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Crop Protection: A Consideration of the Effectiveness and Disadvantages of Current Methods and of the Scope for Improvement

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Crop protection: a consideration of the effectiveness and disadvantages of current methods and of the scope for improvement

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Ideally crop protection should prevent damaging effects of pests, diseases and weeds economically, safely and without harming the environment or inducing subsequent control problems. Present methods, based mainly on pesticides and resistant crop varieties, control many damaging organisms effectively but have important limitations. Vulnerability to the emergence of tolerant strains of pest or pathogen is probably the most severe; chemical methods are also often insufficiently selective and very wasteful. Dependence on these methods will continue, however, and it is therefore essential to seek ways of minimizing their deficiencies. The prospects for improvement are discussed in relation to the need for better intelligence about infestations and their consequences, the need to ensure that control measures remain effective and the need to improve the efficiency of utilization of crop protection agents. Implementation of the suggestions for improvement could require fundamental changes in the organization of crop protection practices.

Introduction

The management of crop protection practices must be evaluated against various criteria relating to efficacy and side effects. Most obvious is the extent to which the measures fulfil their basic function of preventing reductions in crop yield and quality caused by pests, diseases and weeds at a cost repaid by improved productivity. This assessment of performance should include consideration of whether the measure remains effective when applied repeatedly.

A different type of criterion is the extent of any damage to non-target organisms. This must encompass a general concern for environmental quality, but in the present context effects on organisms of agricultural importance, including pollinating insects, natural enemies of pests and, of course, the crop itself are of particular interest. The risk to non-target organisms from a chemical agent depends firstly on its intrinsic physiological selectivity. Existing pesticides differ greatly in their physiological selectivity; the design of more selective molecules is a potentially very rewarding field for future research (Graham-Bryce 1975, 1976) but lies outside the scope of this paper. However, much can also be done to decrease harmful side effects by adjusting formulations and methods of application to favour reception of the toxicant by target organisms rather than unintended recipients. This approach also bears directly on a final criterion for assessing present methods: the efficiency of pesticide application in relation to the minimum amounts required for effective control.

In the light of these requirements, the management of crop protection measures may be discussed under three headings. These are the need for better intelligence about infestations and their consequences, the need to ensure that control measures remain effective and are not circumvented by the pest, and the need to improve the efficiency of utilization of crop protection agents. Underlying this discussion is the fundamental precept that crop protection should embrace all ecologically acceptable methods within the coordinated approach known as integrated control. Crop protection of annual arable crops seems certain to remain heavily dependent on chemical agents and resistant plant varieties for the foreseeable future, however, and these methods will receive most attention.

Infestations and their consequences

Sound intelligence is an essential prerequisite for managing any endeavour. In the case of crop protection this has two aspects: first, reliable information about the effects of infestations on yield and quality and the extent to which these are diminished by treatment, and secondly the ability to forecast infestation levels in different situations.

Losses vary greatly according to crop, pest and conditions; assessing the adverse effects of pests, diseases and weeds is complicated as discussed in subsequent sections. However as background for this discussion, the orders of magnitude involved may be seen from estimates given by Cramer (1967) and Maier (1975) which suggest that even with the present extensive application of control measures, total world losses to pests, diseases and weeds amount to about one third of the value of the growing crop, while another 15 % is lost by attack on harvested produce. The situation in Britain is relatively favourable but nevertheless losses were recently estimated as roughly 10 % of the crop, equivalent to about £500 M per year in 1976 (Strickland 1976). Gough (1977) summarized many estimates of losses in particular cases.

Effects of damaging organisms on crops

When attempts are made to assess how far damaging organisms prevent the crop from achieving its full potential, several basic difficulties are immediately apparent. Where host plant resistance is the means of avoiding damage even the potential yield and quality are difficult to define because imparting resistance may exact some penalty in terms of other characters. The balance of advantage depends on the magnitude of this penalty compared with the probable losses due to the pest. Any sacrifice of potential yield and quality would however be inseparably associated with the variety whether the damaging organism was present or not; in this sense host plant resistance is less flexible than chemical control which in principle can be used to maintain the output of preferred varieties, whatever their susceptibility to damaging organisms.

The interaction of these different factors is illustrated in table 1 which gives selected results from the 1974 Eucarpia/I.O.B.C. trials kindly made available by Dr M. Wolfe. Performance of contrasting barley varieties with and without the systemic fungicide ethirimol applied as a seed treatment was compared at several sites classified as having high or low levels of mildew (*Erysiphe graminis*) infection. Where mildew levels were low, Proctor and Golden Promise gave yields comparable with those of Vada and Julia which incorporate resistance to mildew, both with and without ethirimol. Where mildew levels were high, however, the resistant varieties gave considerably greater yields in the absence of ethirimol. Application of the fungicide increased yields of all four varieties at these sites; the effects were proportionately greater for Golden Promise and Proctor but performance was not restored to that at the sites with little mildew.

Table 1 illustrates clearly that when there is little mildew infection, the mildew resistant varieties offer little advantage, indeed in some cases they may give smaller yields. Other varieties may be preferred on the basis of factors such as malting quality or earliness of maturation. The opportunity provided by chemical control to benefit from these advantages even in the presence of disease, may explain, for example, the extended popularity of the variety Proctor following the introduction of mildew fungicides. Relations between yield increases resulting from fungicide application to different cultivars and their susceptibility to mildew have also been investigated by, for example, Little & Doodson (1972) and Jenkyn & Moffatt (1975).

Table 1. Yields of contrasting barley varieties (eucarpia/I.O.B.C. trials)

(Results for low mildew conditions are the means for 6 sites, for high mildew conditions means for 8 sites.)

	yield/(t/ha)			
	low mildew		high mildew†	
variety	ethirimol	no ethirimol	ethirimol	no ethirimol
Proctor	5.11	5.02	4.26	3.87
Golden Promise	5.21	4.97	4.41	3.92
Julia	5.46	5.12	4.86	4.58
Vada	5.11	5.07	4.96	4.78

† Corrected for site factors, estimated from the performance of varieties fully resistant to mildew, protected by fungicide.

A second basic practical problem is that the agents causing crop losses are often not recognized. Unsuspected losses may be revealed fortuitously by the introduction of new pesticides. Thus significant improvements in yield and quality have been reported from using fungicides such as benomyl even in the absence of observable cause. The observation of Tomlinson, Faithfull & Ward (1976) that carbendazim can suppress virus symptoms in lettuces raises intriguing questions in this connection. A comprehensive and deliberate approach to identifying the causes of yield loss is clearly desirable and the multidisciplinary experiments on factors affecting yield of major crops, now being undertaken by several organizations, should contribute substantially to this end. The advent of an increasingly wide range of crop protection chemicals provides a powerful tool for such work.

In some cases the causes of yield loss have received little attention because they have been underestimated or because the benefits of control have been discounted. An obvious example is grass. There is much interest in grass husbandry in Britain at present because it dominates our agricultural acreage and because of concern as to the correct balance between animal and crop production. It remains true that for the over-whelming proportion of grassland, the potential for increasing yields by improved management and manuring is much greater than that by crop protection, but the benefits from decreasing losses from damaging organisms should not be overlooked. Ryegrass mosaic virus can decrease yield of perennial ryegrass by 30% in the first harvest year (Heard 1973). Its transmission by eriophyid mites, controllable by pesticides, and via sap transmitted during cutting, grazing or trampling by stock has been demonstrated (Mulligan 1960; Gibson & Turner 1973; Gibson & Plumb 1976). Henderson & Clements (1974) found that treatment with pesticides could increase yields in both newly sown swards and old pastures by up to 30% even when no pests were evident. In further experiments (Henderson & Clements 1976) applying the relatively non-persistent systemic insecticide dimethoate to a sward of S23 perennial ryegrass increased dry matter yields by up to 5 % in the first year and 17 % in the second. The cost of the insecticide compared favourably with that of the nitrogen fertilizer producing the same response, but the need to apply the insecticide repeatedly made overall costs much greater.

Table 2. Effect of mildew control at different times on grain yield of barley, cv. Zephyr (Jenkyn 1974)

	yield/(t/ha)	
Ethirimol treatment	1971	1972
none	4.59	5.46
early	4.97	5.75
late	4.70	6.03
full season	5.48	6.59
s.e.d. (±)	0.041	0.108

Even where the causal agent of crop losses is clearly identified, assessing its economic consequences and the extent to which these are decreased by treatment may be complicated by indirect considerations. For some damaging organisms such as certain viruses, nematodes and soil-borne diseases such as take-all of wheat (*Gaeumannomyces graminis*) there are so far no satisfactory direct control measures. There is much current research to find both chemical and non-chemical treatments for these organisms. At present their control depends on crop rotation. There are clearly financial and organizational disadvantages in not being able to grow a crop at will on the most suitable sites, although they are difficult to quantify. The gains from any direct treatments which would allow this flexibility would need to be compared carefully with the substantial benefits which can be achieved by rotation, particularly for soil-borne pathogens. Work over many years at Rothamsted (reviewed by Glynne 1965), for example, showed that where eyespot and take-all are prevalent, yields can be more than doubled when wheat is grown with a 2 year break rather than continuously.

Even if such indirect considerations are set aside, assessing adverse effects of pests remains complex. Relations between infestations and yield are the outcome of dynamic interactions between population levels and plant growth, both greatly influenced by environmental conditions. Several stages may be involved as in the control of vectors of virus diseases. Powdery mildew of barley will again serve as an illustration. Mildew can decrease the growth of roots in addition to damaging foliage and ears (Last 1962) and has been shown to affect all components of yield: number of ears, number of grains per ear and size of grain (Last 1957; Brooks 1972; Rea & Scott 1973). While the importance of the flag leaf in contributing to the yield of grain would suggest that controlling mildew late in the development of the crop would be important, mildew attacking early could also have severe effects by adversely affecting root establishment.

Table 2, based on results reported by Jenkyn (1974), illustrates the effects of mildew infestations on spring barley at different growth stages, Ethirimol was applied as a seed treatment to give early season protection, as two sprays at approximately 3 week intervals about the time of ear emergence to protect the flag leaf and ear during grain filling, or as a seed treatment plus the two sprays to give full season protection. In all cases full season protection gave best results. In 1971 there was severe early mildew attack and the early treatment much increased ear numbers so that yields were greater than for crops protected late. In 1972 the late treatments

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applied to protect the flag leaf and ear increased yield more than the seed treatment because early mildew was less severe. In view of the complexity of mildew attack on barley, it is remarkable that some relatively simple relations between mildew levels and yield have been established, such as the well known example by Large & Doling (1962) who found that yield loss was related to the square root of the leaf area affected by mildew at growth stage 10.5.

The importance of mildew and the benefits of treatment are also affected by other agronomic practices. Severe early mildew is probably most damaging to crops sown late (Last 1957), while mildew fungicides often increase yield most when large rates of nitrogen fertilizer are applied (Jenkyn & Moffatt 1975). The nutritional effects of nitrogen manuring will of course greatly outweigh disease control factors. These factors are therefore hardly likely to determine agronomic practices, but knowledge of such interactions is essential to manage crop protection measures most effectively.

Special considerations apply to weed control, especially where herbicides provide the basis for reduced cultivation methods. Evaluation of the benefits of treatment must include not only direct effects on crop yield and quality of eliminating weeds, but also savings in labour, in energy and any indirect effects on damaging organisms. Thus while the increased costs of energy have further encouraged the development of reduced cultivation techniques by increasing the advantages of spraying over ploughing, there is evidence that some pests such as slugs and wireworms and certain trash-borne diseases are favoured by the greater quantities of plant debris left with direct drilling compared with traditional ploughing (Edwards 1975; Yarham 1975).

Weed control with herbicides has proved remarkably successful and their consequent widespread and repeated use has changed the weed flora of cultivated land significantly (Fryer & Chancellor 1970). Certain problem weeds such as couch grass (*Agropyron repens*) in cereals, which are not readily controlled by herbicides, have become more prominent, stimulating a detailed examination of their biology and interaction with the crop. In the case of couch grass, the key to successful control was identified as the prevention of rhizome growth in the immediate post-harvest period, coupled with fragmentation of the existing rhizomes which stimulated the dormant buds to grow so that they could be killed by cultivations and small doses of non-residual herbicides (Fryer 1977). Implementation of this approach required appropriate organization of harvesting and straw clearance by the grower. In the light of this experience similar investigations were undertaken with wild oats, leading to blueprints for control systems appropriate for different farming patterns (Cussans 1976).

The concept of attacking damaging organisms at vulnerable points in their life cycles is of course not new. A recent example from the field of disease control is the use of dormant season sprays against apple mildew (Hislop & Clifford 1976). There is increasing concern to develop control methods based on sound knowledge of the biology and population dynamics of the target organism in all areas of crop protection.

Forecasting of infestations

The advantages of forecasting infestations for avoiding wastage and improving the selectivity of crop protection treatments are self-evident, particularly for pests and diseases whose attacks are sporadic. Weeds may again be distinguished from other damaging organisms as they are invariably present in all crops and control measures are therefore routinely required.

Many forecasting schemes of varying sophistication are already in operation. Some aim to give relatively long term indications of the general levels of infestation to be expected in the subsequent season. Examples are the sampling of wheat bulb fly (*Delia coarctata*) eggs in late summer to indicate the need for treating winter wheat seed and the monitoring of *Aphis fabae* eggs overwintering on their winter host, spindle trees, to predict levels of infestation to be expected the following season.

The growth, reproduction, movement and activity of organisms are greatly influenced by environmental conditions, particularly temperature. Levels of infestation therefore depend markedly on the weather, and under the capricious climatic conditions of Britain, forecasting must become increasingly unreliable as the period before the event increases. It would seem inevitable that long term forecasting of infestations can never be more predictable than the weather. In the light of this the success over many years of the long range forecasting of *Myzus persicae* vectors of virus yellows on sugar beet based on weather at Rothamsted (Watson, Heathcote, Lauckner & Sowray 1975) was remarkable. While these predictions have been much less effective recently, the results suggest that the possibility of feedback mechanisms operating in population control should be investigated thoroughly as understanding of such mechanisms could be most useful in developing forecasting systems.

Shorter-term warnings of infestation levels can also be of great value, especially where decisions about the need for treatment depend on accurate knowledge of population numbers or where timing of treatments is critical for effective control. These considerations apply to the control of certain pests in orchards, which have traditionally been intensively treated with pesticides and where there has been very active interest in the development of integrated control programmes. Pheromones are an especially useful tool in this approach. An example of the many studies in this field is collaborative work between East Malling Research Station and Rothamsted Experimental Station which showed that male codling moths are caught by lures incorporating the synthetic attractant *trans*-8, *trans*-10-dodecadien-1-ol up to 3 weeks earlier than light traps and followed the emergence of male moths more closely (Greenway & Cranham 1975). Pheromone traps are also cheaper, more mobile and more specific. In conjunction with knowledge of relations between numbers trapped and fruit damage, pheromone traps can therefore be very sensitive indicators of whether or not treatments are required and of the optimum spray timing, thus eliminating unnecessary sprays. Critical timing is also needed for pea moth control, which must be extremely effective to meet processors' specifications. Existing pesticide treatments such as triazophos are applied before larvae attack the pods and are not very persistent. At present spray timing is determined from counting eggs on plants in the field which is time consuming and sometimes unreliable. Recent work (Wall, Greenway & Burt 1976) has indicated that the synthetic compounds (E)-10-dodecenyl acetate and (E,E)8,10-dodecadienyl acetate are powerful attractants for pea moth in the field. Traps incorporating these compounds reveal pea moth infestations significantly earlier than egg counts and should therefore provide the basis for an improved spray warning system.

The principle illustrated by this discussion, that the management of crop protection should be greatly improved by better intelligence about damaging organisms, is readily acceptable. However, it will be clear that this is an exceedingly complex field in which the possibilities for investigation are almost endless. It is crucial to choose subjects for study which will be most rewarding. An obvious omission from the discussion so far is the problem of resistance which requires much monitoring and assessment. This problem is considered in the following section.

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Circumvention of control measures by damaging organisms

Probably the greatest shortcoming of chemical control and of host plant resistance is that their efficacy is often transient due to the emergence of strains of pests and pathogens insensitive to the pesticide or virulent against the resistance factors. This problem is becoming progressively more serious throughout the world; for example insensitivity to insecticides has now been detected in some populations of almost all species of medical, veterinary or agricultural importance. Because insensitivity genes persist within populations the only practicable way of dealing with established insensitivity has been to transfer entirely to a different chemical, which may in turn select other mechanisms of insensitivity. The range of possible replacement compounds can thus contract very rapidly with the sequential development of insensitivity, particularly for insecticides which come from very few chemical classes so that there are already dangers of exhausting all available compounds with some pest populations (Sawicki 1975).

Loss of effectiveness of chemicals and of host plant resistance share many common features. The problem is essentially simple in concept, although its detailed features must be determined in each individual case. Populations of pests and pathogens of agricultural crops may normally be considered so large that they are capable through mutation of providing all the individual variation necessary to overcome a wide range of control measures. Implementation of control measures imposes a selection pressure which tends to increase the frequency of the less sensitive genotypes, leading eventually to the treatment ceasing to be effective at the original rate. Practical experience and fundamental considerations outlined below indicate, however, that failure of control measures is not inevitable, and give grounds for suggesting that more enlightened management of control measures could prolong their useful life, possibly indefinitely. Strategies to avoid loss of effectiveness require two interrelated components: knowledge of the genetic and biological characteristics of the population being treated which condition the response to selection, and understanding of the nature of the selecting agent both in terms of the type of selection pressure it will impose and in terms of the genes selected and the other agents which they will affect.

Genetic and biological characteristics of treated populations

It will only be possible to outline some relevant properties of populations in general terms here, concentrating on insensitivity to chemical agents; more detailed treatments are given in specialist papers such as Wolfe & Dinoor (1973), Greenaway & Whatley (1975) and Wolfe (1975).

A critical property of the treated population is the relative abundance of genotypes with different sensitivities to the control measure which acts as a selecting agent; this must in turn depend on the nature of the agent, but insensitive genotypes will be in a small minority. Genetic and biological factors which influence how this initially small proportion of insensitive individuals increases and becomes established in the population include the length of the pest's life cycle, the numbers of offspring per generation, the relative importance of sexual and asexual reproduction, whether the insensitivity is polygenic or oligogenic and the extent to which it is dominant or recessive.

Establishment within a population is also affected by the relative fitness of the insensitive strain. Many studies have demonstrated that insensitive isolates compete poorly with sensitive strains (see review by Fletcher 1975). The work by Hollomon (1975) with strains of barley powdery mildew, illustrated in figure 1 provides a good example. Mixtures initially containing equal numbers of a strain insensitive to ethirimol and a standard sensitive strain were maintained for several generations in the absence of fungicide. Monitoring with an *in vitro* discriminating dose bioassay (figure 1) and with other tests showed that the insensitive strain was rapidly lost from the mixture. Further work (Hollomon, personal communication) has now demonstrated that under moderate selection pressure both the most sensitive and the most insensitive components of a natural population appear to compete poorly with those of intermediate sensitivity.

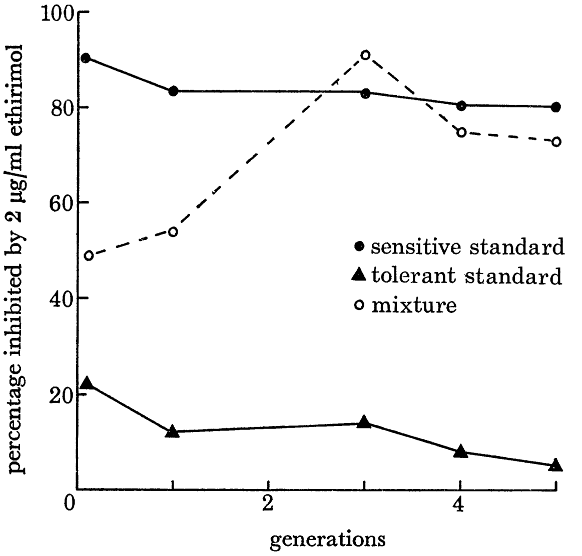

FIGURE 1. Competition between strains of barley mildew susceptible and insensitive to ethirimol, initially present in equal numbers. (From Hollomon 1975.)

Prolonged selection, however, not only increases the frequency of insensitive individuals but also the overall fitness of insensitive populations. Fitness will be selected most rapidly where insensitivity and other characters for deleterious effect are not associated (Wolfe 1975). It is clearly important to minimize selecting for fitness so that the population retains the ability to revert to sensitivity when the control agent is not present.

More generally, it would be of great value for the management of crop protection measures if the composition of target populations in terms of the properties discussed above could be determined before a control agent were introduced, and subsequently monitored to warn of impending dangers. This poses considerable practical problems with characters present at extremely small frequencies.

Characteristics of the selecting agent

The properties of the treated population are largely outside the control of the operator. In contrast there is considerable scope for adjusting the nature of the selection pressure. Both the intensity of the selection and its duration are important, as are the proportion of the population exposed and the degree of intermixing with other populations. In practical terms these factors reflect the persistence of the treatment, its mode of action and the rate and manner of application. The interplay of these factors with the properties of the population will determine the risk of insensitivity developing. Whatever the details in any particular situation the cardinal

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point of any policy to avoid insensitivity should be to minimize selection pressure and to withdraw selection before insensitive individuals become numerous and acquire increased fitness. Ideally withdrawal should be rapid and complete, allowing the population to revert to full sensitivity before the capacity to regenerate the original range of response has been lost. As practical application of crop protection measures is in the hands of many individual farmers, it will be apparent that such a comprehensive and systematic withdrawal would be extremely difficult to organize. Other approaches to decreasing selection pressure include the use of variety mixtures as a means of preventing the establishment of virulent strains (Wolfe & Barrett 1977).

When a control measure is withdrawn to reduce selection for insensitivity or virulence, it is essential that any replacement measure is quite independent in terms of the mechanisms it may select. This requires knowledge of the mechanisms selected by different agents and of the ways they interact.

Obtaining this information is a formidable task. A wide variety of metabolic and physiological mechanisms whereby damaging organisms can circumvent the toxic action of chemical agents has now been identified. Different compounds differ greatly in the mechanisms they select so that the range of pesticides rendered ineffective can vary markedly according to the selecting agent. In favourable cases it is possible to find compounds to which there is no cross-insensitivity. For example Ebben & Spencer (1973) found that although glasshouse populations of cucumber powdery mildew (*Sphaerotheca fuliginea*) readily developed insensitivity to benomyl or dimethirimol applied separately, each insensitive strain was fully sensitive to the unrelated compound, so that prolonged control could be obtained by using the two compounds alternately. It is even more fortunate if there is negative cross-insensitivity as found by van Tuyl, Davidse & Dekker (1974) who reported that among benomyl insensitive isolates of *Aspergillus nidulans* obtained by u.v. radiation were some showing increased sensitivity to thiabendazole. Similarly Lambert & Wuest (1975) showed that sensitivity to zineb was increased in benomyl insensitive strains of *Verticillium malthousei*.

Much useful information to guide the choice of pesticides can be obtained by resolving multiplicate insensitivity found in field strains into its components using genetic and biochemical techniques. Combining the results of such investigations with information on the practical use of pesticides may then indicate the order in which different resistance genes were selected by the sequence of treatments used. One of the best documented cases to illustrate this is the sequential insensitivity of houseflies to insecticides in Denmark analysed in detail by Sawicki (1975). Table 3 summarizes some of the main conclusions. It lists the approximate order in which different insecticides had to be introduced to maintain control as insensitivity developed to each in turn, together with the insensitivity genes selected in each case. While some mechanisms (such as Dld_4 selected by cyclodienes) are relatively specific, others give widespread cross-insensitivity, for example the modified acetylcholinesterase ($AChE_R$) and gene D together confer moderate insensitivity to many organophosphorus insecticides. The table also shows the way in which selection with a given compound can have profound consequences for the efficacy of insecticides introduced many years later. Perhaps the most striking example is the mechanism *Kdr* selected initially by DDT in the late 1940s which remained within the population without manifesting itself until it reappeared in the 1970s to contribute to a rapid development of insensitivity to pyrethroids. Similarly the potential for development of insensitivity to diazinon was already present in the population before it was introduced as a result of the selection of DDT_{md} by DDT and gene a by parathion.

Other historical accidents were more fortunate. For example if dimethoate had been introduced before parathion and diazinon, use of these two compounds would have been precluded by the selection of $AChE_R$ and gene D which although conferring insensitivity to parathion and diazinon do not appear to be readily selected by them.

Such results emphasize that the order in which chemical agents are used can be of crucial importance: the wrong choice could eliminate prematurely many compounds which could otherwise make a valuable contribution to pest control.

Table 3. Insecticidal usage and development of resistance in houseflies on Danish farms (Sawicki 1975)

		resistance genes								
year	insecticide	*DDTase*	DDT_{md}	*Kdr*	Dld_4	*a*	*Carb*	*M*	$AChE_R$	*D*
1946	DDT	X	X	X						
1948	cyclodienes	—	—	—	X					
1953	parathion	—	—	—	—	X				
1954	diazinon	—	X	—	—	X				
1953	malathion	—	—	—	—	—	X	X		
1961	dimethoate	—	—	—	—	—	—	—	X	X
1960s	fenthion	—	—	—	—	—	—	—	X	X
1969	fenitrothion	—	—	—	—	—	—	—	X	X
1969	tetrachlorvinphos	—	—	—	—	—	—	X	X	
1971	pyrethroids	—	—	X	—	(several)				

Recently a further important aspect of this subject has been recognized (Wolfe, M. S., personal communication). For pathogens such as mildew on barley, both resistant varieties and chemical treatments are used to achieve control. The pathogen population is thus subject simultaneously to different types of selection: changes in the popularity of different barley varieties due partly to the emergence of virulent strains will exercise selection on the virulence characteristics of populations, often on a large scale. Selection by pesticides may thus be operating on a continuously changing population and this could work against insensitivity to chemicals becoming established. Such suggestions underline the very great importance of considering the management of host plant resistance and chemical control together within an integrated approach.

Efficiency of utilization of crop protection chemicals

With an ideal pesticide application system, each individual damaging organism would receive a just-lethal dose, and no toxicant would reach any unintended recipient, thus achieving maximum efficiency and selectivity. It will be apparent that in most practical situations it is not possible even to approach this ideal. It is instructive however to examine the reasons for this to clarify the levels of utilization for which it is practicable to aim.

It is necessary first to take into account the variability in response of different individuals within a population, as expressed by the dose/response relation. As it is clearly not possible to adjust the dose for each individual in a population, it is necessary to ensure that all receive the l.d._{99} or some other dose high in the dose/response range. Treatment of all individuals with with l.d._{99} will result in 99% being over-dosed and 1% underdosed. Further unavoidable 'wastage' is a consequence of the very rapid rate of multiplication of many damaging organisms

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and the need to arrest an infestation before significant damage has been caused. In terms of the proportion of the applied dose reaching the intended recipient, utilization is very much poorer if, for example, aphids are sprayed when present at one per four plants (as recommended for sugar beet in Britain) than when the infestation is severe and presents a larger target. The treatment is likely, however, to be very much more effective. In many cases it is obviously both more effective and more convenient to use prophylactic treatment applied before the infestation starts. Soil and seed treatments with systemic insecticides and fungicides often come into this category; in such cases efficiency can only be evaluated in terms of the proportion of the applied dose entering the plant.

Table 4. Utilization of crop protection chemicals (extended from data given by Graham-Bryce 1976)

pesticide	method of application	receiving organism	efficiency of utilization (%)	reference
dimethoate	foliar spray	aphids on field beans	0.03	Graham-Bryce (1975)
lindane	foliar spray	capsids on cocoa	0.02	Winteringham (1974)
ethirimol	seed treatment	barley (for mildew control)	2.2	Graham-Bryce & Coutts (1971)
disulfoton	soil incorporation	wheat (for aphid control)	2.9	Graham-Bryce (1968)
lindane/dieldrin	aerial spraying of swarms	locusts	6.0	MacCuaig & Watts (1963)
paraquat	spray	grass weeds	up to 30	Brian (1976)

Even allowing for these considerations pesticide use is mostly extremely inefficient. Table 4 indicates the scale of this inefficiency; utilization is expressed in terms of the proportion of the applied dose taken up by the receiving organism or calculated as required to eliminate a damaging infestation if applied directly to the individuals in the population. The value for paraquat is the proportion of the applied herbicide penetrating into experimental plants when sprayed in the glasshouse; it thus represents the maximum efficiency which could be expected from any conventional method of application.

Any such estimates must be subject to considerable reservations. The figures do, however, indicate orders of magnitude and emphasize the need for improvement. To achieve this improvement requires better understanding of pesticide behaviour in the local environment and of the locations, movement, and receiving characteristics of target and non-target organisms. This should suggest ways to match the supply of pesticide to the potential for uptake by the intended recipient by appropriate choice of control agent and method of application and formulation. Three contrasting examples will demonstrate that the potential benefits of such an approach are considerable, suggesting that some of the very large resources devoted to the discovery of new active compounds might profitably be directed to expanding investigations into how they should be used.

Size of insecticide spray droplets in relation to efficiency of kill

Traditional spraying equipment emits a wide range of droplet sizes. This has restricted utilization because efficient impact and avoidance of drift require a narrow range of droplet size with a mean size adjusted for the particular crop protection problem. Recently, however, the advent of controlled droplet application (c.d.a.) based on the use of spinning disk applicators has provided the means of obtaining a very narrow droplet spectrum which should make it possible to obtain maximum deposition and even distribution on the target (Bals & Merritt 1975). There is therefore much greater incentive to consider the optimum specification for droplet size and content.

An important factor governing the useful size of droplets in sprays of non-systemic insecticides is the dose necessary to kill the insect with certainty (Hartley & Graham-Bryce 1977).

Table 5. Relation of drop size to efficiency of kill

(*a*) Spraying for lethal dose in average number of contacts

average contacts	percentages of population		
	lethal dose	underdosed	overdosed
1	37	37	26
3–5 (4 ± 1)	55	24	21
5–11 (8 ± 3)	79	10	11

(*b*) Lethal dose in single droplet

average contacts	percentages of population		
	lethal dose	escaping	overdosed
1	37	37	26
2	27	14	59
4	7	2	91
8	negligible	negligible	99.7

If a single drop of 100 μm diameter is large enough to contain this dose, over 90 % of the content of a 300 μm diameter drop could be wasted even if it contacted the insect. Simple statistical considerations suggest that the optimum size should be even smaller. If all insects in a population have an equal chance of contacting all droplets entering their habitat, the relative probabilities of different numbers of contacts can be obtained from the Poisson distribution. The probability of r contacts is given by $n^r \exp(-n)/r!$ where n is the mean number of contacts. For $n = 1$ the relative probabilities of 0, 1, 2 etc. contacts are 0.37, 0.37, 0.18 etc. If therefore we spray for the maximum number of single contacts, with the implication that the single drop contains the just-lethal dose, then we achieve only 37 % of the intended single contacts, with 26 % of insects overdosed and 37 % escaping (table 5*a*). If the size or content of the droplets is decreased and their number increased so that the lethal dose is in the 3–5 droplet range (mean 4 ± 1), 55 % receive the intended amount with roughly 20 % either overdosed or underdosed. These figures are reduced to 10 % if the lethal dose is in the 5–11 droplet range (mean 8 ± 3). If we increase the number of droplets without decreasing their content so that the single droplet still contains the lethal dose but the average number of contacts increases, the proportion escaping falls rapidly, but there is a correspondingly rapid increase in waste (table 5*b*).

This argument rests on various assumptions but the essential principles are generally valid. Application of these principles in conjunction with the facilities for controlled droplet application now available could lead to significant reductions in dose rates and in wastage.

Vapour transfer of biologically active chemicals

Better understanding of vapour transfer would be valuable not only in relation to pesticide use but also for manipulating behaviour controlling chemicals. The use of pheromones for monitoring pest populations was discussed earlier. However, attempts to employ them for controlling pests by disrupting normal behaviour have so far met with little success. This is largely because knowledge of the mechanisms by which a non-directional stimulus can elicit a directional response is inadequate. The requirements for solving this complex problem include a better understanding of how the chemical stimulus is transferred from source to recipient. The following considerations (Hartley & Graham-Bryce 1977) suggest that the patterns of transfer are by no means obvious and require careful investigation.

Reaction to pheromones must involve a response to changes in the concentration (C) of stimulating vapour either with time or space. The sensing of pheromones by pests, like other senses, can be expected to respond to changes in stimulus strength on a logarithmic scale, according to the Weber–Fechner law. There is little information about the threshold concentration gradient which insects can just detect, but comparison with other species and indirect evidence suggest that a $\Delta(\ln C)$ of 0.2 would be a reasonable assumption. To be perceived this difference would have to occur within not more than about 2 cm for most insects or about 0.2 s according to reaction times recorded in the literature. Thus it would seem that $\mathrm{d}(\ln C)/\mathrm{d}x$ must exceed about 0.1 $\mathrm{cm^{-1}}$ or $\mathrm{d}\ln C/\mathrm{d}t$ must exceed about 1 $\mathrm{s^{-1}}$ to produce a response useful for direction finding.

The gradient of concentration produced by a pheromone source is determined by molecular and eddy diffusion and by any other sources and sinks in the surrounding atmosphere. Some important principles are exemplified by considering the model system of a plane source of pheromone which maintains a constant surface concentration C_0. The change of concentration with distance from the surface (x) and time (t) is given by:

$$C = C_0 \operatorname{erfc}\,(x/(4Dt)^{\frac{1}{2}}), \tag{1}$$

where D is the diffusion coefficient and erfc the error function complement. The concentration gradient may be derived from this as

$$(\partial \ln C/\partial x)_t = (1/(\pi Dt)^{\frac{1}{2}}) \exp\,(-x^2/4Dt) \operatorname{erfc}\,(x/(4Dt)^{\frac{1}{2}}). \tag{2}$$

Thus although the concentration decreases with distance from the source, the gradient of log (concentration) *increases* indefinitely with increasing distance. This is demonstrated in figure 2 which shows values of $(\partial \ln C/\partial x)_t$ with increasing distance for a value of $D = 0.05\ \mathrm{cm^2\,s^{-1}}$ after 10 s (dotted line). According to the Weber–Fechner law, therefore, the vapour should become easier to detect further from the source. Obviously, however, there is also a minimum detectable concentration, as well as a gradient. In practice there will be some optimum combination of these conflicting tendencies which may vary widely for different organisms and stimuli. Figure 2 shows that gradients can be well above the estimated threshold within quite short distances of the source, although the value of 5 $\mathrm{cm^{-1}}$ is not reached until a distance greater than 5.5 cm where the concentration will be only 3×10^{-8} of that at the constant source.

The gradients will be very sensitive to other factors in the vicinity. The effects of neighbouring sinks are illustrated in Figure 2 by plotting the gradient resulting when there is a completely adsorptive wall at the plane $x = 1.5\sqrt{2}$. This dramatically increases the gradient beyond about 1 cm after 10 s. The curve for the steady state condition ($t = \infty$) which would result if the supply could be maintained indefinitely is also shown.

The model of an adsorptive sink is not unrealistic. Plant cuticles and their associated oils and waxes could have a very significant capacity for lipophilic pheromone molecules. The decreasing gradient with proximity to the source is also consistent with some aspects of behaviour in the field, for example the apparent loss of directional stimulus when moths arrive at pheromone traps after relatively unswerving approach from a distance, and the apparently large stimuli received near foliage. Such theoretical curves suggest that more attention should be given to behaviour at a distance from the source in seeking practical methods of using attractants and the efficacy of attractants might be greatly enhanced by combining them with repellents or some form of sink.

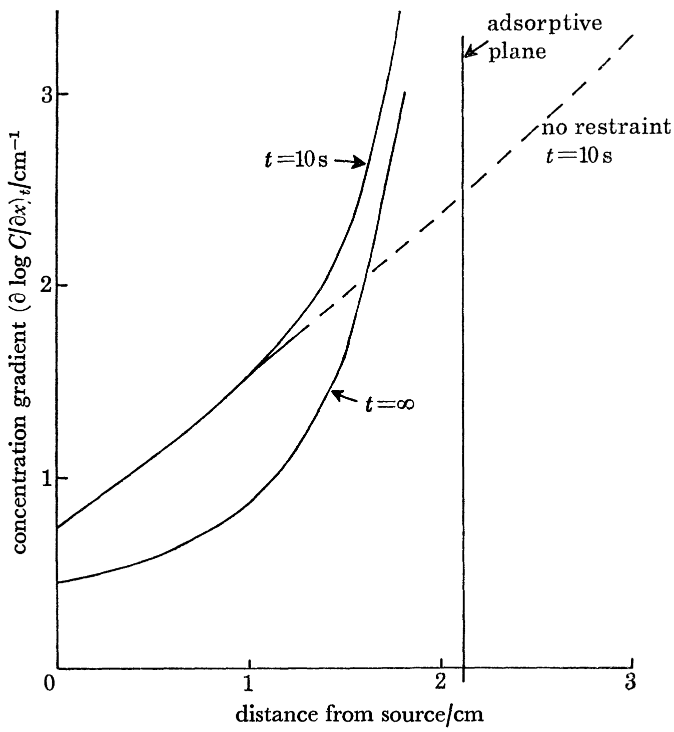
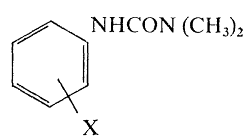


FIGURE 2. Theoretical curves for gradients of pheromone from a plane source after 10 s and at the steady state ($t = \infty$) in the presence of an adsorptive plane at the position indicated. The dotted line indicates the gradient after 10 s in the absence of any restraint.

Availability of pesticides in soil

The herbicidal *N,N*-dimethyl *N′* phenyl ureas provide a different type of example of how knowledge of behaviour in the environment can improve approaches to crop protection, in this case at the early stage of selecting chemicals for practical development (Briggs 1977). Hansch & Deutsch (1966) showed that the relative inhibition of the Hill reaction by 12 ureas of the general formula



could be described by the relation

$$\lg 1/C = 0.54\sigma + 1.29\pi + 4.18. \tag{3}$$

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where σ is the Hammett constant and π the partition constant for the substituent concerned, and C is the concentration causing a standard response. Inhibition of the Hill reaction should provide an index of intrinsic herbicidal activity for compounds thought to act by blocking the electron-transfer step in the photochemical reactions of plants.

In practical use, however, performance depends not only on intrinsic activity, but also on efficiency of movement to and uptake by the plant following soil application, both of which are greatly influenced by the extent of adsorption by the soil constituents. For adsorption of compounds such as the urea herbicides, soil organic matter is the dominant constituent, and Briggs (1977) showed that the organic matter/water distribution coefficients (Q) for a similar set of compounds to that considered by Hansch & Deutsch were described by the relationship:

$$\lg Q = 1.29\sigma + 0.1\pi + 1.1. \tag{4}$$

It will be seen that availability in soil, as reflected by lg Q, decreases with increasing values of σ and π, while intrinsic activity increases in this direction. Optimum performance in practice should result from a compromise between these conflicting trends and the compounds most active in preliminary screening would probably not prove most effective in the field. By combining the relations given in equations (3) and (4), Briggs was able to predict successfully compounds with potential for practical development.

Conclusions

While modern methods of crop protection, based largely on chemical agents and resistant crop varieties, are remarkably successful and contribute substantially to agricultural productivity, the discussion in this paper suggests that there is considerable scope for improving both their short and long term effectiveness, decreasing harmful side effects and reducing wastage. To achieve these improvements would require, in addition to the improved management discussed here, the development of more sophisticated chemical agents (Graham-Bryce 1975). These would encompass both novel types of agent such as insect growth regulators and conventional pesticides with additional properties such as phloem-mobility or greater selectivity, possibly attained by exploiting chemical conversion processes in the environment. Many of the compounds would be less profitable to develop than traditional pesticides, particularly as the costs of meeting regulatory requirements are increasing rapidly.

The improved management of crop protection measures proposed in this paper also implies not only much greater integration of different methods but also a greater supervision of pest control practices than has been customary in the past. It would be unrealistic to propose such changes without giving some thought as to how they might be implemented. A possible solution considered elsewhere (Graham-Bryce 1975, 1976; Roberts 1975) would be for industry to move more to providing a complete crop protection service, perhaps developed partly in collaboration with the public sector. This would enable the very considerable resources and expertise of industry to be utilized fully in improving crop protection, making the best use of all methods, not merely agrochemicals. Considerations in the preceding sections suggest that this should involve the development of new plant varieties and of application techniques. Such developments are inseparably associated with other agronomic considerations so that it becomes necessary to consider crop protection within a wider context. This line of argument therefore serves as a reminder that the most effective management of crop protection measures requires that they are integrated fully with other aspects of crop production.

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