced (Coffee, 1979), there have been several developments.

For example, last year 50 hand-held Electrodyn sprayers were put at the disposal of 50 small-scale farmers in Paraguay, in order to gain user reaction and to test the machine's performance over a whole season. A number of prototype development faults were revealed but, in spite of this, the user reaction was overwhelmingly enthusiastic. Good biological results were achieved, and these will be reported by Morton (1981).

Many other tests, both small and large scale, have been made with herbicides, fungicides, plant growth regulators, and insect pheromones, in addition to insecticides. These will eventually be reported by the biological scientists involved.

In this paper I wish only to mention some of the salient technological work that has progressed during the past two years.

CLOSED SYSTEM SPRAYING

One of the most significant features of electrodynamic atomization is that small droplets may be produced accurately without the need for mechanical-energy devices such as spinning discs. High-voltage nozzles may be mass-produced very cheaply from plastic materials, and these may readily form an integral part of a plastic pesticide container.

Thus we have the necessary ingredients for a closed system, one in which a sealed chemical container may be 'plugged' into the sprayer so that the operator has no need to fill or mix chemicals.

The first embodiment of this principle has been the recently announced "Bozzle" packaging device (Coffee 1981). This is a disposable package, in which bottle and nozzle are combined (hence the name 'Bozzle'). In order to contain hydrocarbon materials satisfactorily, the container portion has been specially made out of Polyethylene Terephthalate (PET). The plastic nozzle is also special in that, in addition to the need for dimensional accuracy and stability, it is required to conduct electricity. A semiconducting material has been developed for this.

The Bozzle package, which is being marketed this year, for the first time, contains 750 ml of pesticide. The pesticide is formulated so that, together with the electrical characteristics of the Electrodyn machine, the correct droplet-size, charge-to-mass ratio, and flow rate are all ensured.

Marketing of these devices in 1981 has been restricted to a limited number of countries, including Paraguay, Nigeria, and Thailand. The chemical products being used are those most suitable for cotton pest control, particularly cypermethrin. Both the product range and the marketing regions will increase in the near future.

Several advantages to the user are immediately apparent:

1) No filling nor mixing of chemicals.
2) A high order of spray accuracy is achieved without need for nozzle adjustment or maintenance.
3) Instant use.

Thus there are no toxic hazards due to the handling of chemical concentrates. A new nozzle is supplied with each package, obviating the need for maintenance, and the machine is ready for use by simply inserting a bozzle package and pressing a switch.

One could argue that, by the introduction of the closed system concept, most of the effort and skill required to accurately set up and use a hand-held sprayer have been transferred from the operator to the chemical manufacturer. Such a system has the potential to raise significantly the levels of efficacy and efficiency of hand-held spraying operations wherever it is employed.

The Electrodyn technique can equally well be applied to vehicle-mounted equipment; so too can the closed system concept. This latter, of course, being virtually essential in ultra-low-volume application, where chemical is sprayed in high concentration. Although such a development involves a number of formidable tasks not least of which is determining chemical rates, a program has been in hand at ICI for the past two years, and has progressed very satisfactorily. Field tests so far indicate that biological results are at least as good as those achieved with hand-held Electrodyn sprayers. It is hoped that the first of these units will be developed and ready for limited marketing by 1984.

THE 'DEFLECTRODE'

The shape of an electrically charged spray cloud can be usefully modified by the application of an intense electric field. Using the high voltage source (25 kV) of an Electrodyn sprayer it is possible to manipulate droplet trajectories with one, or more, electrodes attached to the machine. Such electrodes consist of a conducting wire, sleeved with insulating material. The device operates on a field-effect principle, in which a force $q\vec{E}$ is imparted to each droplet; where q is the droplet's charge and E is the strength of the electric field derived from the high voltage source. The technique thus consumes zero energy.

Figure 1 shows the effect of a pair of such electrodes on the shape of a spray cloud close to the nozzle. The exposure time of these photographs was 0.1 second, thus the trajectories seen were created by approximately 100,000 droplets ($\sim$45 μm vmd at flow rate 0.05 ml/sec). The asymmetry of the spray cloud in upper photograph is due to the field-effect of an unscreened high-voltage cable within the handle of the sprayer.

This version of the Deflectrode has been designed for the hand-held sprayer, in order to increase its swath width for use in cotton pest control. The Deflectrode has two limbs which articulate so that they may be placed along the length of the handle when not in use.

Figure 2 illustrates the effect of swath widening. By opening the Deflectrode limbs and holding the sprayer at about 80 cm above the crop (cotton), a swath of about 2.7 m was observed in the first trial. The asymmetric pattern of the spray indicated in the sketch ensures that the operator is not contaminated by the spray. Tests indicate that operator contamination is as low when the nozzle is held at 80 cm above the crop, using the Deflectrode, as it is when the sprayer is held at 40 cm (normal usage) without using the Deflectrode.

Deflectrodes may, of course, be used to manipulate droplet trajectories in other modes of use, such as might be required on vehicle-mounted electrodynamic sprayers. Swaths may be widened, or compressed, symmetrically or asymmetrically, about the nozzle.

ULTRA-SMALL DROPLETS

Oil-based carriers for pesticides are favoured over aqueous ones, because of such features as low volatility, good wetting, and rainfastness. In conventional spray systems however considerable amounts of energy are required to achieve atomisation of such viscous liquids, and volume application rates are often too high for reasonable economic return. Fortunately, however, the electrodynamic method achieves atomisation of heavy oils by acting at a molecular level, within the liquid, thus using ultra-low amounts of energy. The power consumed is, in fact, merely that which is required to raise the electric potential of the microscopic charge carriers within the pesticide liquid. Under typical agricultural conditions this is of the order of milliwatts per nozzle, rather than watts, or even hundreds of watts, employed by conventional atomisers producing droplets of sizes in the range, say, 20–100 μm.

Fig 1 Electrodyn spray cloud without Deflectrode (top) and with Deflectrode (to the right of the nozzle) (bottom)

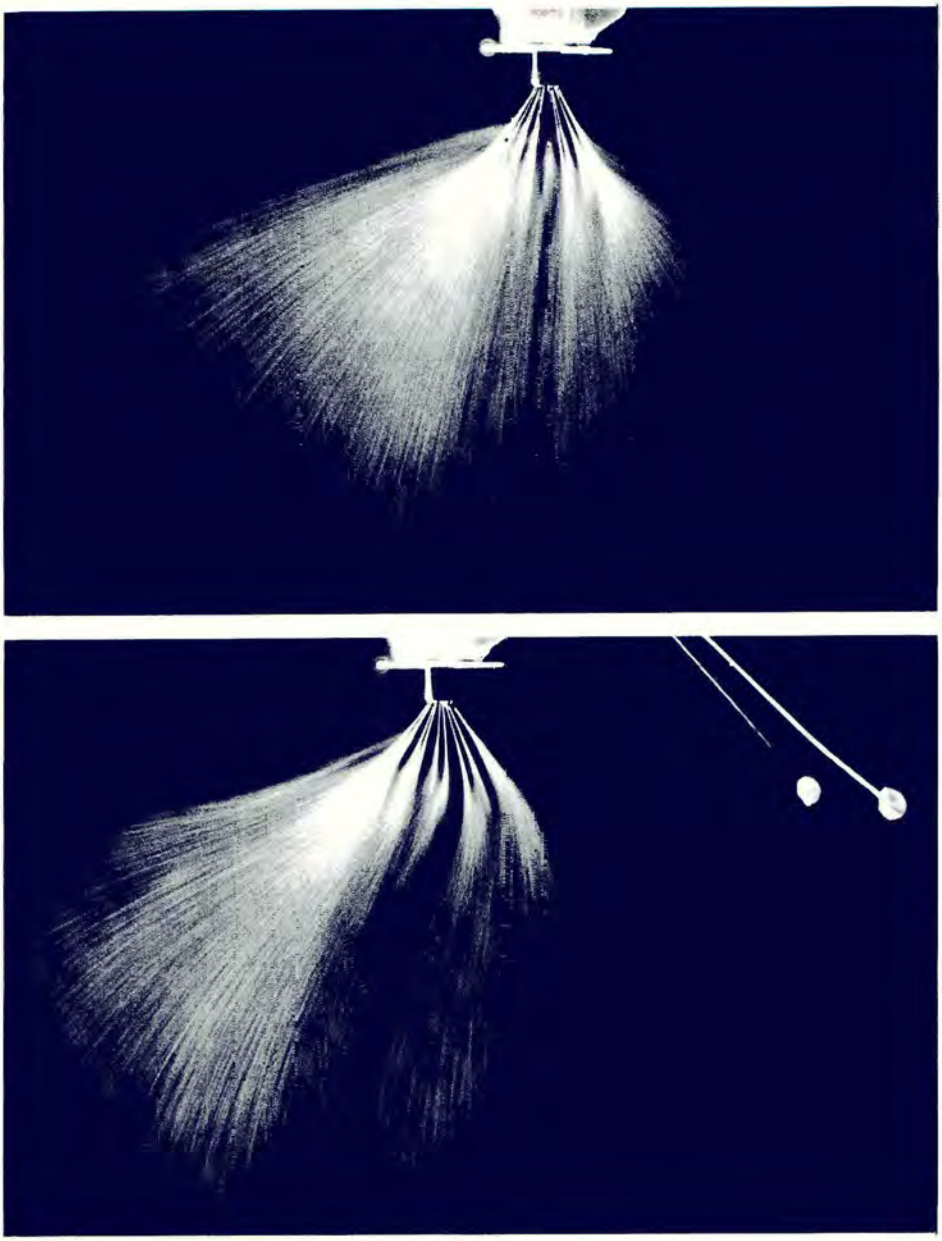
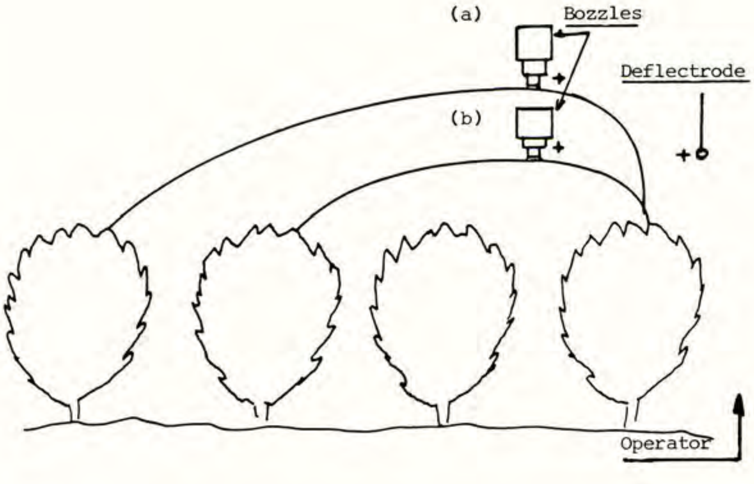


Fig 2 Approximate spray-cloud contours for (a) sprayer with an experimental Deflectrode held 80 cm above the crop canopy (cotton); and (b) sprayer with Deflectrode, held 40 cm above the crop



Because the internal energy transfer mechanism of the electrodynamic process takes place at a microscopic level, droplet size control is excellent, even down to volume median diameters (vmd) of the order of 10 µm. Further, because heavy oils are employed, the viability of such droplets is high, compared with water. Finally, because the droplets are highly charged, with charge-to-mass ratio of the order of 10^{-1} coulomb kg^{-1}, they can be made to settle in a target application mode.

The potential toxicity of ultra small droplets in direct impingement onto insects is well known (eg Himmel & Moore 1969), but the problems of practical application have generally been thought to be prohibitive (Coutts, 1969, Johnstone et al 1974).

Lethal dose requirements may sometimes be significantly reduced when droplet diameters are lowered. For example Scopes (1981) has indicated that the LD_{50} for whitefly eggs might drop roughly tenfold, with a reduction of droplet diameter from 50 µm to 25 µm, using 30 percent permethrin. Droplet number density would, of course, increase eightfold for a given application rate, with this twofold reduction in droplet diameter. This research has also indicated that lower concentrations of chemical may be achieved with ultra-small droplets.

Whilst the Electrodyn sprayer may readily be made to produce and propel droplets with vmds around 25 µm or less, there are still several problems to be resolved before such use can be recommended. For example, operator contamination and crop penetration need to be studied, in addition to biological effect. Research is now in progress, but much work remains to be done.

The potential importance of ultra-small droplets has been recognised for some time. However, although atomizers have been developed to accurately produce droplets down to about 30 µm vmd (Bals, 1975) the difficulties of application of such small masses using gravity-field and viscous-drag forces, are severe. It is probably true to say that if any spray system can be developed for general application with ultra-small droplets, down to say 10 µm vmd, it will be one such as Electrodyn, in which heavy oils may be accurately atomized and efficiently applied in an electric field.

Clearly, one of the main attractions of ultra-small-droplet (usd) application would be the potential to reduce volumes from the 250 ml per hectare currently being achieved by the Electrodyn sprayer (vmd 40 µm - 50 µm) down to as little as, say, 50 ml per hectare.

FURTHER DEVELOPMENTS

There are several areas of application research in electrodynamic spraying currently in progress. Among these are:-

Animal Health -

Cattle, sheep, pigs and poultry have been sprayed with hand-held Electrodyn nozzles, indicating that this may be a convenient device for fly and tick control.

Additionally, cattle pens and pig-sties have been sprayed and have produced excellent, quick control of nuisance flies.

Air-Assisted Spraying -

In order to achieve spray penetration into dense foliage, and to increase the 'throw' of the spray, the electrodynamic deposition force has been augmented by viscous drag force from various types of fan. In one such experimental arrangement, a Solo* vine-spray machine is currently being used to assess the combined aerodynamic and electrodynamic depositional forces on vine foliage. Initial results indicate good penetration and droplet distribution. Similar work has been carried out in cotton (Morton 1981) and has been initiated in orchard crops and rice. Experimental measurements indicate that the high degree of droplet size control achieved by electrodynamic atomization is not affected by the aerodynamic forces used.

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THE 'ELECTRODYN' SPRAYER - CONTROL OF HELIOTHIS SPP. IN COTTON

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Summary Four field trials were carried out on cotton in Australia and Tanzania to compare the performance of the 'Electrodyn' sprayer with rotary atomiser and hydraulic nozzle knapsack sprayers. The sprayers were used to apply permethrin and cypermethrin to control *Heliothis* and *Earias* spp bollworms. The 'Electrodyn' sprayer performed better than other sprayers at spray volumes between 0.36 and 0.7 litres per ha. To maximise the level of pest control, the nozzle needs to pass along every row. Alternatively, in situations where rotary atomisers have created a demand for fast work rates by treating multiple rows in a single pass, the 'Electrodyn' sprayer can be used on a two row interval with results superior to those using rotary atomisers.

Fifty farmers tested the 'Electrodyn' sprayer/'Bozzle' container system in Paraguay in 1980/81 and their response to its speed, safety and ease of use was very enthusiastic. Compared with conventional knapsack sprayers applying a range of synthetic pyrethroids and organophosphates the 'Electrodyn' sprayer/'Bozzle' container using cypermethrin ('Cymbush') and dimethoate resulted in an average increase of 34% in yield and 47% in net profit.

Sommaire Quatre essais de plein champ on été réalisés sur contonniers en Australie et en Tanzanie afin de comparer la performance du pulvérisateur 'Electrodyn' avec celle des pulvérisateurs à dos centrifuges à jet porté. On utilisa les pulvérisateurs pour épandre de la permethrine et de la cypermethrine pour lutter contre les vers de la capsule des espèces *Heliothis* et *Earias*. Le pulvérisateur 'Electrodyn' donna de meilleurs résultats que les autres pulvérisateurs à des volumes d'épandage compris entre 0,36 et 0,7 litres/ha. Afin de maximiser le degré de lutte contre les parasites, il faut que la buse soit passée le long de chaque rangée. Comme alternative, dans les situations où les pulverisateurs centrifuges on créé une demande de vitesses de travail élevées en traitant plusieurs rangées en une seule passe, on peut employer le pulvérisateur 'Electrodyn' à intervalles de deux rangées et obtenir des résultats supérieurs à ceux obtenus au moyen des pulvérisateurs centrifuges.

Au Paraguay, cinquante exploitants ont testé le système composé du pulverisateur 'Electrodyn'/recipient 'Bozzle' en 1980/81 et ont réagi de manière très enthousiaste à sa rapidité, sa sécurité et son emploi facile. Par rapport aux pulvérisateurs à dos conventionnels épandant une variété de pyréthrinoides synthétiques et de composés organophosphorés, le pulvérisateur 'Electrodyn'/récipient 'Bozzle' employant de la cypermethrine ('Cymbush') et du diméthoate a produit une augmentation moyenne du rendement de 34% et des bénéfices nets de 47%.

INTRODUCTION

The 'Electrodyn' sprayer (Coffee 1979) was first evaluated in cotton in 1977 (Morton, 1982). The objective of these early trials was to determine the optimum way to use the machine using total spray recovery, as visualised by fluorescent tracer, as the main criterion. It represented the first in a five step programme of development planned as follows:

Phase I Optimisation of sprayer and its mode of use.

1. Factors affecting spray recovery; horizontal and vertical position with regard to the row, speed of travel, wind, and spray cloud charge.
2. Influence on pest control of varying droplet size, spray volume/concentration and spray cloud charge.

Phase II Comparative performance and market development.

3 Comparison of 'Electrodyn' sprayer peformance with established sprayers.

4. Market testing.

5. Commercial development.

This paper reports a later series of trials conducted in step 3 of the programme on the performance of the sprayer in controlling Heliothis spp bollworms. This was best evaluated using non-mobile contact/residual insecticides and the synthetic pyrethroids, permethrin and cypermethrin were accordingly used.

A report of the first farmer usage exercise conducted in Paraguay as part of step 4 of the development programme is also included.

METHOD

Four trials were conducted, two in Australia and two in Tanzania. Both trials at Griffith, Australia compared the 'Electrodyn' sprayer with a rotary atomiser and a knapsack sprayer, the latter applying 125 l/ha and 20 l/ha in the two trials, respectively. Rate of active ingredient and swath width were the other factors tested. The two trials, in 1977-78 and 1978-79 were conducted on irrigated Riverina Gold var. cotton at 1.0m spacing. 7 and 9 treatments respectively were randomised in 4 replicate blocks in plot sizes of 12m x 16 rows and 13m x 14 rows. Spray run interval and volumes appear in Table 2 and 3 and other experiment details in Table 1. Spray applications were as follows; Trial 1. Two sprays were applied - 1 on 7.III.78 @ 20-25°C and 2 on 15.III.78 @ 19-20°C. Trial 2. Five sprays were applied - 1 on 3.II.79 @ 20-24°C, 2 on 9.II.79 @ 22-23°C, 3 on 21.II.79 @ 20-21°C, 4 on 5.III.79 @ 16-18°C and 5 on 19.III.79 @ 18-21°C.

In Tanzania in the 1978-79 season the 'Electrodyn' sprayer was compared in two trials with a rotary atomiser in each applying two spray volumes, in trial 3 in a range of a.i.s and in trial 4 at different row intervals. One trial was conducted at Mabuki, and the other at Igokelu, both in Mwanza Province. The cotton variety was UK77, rain grown, and planted on ridges 1.52m apart each bearing two rows 0.46m apart. There was 0.3m between plants. There were 7 treatments in 4 randomised blocks in plot sizes of 20m x 15 ridges and 17m x 15 ridges respectively.

Spray run intervals and volumes appear in Tables 4 and 5 and other experiment details in Table 1. Spray applications were as follows;

TABLE 1

Nozzle flow rates and emission heights used in the trials

Trial	1	2	3	4
Nozzle flow rate				
'Electrodyn'	0.1 ml/sec	0.15 ml/sec	0.2 ml/sec	tr 1-3, 0.2 ml/sec tr 4-5, 0.11ml/sec
Rotary atomiser	0.2 ml/sec	0.5 ml/sec	1.1 ml/sec	1.1 ml/sec
Emission height				
'Electrodyn'	0.4m	0.4m (.8 in tr 8)	0.75m	in Table 5
Rotary atomiser	0.75m	0.75m	0.75m	

Trial 3. Six sprays were applied - 1 on 13.II.79 @ 22-28°C, 2 on 27.II.79 @ 21-26°C, 3 on 13.III.79 @ 23-28°C, 4 on 27.III.79 @ 22-29°C, 5 on 9.IV.79 @ 23-28° and 6 on 24.IV.79 @ 22-27°C. Trial 4. Four sprays were applied - 1 on 5.III.79 @ 30-34°C, 2 on 19.III.79 @ 21-23°C, 3 on 3.IV.79, and 4 on 18.IV.23-26°C.

The active ingredients permethrin, cypermethrin used in the 'Electrodyn' sprayer were specially formulated as 'Ambush ED' and 'Cymbush ED'; Trade Marks of Imperial Chemical Industries, PCL, London, England.

RESULTS

In the first comparison with other sprayers, in Australia in 1977-78 season, there were two rates, 50 and 20g ai/ha permethrin. Against a light mixed infestation of Heliothis armiger and H.puntiger (90%) and Earias spp (10%) the 'Electrodyn' sprayer was most effective (even using 0.36 l/ha) and conventional low volume, 125 l/ha, least. The main differences occurred between sprayers rather than between rates for a single sprayer. Table 2.

In the following year the comparison between sprayers was made more precise by using different formulation strengths, enabling the effect of dose rate to be investigated independent of the effect of volume which was held constant for all the 'Electrodyn' sprayer and rotary atomiser treatments. In addition a simulated aerial application (20 l/ha) was included in the trial.

In protecting squares from bollworm damage the 'Electrodyn' sprayer performed exceptionally well, far surpassing the aerial mimic and rotary atomiser. As in the first trial differences due to rate were less than those due to sprayer, Table 3. Yield differences reflected pest counts but were not significantly different.

The Tanzanian trials were conducted on cotton of different row spacing and in a cooler climate than in Australia. The 'Electrodyn' sprayer used at a 2 ridge spray run interval (ridges 1.5m apart, each bearing two rows) and applying 1.3 l/ha gave equivalent season long protection of fruiting bodies in the face of a light-moderate Heliothis armiger infestation to that of a rotary atomiser used at a 3 ridge run interval applying a higher rate of active ingredient and twice the volume

TABLE 2

Comparison of sprayers for bollworm control(1) - Trial 1 Australia 1977-78

Treatments(3)		Percent Buds Damaged(2)			Counts of Larvae(2)				
Sprayer	permethrin g/ha	22.3.78 2 DAT 2	29.3.78 14 DAT 2	10.4.78 26 DAT 2	8.3.78 8 DAT 1	13.3.78 6 DAT 1	22.3.78 7 DAT 2	29.3.78 14 DAT 2	10.4.78 26 DAT 2
Electrodyn sprayer	50	$.5^{c}$	$.75^{b}$	1.0^{c}	.05	0^{c}	.5	.25	2.0^{cd}
Electrodyn sprayer	20	2.0^{bc}	1.75^{b}	1.25^{c}	.10	$.02^{c}$	.25	.25	2.0^{d}
Rotary atomiser	50	2.25^{bc}	1.25^{b}	6.25^{b}	.10	$.03^{c}$	1.25	1.0	4.25^{bcd}
Rotary atomiser	20	2.5^{bc}	3.25^{b}	6.00^{b}	.12	$.15^{ab}$	.75	1.75	5.25^{ac}
Hydraulic knapsack	50	1.5^{c}	1.0^{b}	7.5^{b}	.15	$.07^{bc}$	1.25	.75	8.0^{ac}
Hydraulic knapsack	20	6.0^{b}	5.5^{b}	11.5^{b}	.26	$.21^{ab}$	2.25	1.75	9.0^{ab}
Unsprayed		17.25^{a}	20.0^{a}	25.5^{a}	.28	$.34^{a}$	7.5	8.5	12.5^{a}

(1) The bollworm infestation comprised 90% *Heliothis* spp (*H. armiger* and *H. punctiger*) and 10% *Earias* sp

(2) On 8 and 13.3.78 15 plants, and thereafter 100 buds per plot, were examined for damage and larvae.

(3) At 50 and 20g permethrin the Electrodyn sprayer and rotary atomiser applied 0.9 litres and 0.36 litres per ha respectively. Walking speeds were 1.1 m/sec for 50g and 2.8 m/sec for 20g/ha. Electrodyn sprayer operated at 0.1 ml/sec at a one row spray run interval; rotary atomiser at 0.2 ml/sec and a two row spray run interval. Both used a 5.6% permethrin solvent formulation: Conventional volume utilised a knapsack sprayer applying 125 l/ha through four cone nozzles on an interrow dropleg along every row. Walking speed 0.8 m/sec

(4) Means per column with the same letter are not significantly different at p = .05. Larval numbers were too low for analysis on 8, 22 and 29.3.78.

TABLE 3

Comparison of sprayers for bollworm control(1) - Trial 2 Australia 1978-79.

Treatments(2)				Percent bollworm damaged squares on stated day after spraying(1)(4)							Yield
Sprayer run interval	Volume l/ha	spray % strength	ai g/ha	13.2.79 7 DAT 1	21.2.79 6 DAT 2	26.2.79 11 DAT 2	5.3.79 6 DAT 3	8.3.79 9 DAT 3	15.3.79 6 DAT 4	20.3.79 11 DAT 4	(3)(4)
Electrodyn 1 row	2.0	1.25	25	3.5	1.8	0.4^{d}	0.1^{c}	0.4^{b}	0.1^{c}	0.1^{bc}	83
Electrodyn 1 row	2.0	.63	12.5	11.9	1.8	2.4^{bc}	0.1^{c}	0.4^{b}	0.1^{c}	0.1^{bc}	61
Electrodyn 1 row	2.0	.31	6.25	3.5	4.1	2.1^{c}	0.9^{bc}	0.1^{b}	0.3^{bc}	0.2^{bc}	62
Rotary at. 2 rows	2.5	2.5	62.5	12.2	4.6	5.0^{bc}	1.4^{bc}	0.9^{b}	0.1^{bc}	0.1^{bc}	73
Rotary at. 2 rows	2.0	1.25	25	4.6	6.0	5.5^{b}	2.6^{b}	0.8^{b}	1.4^{ab}	0.9^{bc}	63
Aerial mimic 1 row	20	.31	62.5	8.0	1.3	2.1^{c}	1.6^{bc}	0.5^{b}	0.1^{c}	0.1^{bc}	80
Aerial mimic 1 row	20	.13	25	11.7	1.8	3.9^{bc}	2.4^{b}	0.9^{b}	0.7^{bc}	1.6^{ab}	63
Electrodyn 2 rows	2.0	1.25	25	7.4	4.2	2.1^{cd}	1.1^{bc}	0.3^{b}	0.9^{bc}	0.0^{c}	54
Not sprayed				19.7	6.3	11.1^{a}	8.6^{a}	7.2^{a}	3.9^{a}	4.1^{a}	57

(1) The bollworm infestation was mainly <u>Heliothis</u> spp. with some <u>Earias</u> sp. 25 on 13th, 50 on 21st February and 100 thereafter buds per plot were examined for damage.

(2) The active ingredient was cypermethrin. The aerial mimic was a hydraulic knapsack sprayer operating at 2.72 bar with a single Spraying Systems TY 020 hollow cone nozzle held 0.3m above each inter-row. Walking speed 1.0m/sec.

(3) Yield. Open and large bolls per 3m of row per plot counted on 18.5.79. Mean plot count given.

(4) Means per column with the same letter are not significantly different at p = .05. Columns with no letters have no significant differences.

TABLE 4

Comparisons of sprayers for bollworm control - Trial 3 Tanzania 1978-79

Treatments(1)					Percent of fruit damaged(3)								Yield(4)
Sprayer(2)	ai g/ha	ai	volume l/ha	spray % strength	2.3.79 3 DAT 2	9.3.79 10 DAT 2	16.3.79 3 DAT 3	24.3.79 11 DAT 3	30.3.79 3 DAT 4	6.4.79 10 DAT 4	13.4.79 4 DAT 5	Average	kg/ha
Electrodyn sprayer	32.8	Cy	1.3	2.5	0	0^{c}	1.2^{b}	0^{c}	0.1^{c}	0.4^{c}	0.1^{d}	0.25	2000
Electrodyn sprayer	16.4	Cy	1.3	1.25	0	0.2^{c}	2.2^{b}	0.7^{b}	0.2^{bc}	0.3^{c}	0.1^{d}	0.52	1815
Electrodyn sprayer	8.2	Cy	1.3	0.63	0.5	0.5^{c}	1.6^{b}	0.4^{b}	0.5^{bc}	0.2^{c}	0.2^{cd}	0.54	2181
Rotary atomiser	62.5	Cy	2.5	2.5	0.1	2.4^{b}	1.3^{b}	0.1^{b}	0.5^{bc}	0.2^{c}	0.2^{cd}	0.69	1986
Rotary atomiser	31.3	Cy	2.5	1.25	0.7	3.2^{b}	3.4^{b}	2.6^{b}	1.8^{b}	2.0^{bc}	2.0^{bc}	2.25	2327
Rotary atomiser	625	En	2.5	2.5	1.9	3.25^{b}	1.75^{b}	1.9^{b}	1.1^{bc}	5.5^{b}	4.75^{b}	2.88	1925
Not sprayed					3.1	7.2^{a}	12.5^{a}	16.5^{a}	13.8^{a}	19.2^{a}	23.1^{a}	13.62	1749

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(1) Active ingredients; Cy = cypermethrin, En = endosulfan

(2) Spray run interval; Electrodyn sprayer 2 ridges, rotary atomiser 3 ridges. Ridges were 1.52 m apart bearing two row .46 m apart. Walking speeds; Electrodyn sprayer 0.5 m/sec, rotary atomiser 1.0 m/sec.

(3) Fruit examined on 10 whole plants per plot until 30 3 79, thereafter 30 cm terminals on 15 plants per plot

(4) Yield. Eight weekly harvests were made. The data was not statistically analysed.

(5) Means per column with the same letter are not significantly different at p = .05.

TABLE 5

Spray run interval for bollworm control - Trial 4 Tanzania 1978-79

Treatments(2)					Larvae/ plant(1)	Percent fruit damage(1)(3)				
Sprayer	ai g/ha	volume l/ha	run interval	nozzle height(m)	7 3 79 2 DAT 1	14 3 79 9 DAT 1	22 3 79 3 DAT 2	29 3 79 10 DAT 2	5 4 79 2 DAT 3	12 4 79 9 DAT 3
Electrodyn	33	1.3	1 ridge	.4	0.03	0.2^{c}	0^{b}	0^{b}	0.3^{bc}	0.4^{c}
Electrodyn	33	1.3	2 ridge	.75	0.03	0.6^{bc}	0^{b}	0.1^{b}	0^{bc}	0.7^{c}
						0.5	0.7	0	0.2	0.9
Electrodyn	33	1.3	3 ridge	1.0		3.5	0.3	0	1.5	5.2
					0.06	0.6^{b}	0.2^{b}	0^{b}	0.4^{b}	1.2^{bc}
						0.40	1.2	0.7	0.3	2.6
Electrodyn	36	0.7	1 ridge	.4	0.06	0.9^{bc}	0^{b}	0^{b}	0^{c}	0.9^{c}
Electrodyn	18	0.7	1 ridge	.4	0.13	2.2^{b}	0.1^{b}	0.2^{b}	0.1^{bc}	2.5^{b}
Rotary atomiser	62.5	2.5	3 ridge	.75	0.12	1.6^{b}	0.2^{b}	0.3^{b}	0.8^{bc}	3.0^{b}
Not sprayed					0.30	8.9^{a}	8.7^{a}	8.7^{a}	8.1^{a}	34.5^{a}

(1) Larvae and fruit were counted on 10 entire plants per plot until 5.4.79, and then on 15 terminals per plot.

(2) Treatments 1, 2, 3, 5 and 6 used 2.5% cypermethrin, 4 used 5.0% cypermethrin. Walking speeds were treatments 1, 4, 5 and 6 1.0 m/sec, treatment 2 0.5 m/sec and treatment 3 0.33 m/sec.

(3) Statistical analysis was carried out on treatment means but the table above comprises raw data to enable presentation of the separate rows of treatments 2 and 3. Means per column with the same letter are not significantly different at p = .05.

(2.5 l/ha) (Table 4). The potential for statistically significant yield increases resulting from differences in pest control is low in most seasons and in Tanzania none occurred amongst the sprayed treatments in this trial.

Spray run interval

In Australia using 25g/ha cypermethrin, assessments of bud damage and cotton yield showed that the 'Electrodyn' sprayer was more effective when used at a one row than at a two row spray run interval. Nevertheless the two row interval was as good as the rotary atomiser treatment at a two row interval Table 3. The Tanzanian trial, using 33g/ha, confirmed the decreasing effectiveness of the 'Electrodyn' sprayer as spray run interval increased but, again, the three row interval matched the effectiveness of the rotary atomiser at a three row interval, Table 5. There were no yield differences between treatments because of the lightness of the attack and high plot to plot variation. Examination of pest counts on a row by row basis showed a clear fall off in pest control with increasing distance from the nozzle at a three row interval. The generally acceptable level of control obtained at the three row run interval was thus the net result of good control on the nearest row to poor control in the furthest row - these altering depending on wind direction on each spraying occasion. The maximum reliable spray run interval thus appears to be two rows, or ridges.

DISCUSSION

The purpose and hence expectation of hand spraying and, indeed, ground spraying generally varies between two extremes: 1) From reliably protecting a potentially large yield which is normally at low risk from unfavourable climatic or poorly controlled agronomic factors to, 2) providing with the minimum of effort protection for a crop the yield of which is at high risk from factors not controlled or controllable by the farmer. Knapsack hydraulic nozzle or motorised air blast sprayers have tended to remain in the former sector whilst, because of their convenience and high work rate, rotary atomisers have significantly penetrated the latter. The performance of the 'Electrodyn' sprayer has thus to be compared with established sprayers for both purposes.

Reliable protection for crops at low risk.

Without entrainment in an air blast after leaving the nozzle charged droplets are strongly attracted to the nearest crop row. There is little or no uncontrollable spray cloud movement and for the most effective and even cover of all the rows of a crop, the nozzle needs to be positioned close to each row viz held in the inter-row at 0.2 to 0.4m above the crop canopy (Morton (1982)). Used in this way the trials in this paper show the 'Electrodyn' sprayer can provide more effective bollworm control than conventional hydraulic nozzle sprayers. The relatively high cost of solvents used in the system has meant that the principle objective for development is to reduce the volume of spray applied. Spray recovery data at ULV with charged and discharged 'Electrodyn' sprayer sprays showed a 2.5 times increase with the charge (Morton, 1982) and hence because 2.5 l/ha provides acceptable pest control with rotary atomisers less than 1.0 l/ha was taken as a basis for further work. Volumes as low as 0.26, 0.36 and 0.625 l/ha have provided good bollworm control (unpublished data) and so 0.5 l/ha was selected as a basis for further development work. Subsequent use of 0.5 l/ha using lower than conventional rates of ai have provided reliable cotton pest control.

Minimum effort protection for crops at high risk.

Using the 'Electrodyn' sprayer at a three row run interval, poor control of bollworms on one row occurred, as suggested by spray coverage data (Morton, 1982).

Theoretically, if the wind blew from the same direction on each spraying occasion 12.1% fruit damage would have occurred on one row with a mean of 6.0% over all three rows (Table 5). This compares with a mean of 1.6% at a two row interval and 0.8% at one row. The mean of all three rows for the rotary atomiser was 5.9% but the variability from row to row was probably lower than the 'Electrodyn' sprayer (Matthews, 1973) and hence, for the latter, a maximum of two rows is indicated. At this run interval and using 0.5 l/ha, the 'Electrodyn' sprayer provides the same or better pest control than a rotary atomiser.

Further consideration of work rate is necessary, since it is a prime factor in the suitability of sprayers for this type of farming.

Rotary atomisers applying low volatile formulations may be used at three to five row run intervals but they use a higher volume application rate (normally 2.5 l/ha) than the 'Electrodyn' sprayer and the reservoir (1 litre) of necessity requires frequent re-filling. The 'Electrodyn' sprayer uses a ready for use 0.75 litre 'Bozzle' container, sufficient to spray 1.5 ha. An average small farm of 2.5 ha would thus need only one 'Bozzle' container change compared with four re-fillings of the rotary atomiser reservoir from a bulk supply at the field's edge. Taking this aspect into account and ignoring possible increased latitude with the 'Electrodyn' sprayer in time available for spraying, in higher winds or thermals, it takes only 41 minutes or 21% longer than a rotary atomiser used at a four row run interval.

In a short crop of less than 0.5m height the 'Electrodyn' sprayer must be used with the nozzle above every row and although a faster walking speed is possible (1.5 m/sec) its work rate is reduced and is significantly poorer than a rotary atomiser.

Farmer testing.

Paraguayan cotton farming falls between the two extremes of high inputs/low risk and low inputs/high risk cotton cultivation. The Paraguayan cotton farm, though similar in terms of size and appearance to most central eastern and southern African cotton farms is managed to a higher standard and it has not been fully accepted locally than rotary atomisers will provide a sufficiently reliable level of pest control. The 'Electrodyn' sprayer is thus being developed here for use at a one row run interval, which should provide a much greater level of 'convenience' and ease of use than the knapsack sprayers in common use but also more reliable pest control than either the knapsacks or rotary atomisers.

In Paraguay two sprays of a cheap systemic insecticide are traditionally applied to control early season thrips, aphids and leaf-eaters (Alabama argillacea) followed by three sprays in the last two seasons of synthetic pyrethroids for the control of the bollworms Heliothis, Spodoptera and Pectinophora spp. Two seasons of replicated trials with the 'Electrodyn' sprayer (unpublished data) have confirmed the general utility of the rates and volumes suggested for bollworm control in this paper but to provide a full season package dimethoate has been made available for early season sucking pest control. Based on these trials an evaluation of farmer acceptability of the 'Electrodyn' sprayer/'Bozzle' container was carried out in the 80/81 season amongst 50 small farmers (average farm size 12.5 ha, average cotton area 3.4 ha (J. Shoham personal communication)). Each farmer was trained and provided with all requisites free of charge, in return for a commitment to co-operate fully. Sprays were only applied with the approval of local ICI agronomists and the reactions of farmers and performance of the sprayers was monitored throughout the season. In each case the area sprayed by the 'Electrodyn' sprayer (2.5 ha each) using cypermethrin and dimethoate was compared with a closely similar area of his own or neighbour's cotton sprayed with a knapsack sprayer using mainly a range of synthetic pyrethroids for bollworm control with organophosphates for early season use.

Farmer reaction was unanimously favourable mainly in terms of speed, safety, ease of use, and the 'ready to use' 'Bozzle' container. Pest control was superior to their conventional methods and in every case except one (whose yields were the same) of the twenty-seven farmers who measured yields with both sprayers the 'Electrodyn' sprayer yielded more. An economic analysis amongst all farmers using estimated 'Electrodyn' sprayer and insecticide prices showed there to be a £54/ha or 47% increase in profit, Table 6.

Table 6

Farmer comparisons of spraying systems in Paraguay 1980-81

(All quantities are per hectare)

	'Electrodyn' sprayer	Conventional sprayers
Insecticides:	cypermethrin* & dimethoate*	Various pyrethroids and organophosphates
Average crop area:	2.5 ha/farm	approx 2.0 ha/farm
No of farms:	40	27
Average yield seed cotton	2024 kg	1518 kg
A Gross return	£381	£283
B Basic production costs seed, fertiliser, weeding	£68	£68
C Insecticide costs	£41	£23
D Harvest costs	£102	£76
Net profit A - (B+C+D)	£170	£116
Profit increase	£54 or 47%	

*formulated as 'Cymbush ED' and 'Dimethoate ED' insecticides

CONCLUSION

This paper concerned the control of pests in the upper part of the cotton crop. Exceptionally high spray recovery, particularly in the top 0.3m of the crop, was recorded in early development work (Morton, 1982) and the trials recorded here constitute a confirmatory bio-assay. It can be concluded that the current simple 'Electrodyn' nozzle can give superior control of pests inhabiting the upper parts of crops. With the nozzle used down every row, either hand or tractor borne, volumes about 0.5 l/ha seem attainable.

Used in this mode crop penetration to control bollworm 'escapes' may be limited in dense crops, and so either a scheduled programme of sprays (Morton, (1979), Morton et al (1981)) or spray placement using droplegs or an air blast will be necessary. The latter developments will be the subject of future publications.

The current 'Electrodyn' sprayer/'Bozzle' container, like conventional hydraulic nozzle equipment, suffers a disadvantage in its mode of use compared with rotary atomisers in terms of the interval betwen spray runs, 2 rows being the maximum. In contract spraying this disadvantage may weigh more heavily than the advantages of trouble-free operation, longer battery life, no wearing parts, reduced risk of contamination and capability to spray in erratic winds, but for the private owner having usually only a small area to spray and less pressure on time the advantages are likely to be crucial. In the farmer testing exercise in Paraguay using the 'Electrodyn' sprayer at a one row interval, both the benefits of 'convenience' (vital for sprayers to be used in low input/high risk cultivation), and reliable pest control (vital for sprayers used in high input/low risk cultivation) were well demonstrated in farm use.

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A NEW DISPENSING SYSTEM USING A PRESSURISED GAS CYLINDER

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BOC Limited Special Gases

Summary A system of producing an aerosol suitable for space sprays in glasshouses and other enclosed areas is described. The system uses a pressurised CO_2 cylinder with manually or electrically operated valve and nozzle assembly.

INTRODUCTION

Several years ago a method for dispensing insecticides which was based on the use of liquid carbon dioxide as both the solvent and the propellant was developed.

This new spraying system, called Envirosol*, quickly became popular with many companies associated with the food chain as is it offered a simple to operate, ready to use, large scale technique for generating an aerosol. The non flammable nature of the product is also important.

DESCRIPTION

The basic units of the system are:-

(1) Cylinder, either a 10 Kg tare aluminium cylinder containing 6 Kg of fill, or a 71 Kg tare steel cylinder (No 1) containing 30 Kg of fill. The operating pressure is 725 psig (50 Bar).

(2) The fill itself consists of active ingredient dissolved in liquid CO_2 which acts as both solvent and propellant.

(3) An armoured hose.

(4) A valve fitted with an appropriate nozzle to give the desired rate of output. This valve can either be operated manually (spray gun) or electrically (solenoid).

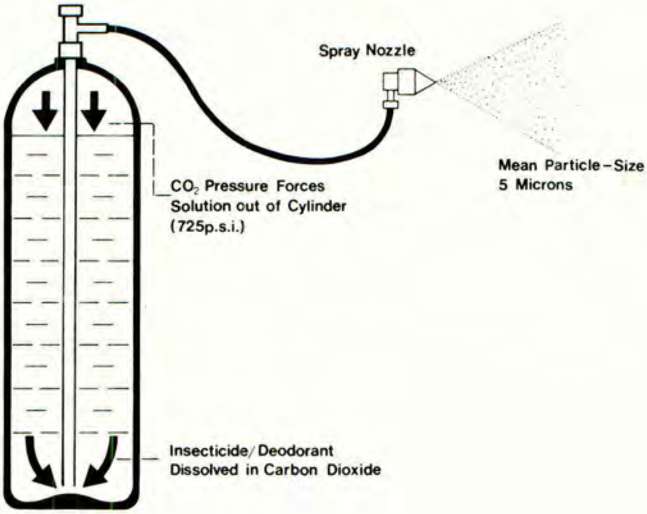

Fig. 1 : Diagram showing basic unit.

OPERATING PRINCIPLE

As can be seen from the diagram the operating principle is similar to that of an aerosol can.

(i) Into the cylinder is put the active ingredient (e.g. Pyrethrum) and liquid CO_2, which has a vapour pressure of 725 psig.

(ii) When the cylinder valve is opened the pressure of the CO_2 gas pushes the liquid mixture up the dip tube, along the armoured hose to the spray valve.

(iii) When the valve is activated the mixture "flashes off" to give a very fine aerosol with most droplets approximately 5 microns in diameter and finer than the products of most other space spraying systems that are available.

PHYSICAL PERFORMANCE

The beauty of the very small droplet size is that it will persist in the air for a considerable period of time. This obviously gives the spray the opportunity to remain active for prolonged periods with the added possibility of penetrating hitherto protected areas.

The rate of output is consistent for any given nozzle size and accordingly dose rates can be defined readily on a basis of time rather than spray mass or volume. It is therefore possible to talk in terms of dose rates of 17 seconds/300 cu. m a very simple concept.

METHOD OF OPERATION

The insecticide can be sprayed manually or automatically. The manual system utilises a high pressure spray and the smaller cylinder. A selection of nozzle sizes are available including one which resembles a hyperdermic needle and is ideally suited for injecting insecticide into cracks and crevices. System mobility is achieved via a cylinder trolley or back-pack.

For the control of flying insects the cylinder, in the case of the pyrethrum formulation contains enough insecticide to treat a volume of 30,000 cu. m (1 million cu. ft).

The automatic system provides an efficient means for dispensing insecticides accurately into a designated area at a predetermined time.

The system consists of a number of spray jets, sited along the length of a building and positioned such that each jet will treat 1500 cu. m (53,000 cu. ft), depending on the exact geometry of the treatment area.

The spray jets are linked via solenoid valves to an electrical timer (24 v output) which can be programmed to activate the system at any particular time during the day or night, seven days per week. Such a system could be fitted in a glasshouse to treat it when the adult stage of a pest is most active.

The "spray stations" are fed from either:-

(i) a piped in system supplied from a bank of cylinders

(ii) a cylinder connected to each "spray station" with a length of armoured hose i.e. no pipe installation required.

Once installed the system can be tuned to fog the treatment area to achieve an effective kill or, it may be adjusted to give discrete doses of insecticide so as to repel insect pests without causing disruption to staff work schedules.

	Food Warehouse	Flour Mill
Total Area	13,000 m^3	7,000 m^3
Applications	3 times/week	2 times/week
Requirements	7 x No. 1 cylinders	3 x No. 1 cylinders
Duration	approx 10 weeks	approx 10 weeks

At present one of the formulations is based on natural pyrethrins (0.4% w/w) synergised with piperonyl butoxide (2.0% w/w) in odourless kerosene (10% w/w). Alternatively the pyrethrins can be replaced by bioalethrin (0.13%) mixed with bioresmethrin (0.4%). Other insecticides used in the system include dichlorvos and fenitrothion, and methyl bromide is also available for fumigation.

CONCLUSIONS

This system provides an aerosol with a low proportion of solvent thus eliminating a fire hazard associated with some fogging techniques. Use of a non hazardous propellant is another advantage. The 'dry' aerosol is nontainting, and the method of packaging the insecticide in the pressure cylinder eliminates the need to measure out concentrate material. The system is very convenient, quiet and reliable as there is no engine driven equipment, and the dosage can be precisely measured on a time basis. Normally spraying is needed only briefly.

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PRECISION SPRAYING DEVELOPMENTS FOR PESTICIDES

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Summary One of the most significant problems facing plant protection and pesticide users the world over is that of (a) worker-applicator safety and (b) reduction of pesticide contact with non-target crops while maintaining target contact efficiency. Physical scientists are busily developing schemes for increasing spray target efficiency through such means as (a) determinate or narrowed drop size range atomizers (b) use of visco-elastic spray additives to reduce drop size range, as well as (3) use of electrostatic charge and other techniques while biological scientists are endeavoring to obtain greater target contact efficiency for insect, disease and weed control. It is quite evident that their requirements are not always compatible. However, better communication between these groups should result in benefit to both.

The Agricultural Engineering Department at the University of California at Davis has had an on-going project for many years on monodisperse and narrowed drop size devices. The PMS (Particle Measuring System) drop size counter and sorter, provides a new level of proficiency for studying in detail the entire range of drop size phenomenon as produced by a variety of hydraulic and spinner atomizers. As well as the means for assisting in the development of more determinant drop size atomizers.

Recovery of spray materials from various aircraft applicators and correlation to drop size clearly indicates the range of capability available which should be exploited to best fit specific spray applicators needs and to obtain maximum application efficiency with minimum spray losses.

INTRODUCTION

Precision spray application appears to be a primary objective of both physical and biological oriented scientists concerned with pesticide use the world over. In the United States this concern has been expressed for better control by increasing target contact efficiency but not to increase the exposure of applicators and workers or other persons appearing in a pesticide application area (Yates et al., 1981). Other concerns have risen over illegal residues of pesticides on food and feed crops and damages to crops from misapplied herbicides. There are many techniques which may help reduce exposure to pesticides, but all too frequently regulation of the offending product is pursued with close restriction on its use on a given crop. Such legal action does provide immediate relief from a specific material, but there is then no further incentive to continue development of means to assist in reducing losses relating to the product and, as a consequence, many excellent materials are banned or regulated to the extent that their use is greatly reduced or eliminated. This exposes growers to the likelihood of increasing costs and less effective control of crop pests.

The amounts of active material missing the intended target as losses occurring during and following a specific application of material can best be separated into two broad but interrelated groups based primarily on the spray drop size and size range of the released materials (Akesson et al., 1981). The first, swath displacement is related to the downwind displacement of the relatively large or ballistic size drops, generally over 100 μm (micrometers) diameter. This swath displacement occurs with every release of pesticide spray, varying with (a) ground machines using air delivery or hydraulic and spinning atomizers or (b) aircraft where height of release and intensity of crosswind (along with the amounts of material released in different drop sizes) will affect the extent of the swath displacement. The second, airborne transport is related basically to the drops below 100 μm diameter which constitutes the potential "drift-loss" aspect of the spray release. Drops as large as 100 μm diameter may be carried by ambient air motion for many miles before sedimenting to earth or contacting a target (Akesson et al., 1974).

However, it must also be recognized that target contact by drops as small as 20 μm diameter may be highly effective for small specific targets or providing the necessary air concentration for effective flying insect contact. But, it must be accepted that while very small aerosol or airborne drops may be highly effective for certain insect and disease control situations the losses of these small drops to airborne transport is very high and can be damaging if an especially toxic material is being used (Akesson, 1979).

In spite of the problems of increased cost for production of food and fiber that can and does result from limitations on pesticide use, it is of first importance to protect people, domestic animals, non-target plants and the wildlife environment from toxic substances such as pesticides. If the production cost can be held within bounds by use of application machines and methodology that maximizes target contact and minimizes improper non-target exposure then we will have achieved a major break-through in pesticide technology, a goal we are all anxious to reach.

Aerosols composed of small drops of the order of 20-30 μm vmd (volume median dia.) are widely used for contacting adult mosquitoes in the USA. Somewhat larger drops are used for grasshopper and locust control where the larger insect target will be more effectively contacted by larger drops. Small drops may remain airborne for considerable time. Stokes law is often misused to predict sedimentation of drops under 100 μm when in fact the essential "still air" which is a Stokes law requirement, is virtually impossible under field conditions.

The closest condition to "still air" is achieved under a low ceiling temperature inversion where air is highly stable. The effectiveness of an aerosol release becomes totally dependent upon this stable air ceiling. However, small airborne amounts of toxicants can be concentrated under inversion conditions. It is quite common to find large scale circulations of dusts, pollens and aerosol size toxicants in the atmosphere and prediction of dispersions and concentrations of these in an "air basin" such as a broad valley or other confining area has been made by several observers (Bergen, 1979; Dumbauld, 1980) while actual measurement of downwind dispersions and predictions of exposure levels have also been made by others (Akesson, 1981; Miller, 1980). The effects of local meteorological conditions, which include wind and temperature gradients and their effects on movement of spray drops becomes a significant factor in dispersion and losses of the spray materials. Thus (a) the ventilating capability of a given air-basin, primarily related to the confining characteristics of a temperature inversion and a valley terrain and (b) the vaporization rate (or non-vaporization) of the aerosol which further expands its airborne capability both become additionally important to dispersion of sprays.

With presently available equipment, including all commercially used atomizers, there will take place specific amounts of these two forms of movement of a pesticide during the release process. The swath displacement is particularly noted with aircraft, but air-carrier equipment can frequently produce wide swathes as well. From this displacement phenomenon the use of "border" or "guard strips" has been widely developed in many places as a means to reduce the direct contact on non-target areas from the released spray. But the airborne drift-loss is less amenable to any control and once released to the atmosphere remains in motion with the air and can be carried significant distances well beyond any practical "guard strips" before reaching ground or contacting an insect or a plant target. It is with the second function or airborne transport that we must deal with if we are to effectively reduce and control drift-losses while maintaining effective target contact. In general this might be accomplished by (a) some means for increasing sedimentation rate of small drops (under 100 µm diameter) or (b) increasing deposit rate through electrostatic charge (Coffee, 1981) or by "directed" sprays with increased drop velocity (such as from an airstream) resulting in increased deposit efficiency. When dealing with small drops the control of carrier evaporation also becomes a dominant concern. There is significant use of drops under 50 µm diameter, specifically in direct flying insect control and also for certain forest insect control. But for most agricultural uses if we could eleminate the production of drops below 50 µm diameter then it would be possible to basically eliminate the airborne transport losses. It is these losses that make up the critical part of the presently uncontrollable small amounts of pesticides which cause greatest concern. From a target contact efficiency viewpoint it is also desirable to cut off production of large drops which are wasteful of active material, the cost of which is becoming of increasing concern. Thus, our ideal concept would be controllable drop size capabilities of from 20 to 2000 µm but with a narrow range of sizes as for example 10 to 30 µm and 800 to 2200 µm for the extremes noted above. This ability is a dominant need in all aspects of pesticide use today (Spillman, 1980; Taylor, 1981).

CONTROLLED DROP SIZE TECHNIQUE

There are but two commercially available types of atomizers available today which can achieve any significant narrowing of the normal or gaussian drop size spectrum that occurs from any atomization process. These are (1) aerodynamic forms as operated in an airstream and (2) certain low feed rate spinning devices not operated in an airstream. The commercial aerodynamic Microfoil^R is characterized by relatively large drops emitted from a tube orifice having a 0.3 or 0.7 mm inside diameter. The drop size produced is roughly two times the orifice diameter; hence, this device produces drops of 600 to 1400 µm diameter, but with an extremely narrow size range with no satellites. The spinning devices effectively function to reduce size range only in still air (no high velocity aircraft or air-carrier slipstream) and tend to produce a major size with a satellite size of 1/10 the major diameter (see Figure 1). The cost of producing either the aerodynamic (Microfoil) or a desirable spinning device is high com-

Table 1

Operational data from different atomizers

Atomizer Type	Fluid H_2O + % ad.	Air Vel. km/hr	Per. Vel. m/min. P. Bar	Flow ℓ/min	$D_{NO.5}$ nmd µm	$D_{VO.5}$ vmd µm	Relative Span
Micromax	.03	0	760	1.4	238	296	.62
Micromax	.03	0	1900	0.136	62	96	.67
Herbi	.03	0	96	0.25	252	334	.84
Herbi	.03	0	96	0.034	330	335	.26
Micronair 3000*	50	184	4255	2.0	84	140	1.23
Beecomist 350*	2.8	161	2164	7.6	180	240	1.25
Aero (exp.)	.03	165	.14	--	312	342	.44
Fan 8001	.03	0	2.76	0.375	110	205	.8
Fan 8004	.03	0	2.76	1.5	109	288	1.24
Cone D4-13	.03	0	2.76	1.1	119	170	.67
Cone D4-46	.03	0	2.76	2.0	106	208	1.3
Cone D6-46	.03	165	2.76	3.0	263	435	.96
Cone D6-45	.03	165	2.76	2.6	253	327	.71
Cone D6 jet	.03	165	2.76	3.78	215	1190	1.05

* Data obtained by Quantimet

pared to the customary hydraulic nozzles, and obviously not all spray applications can benefit sufficiently to make up that cost.

The spray drop distribution from a few different atomizers are shown in the figures. Figure 1 and 2 are for the Micromax^R cup type spinner operated at 2000 and 5000 rpm with flow rates of 1.42 and 0.136 respectively. The liquid was water with an addition of .03% surface active ingredient typical of water base pesticide sprays. As can be seen the drop size range (R.S.) is less than a normal or Gaussian under "no-air" conditions. When a high velocity airstream is used of 160 km/hr with the spinners the results are clearly shown in Figures 3 and 4. Now the size range has broadened even well beyond that of a hydraulic hollow cone nozzle as shown in Figure 5. As the drop size or vmd is increased the cone nozzles also show a wider size range (Figure 6).

True monodispersion can be obtained with aerodynamic nozzles (Microfoil^R) and also for small drop size such as developed at the University of California. The use of a pulsing device on the liquid emitted from an aerodynamic nozzle can result in a single drop size being generated. However, even without the pulsed system a very narrow range is achieved as shown in Figure 7 even at 165 km/hr. This nozzle is shown in Figure 8 and illustrates the protective shielded trailing edge of the airfoil section through which the spray is discharged.

The obvious limitation on such a nozzle is the very small orifice of 150 μm diameter to produce 300 μm diameter drops. However, if larger average drop size is acceptable then larger orifices might be used. This appears to be possible for many herbicide applications such as 2,4-D, Propanil, Parquat, and others where drift-losses are of concern but large drops up to 600 to 1000 μm diameter vmd can also still be effective. Several atomizers which may overcome the small orifice limitation designs are being considered and include aerodynamic forms (for air-carrier and aircraft use), two-fluid and also certain spinning devices as well.

The table gives operational data on a few of the atomizers we have examined for drop size distribution. The R.S. or relative span is defined as:

$$RS = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}}$$

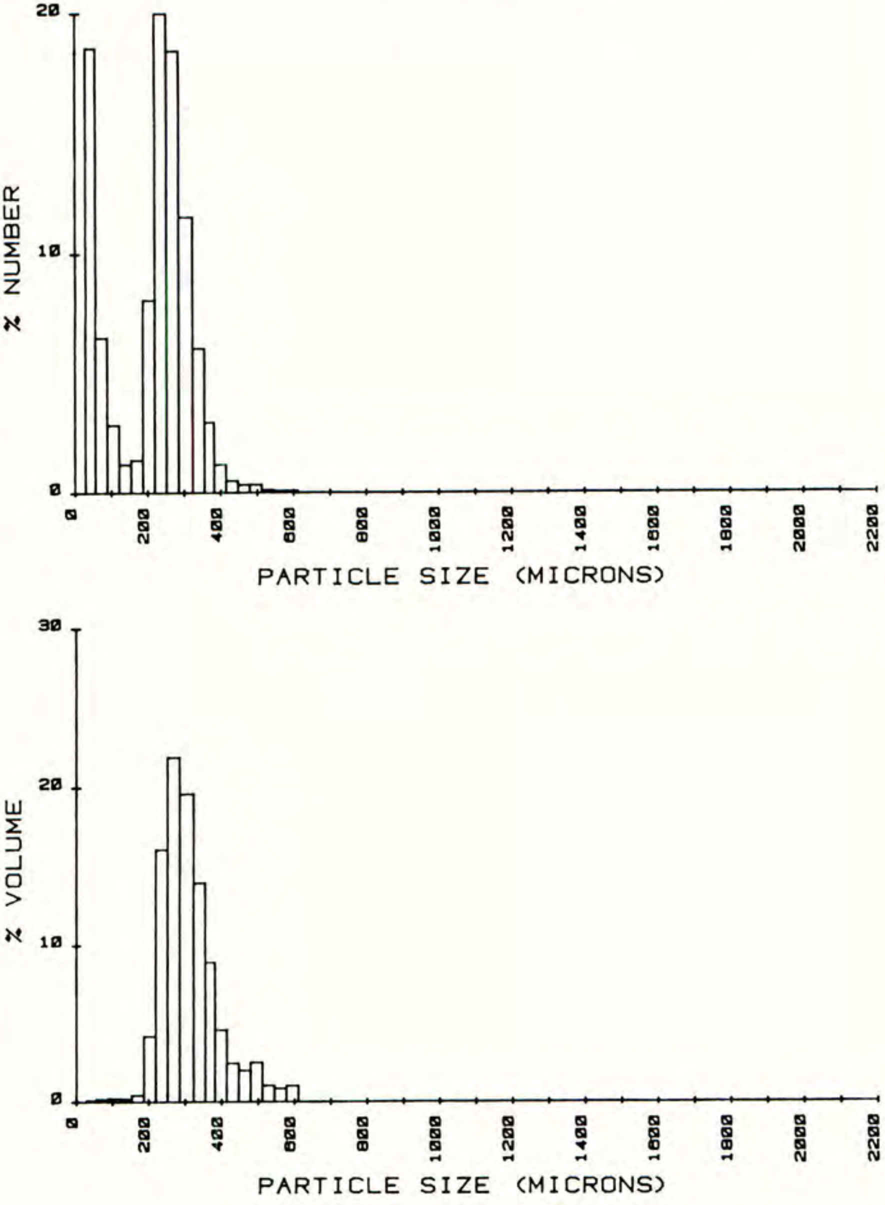
This states that R.S. is equal to the drop size found at the 90% vol. level (from a log size--log probability graph) minus the size at the 10% level divided by the size at the 50% or vmd. A value of zero R.S. would indicate a monodisperse or one-drop-size while at unity or one the distribution would approach the normal or Gaussian form. The drop size range broadens rapidly as the R.S. goes above one.

USE OF SPRAY ADDITIVES

Spray Additives are used for reducing surface tension of water base sprays and are also being sold to aid in limiting drop size range. The theory of use for water soluble polymers is to stabilize the atomization process primarily by drawing small satellite drops back into the main body of drops during atomization. The elasticity effect need not increase the mixture viscosity, but amounts above about 1% of polymer in water will cause viscosity increase. The

Figure 1

Spray drop distribution



MICROMAX, 2000 RPM, ad .03%, 1.421/min

DTG 81/09/23 17:05:37 R.S. ... .62

Figure 2

Spray drop distribution

MICROMAX, 5000 RPM, ad .03%, .136 l/min

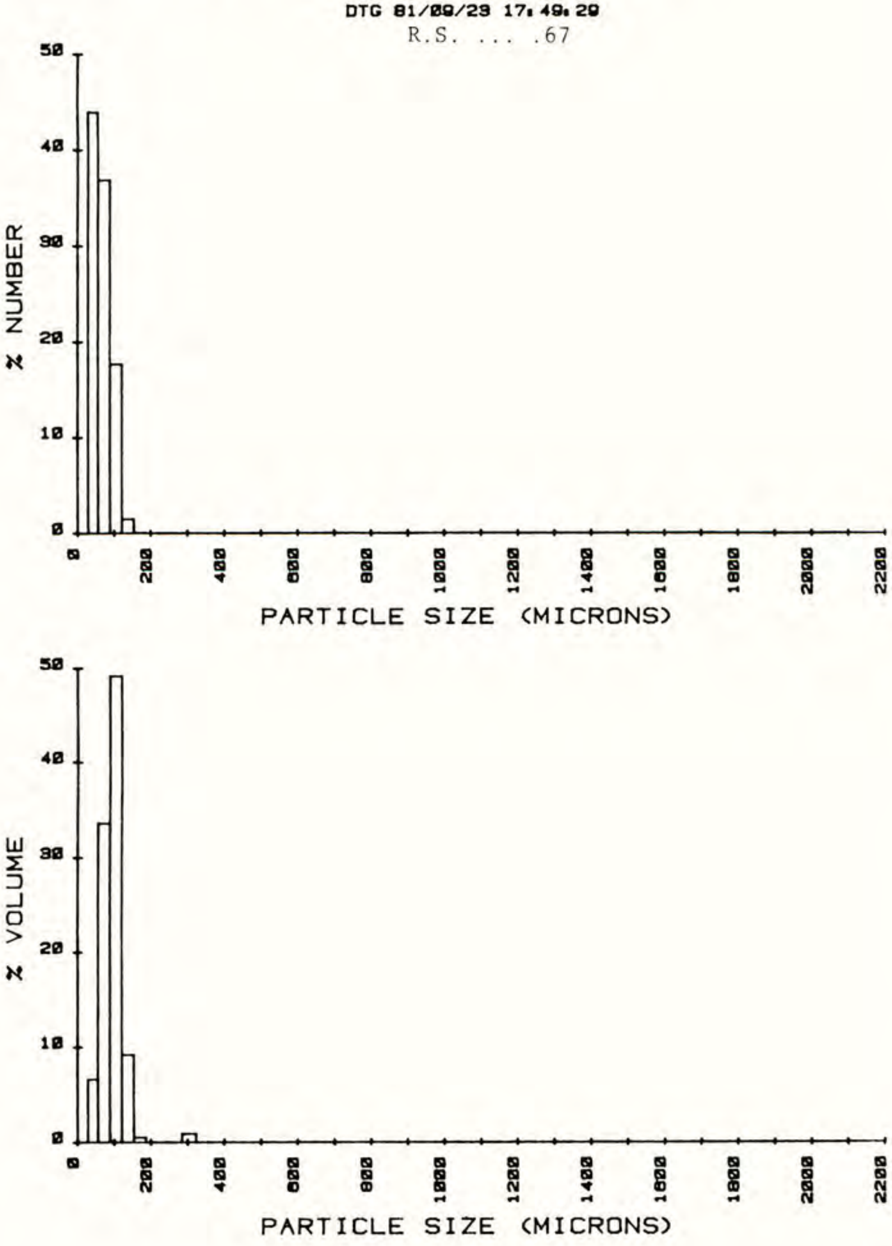


Figure 3

Spray drop distribution

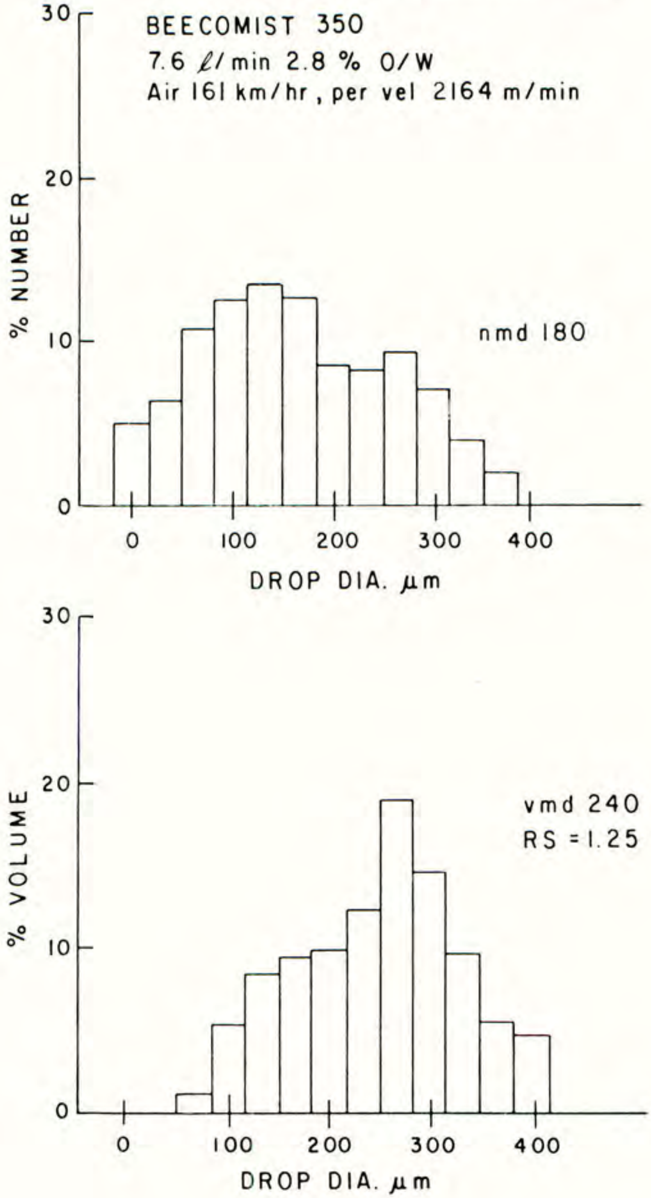


Figure 4

Spray drop distribution

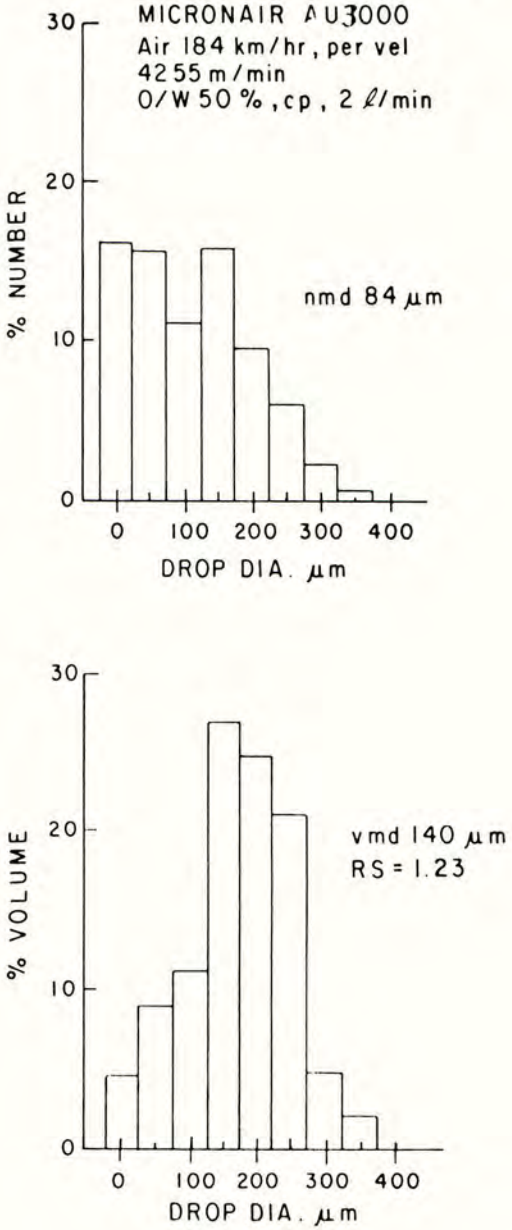
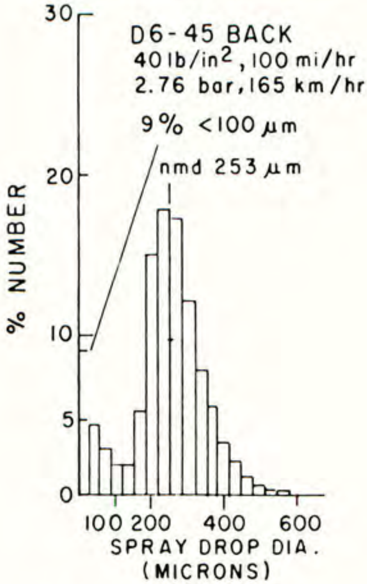


Figure 5

Spray drop distribution



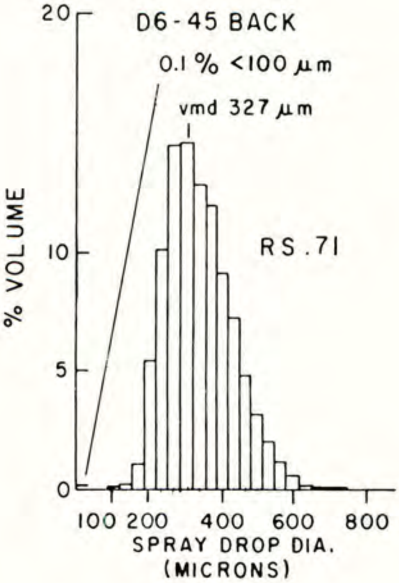
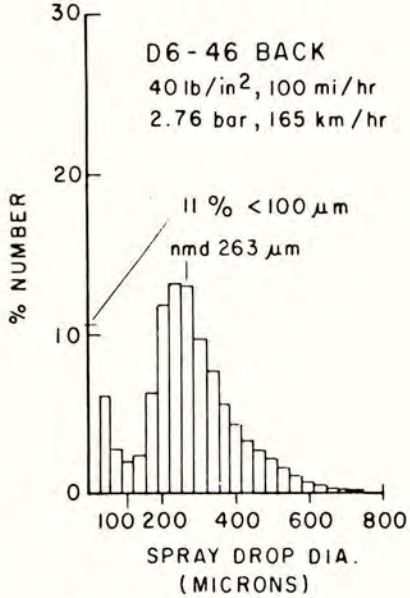


Figure 6

Spray drop distribution



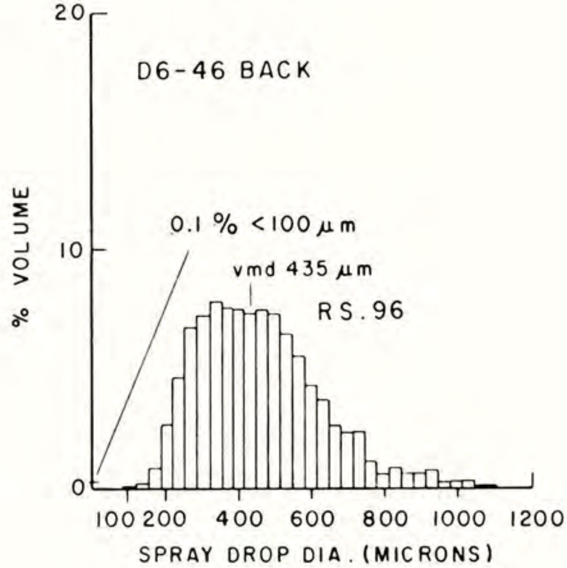
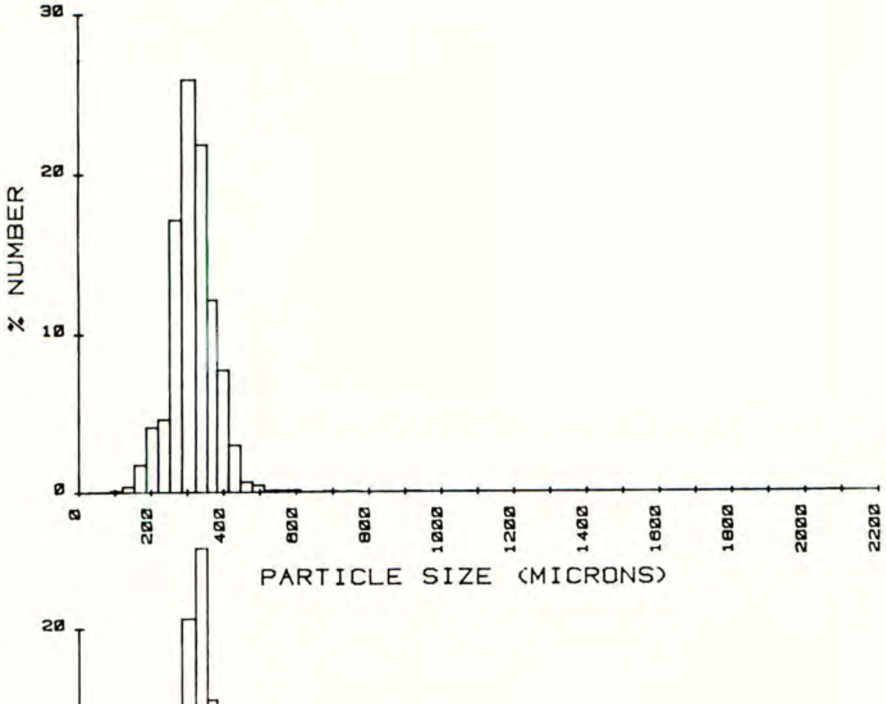


Figure 7

Spray drop distribution

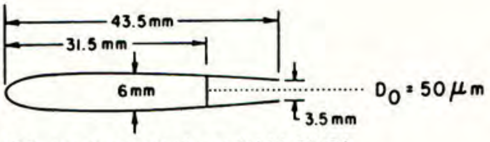
SHIELDED NOZ, 0 Hz, 45.7 cm back, .4 bar, 165 km/hr
R.S. .... .44



R.S. ... .44

Figure 8

Shielded nozzle for mounting on aircraft



14% short shielded (mod. NACA 0012)

42 % streamlined tubing

elasticity effect is very sensitive to formulations, particularly the addition of soluble salts such as many of the herbicides may contain. The addition of a polymer will not always provide any drop size control and so it should not be recommended for all uses. Where high shear rates are imposed on the spray such as from an aircraft producing small spray drops or with high pressure ground machines the polymer is broken down and effectiveness is limited or lost. The material must be checked with each formulation and rate of dilution to determine proper and effective amounts of polymer to use.

Other viscosity and surface tension affecting additives are available, but largely have little or no effect on drop size. The principle effect of additives is on the evaporation process. Many of these have low vapor pressure such as petroleum and vegetable oils and glycols and a wide variety of formulations without water are being made available particularly for low volume work at less than 2 litres/hectare.

ELECTROSTATIC SPRAYING

The use of electrostatic charge to either trap out small drops or increase their deposit rate has been examined by many researchers dating back 50 years. The work continues at several places in the USA and elsewhere but field tests with either aircraft or ground rigs do not show (1) significant increase in deposit on target or (2) reduced drift-loss to areas surrounding treated fields. The most recent work by the FMC Corporation has now been stopped, ostensibly because benefits of electrostatic charging could not be shown to offset the additional cost and maintenance of the machine.

We are presently working with a number of pyrethroid in oil formulations and are looking carefully at several atomizers for handling this low application volume work. There are many new pesticide products that are biologically effective at dosages of 0.1 kg/ha and less. There is need for determinate drop size producing equipment as well as for low volume pumps and booms which are required for this type of work. We plan to expand our drop size capability around the basic PMS Two-D system. We have laboratory facilities to work with physical properties of the spray liquids and are looking carefully at evaporation rates and final deposited residues such as crystals which may be removed by wind for redistribution from a sprayed crop. We feel that work of this physical nature is essential for progress toward greater handling safety and maintenance of biological efficiency with our plant protection and pesticide programs.

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