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Integrated Use of Fungicides and Host Resistance for Stable Disease Control [and Discussion]

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Integrated use of fungicides and host resistance for stable disease control

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For many crop diseases, stable control at desirable levels can be achieved only by using the two major control measures, fungicides and host resistance. Misuse of each method has often led to a loss in effectiveness and the need for expensive replacement chemicals and varieties. Much effort is now centred on the search for greater inherent durability of the control measures, and for methods of using them that will enhance their durability.

Better progress might be made if fungicides and host resistance were to be used more as part of a single control system. This could provide greater efficiency and economy of disease control and overall strategies of deploying the components that would lessen the chances of selecting pathogen forms that could overcome them. To achieve these ends, some advantages of between-crop and within-crop heterogeneity of the control components are demonstrated.

Introduction

During the twentieth century there has been a phenomenal increase in the output of agricultural crops per unit area. Many factors have been involved in increasing potential yields and in realizing those potentials. The consequent ecological changes have also led to increases in the potentials for increase and spread of pests and diseases, and great efforts have been required to try to ensure that these potentials have not been realized. Two of the major weapons in this negative aspect have been resistance breeding and the provision of highly effective pesticides. This paper is concerned with problems of pathogen response to the widespread use of disease-resistant varieties and fungicides, and some ways in which these may be ameliorated by integrating the two control measures.

Because of the high unit area outputs, on the one hand, and the efficiency of the fungicide industry, on the other, costs of fungicide use have been apparently small in relation both to the scale of crop production, and the need to insure that production. This has led to a tendency towards routine prophylactic treatment with fungicides, on the grounds that, even if the disease does not occur in every field or season, over a period of years the cost of the insurance and the consequent stability of crop production would have been worthwhile. Further, a routine control system simplifies crop management and allows concentration on other problems.

Unfortunately, there are several factors that, when taken together, strongly suggest that this approach is not economic, and may jeopardize the effectiveness of fungicides. Economic analyses of farm returns or of large numbers of field trials show that profit margins on fungicide use may not be as large or reliable as is often suggested. Further, the concerted widespread and indiscriminate use of fungicides has often led to development of serious problems of insensitivity to the control agent in the target organism. The Royal Commission on Environmental Pollution (1979) has also pointed out that better strategies for optimizing pesticide use should be generally adopted so as to minimize possible pollution and side effects. An improved approach is therefore needed that is cheap and simple to apply, that limits selection for insensitivity, and that is environmentally acceptable.

Some economic problems

The present economic climate is not conducive to the liberal use of fungicides. Real prices for crop products are falling, while fixed and variable costs for pesticide use are rapidly increasing. Among recent economic surveys, Murphy (1980) considered that profitability in wheat farming was being seriously reduced by rising costs and the indiscriminate use of sprays. He found that very little of the variation in wheat yields between farms could be attributed to the level of expenditure on seed, fertilizers and sprays.

Part of the problem arises from the extrapolation of field trial results with fungicides to farmer expectations. Field trials are generally carried out carefully under good growing conditions in terms of site, cultivations, fertilizers and herbicide application, so that if disease does occur it is likely to be a major limiting stress on crop production. This is emphasized, at least in the early stages, by using known disease susceptible varieties. As a consequence, if the fungicide is at all effective, a large and significant yield response should occur. Over a wider range of environmental conditions, crop disease varies considerably in amount and in effect because of variety–site interactions and the variable importance of stresses other than disease. Consquently, disease control measures often bear little relation to yield performance.

The problem may be illustrated by the distribution of yield increase after fungicide treatment over a large number of trials. Jenkins & Lescar (1980) provided histograms showing such increases for winter wheat over 259 trials in France in 1975. The mean yield increase was about 0.5 t/ha, giving a financial return equivalent to twice the cost of fungicide application at today's prices. If the factors affecting the influence of disease over all trials had been random in their effect, there would have been a normal distribution of gains about the mean. Calculation shows, however, that Jenkins & Lescar's data provide a close fit to a Poisson distribution, consistent with the suggestion that disease was either sporadic or was only one of a number of stresses limiting yield, so that there was only a limited probability of a yield gain being associated with fungicide use. From the shape of the distribution, the probability of occurrence of a yield increase less than the mean was about twice that for an increase above the mean; the mode, experienced in about one-third of the trials, was in the range 0–0.2 t/ha, which would have represented a financial loss in terms of fungicide application. Advice may therefore be better related to the probability of obtaining a return on investment rather than the average size of yield increase obtained under experimental conditions.

This point is particularly important in relation to interpretation of yield data from untreated and treated cereal plots recently introduced into the farmers' leaflets from the National Institute of Agricultural Botany (Anon. 1981). These data are intended only to give an impression of yield potential in the absence of disease: they represent the maximum benefit that might be gained under favourable conditions. In extrapolating the data to farm production, it should be remembered that the fungicide treatments are not designed for economy, and that the trials are conducted in such a way as to limit other stresses, which may not be possible on the farm.

Fungicide insensitivity

Continuous and widespread use of a single fungicide implies intensive selection for insensitive forms of the pathogen, which can lead to the total loss of fungicide effectiveness as has occurred

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in some instances, for example with benomyl and with metalaxyl. In other cases, the selection of insensitivity may lead to an erosion of effectiveness that is variable and difficult to measure, as probably occurred with the use of ethirimol on barley in the U.K. (Wolfe 1981). Still other fungicides may be regarded as durable: despite massive use, the effectiveness of disease control has not declined, which appears to be true for organomercurial fungicides, at least on wheat and barley. These observations suggest that fungicides vary in whether or not the target pathogen is able to produce any response at all. With any newly introduced compound, however, it is not possible to predict whether or not such a response can occur. Laboratory experiments with artificial mutagenesis provide little help in this direction since sufficient diligence will generally reveal some response, whose practical importance cannot be judged. A realistic assessment of field performance depends on field monitoring.

Whether or not fungicide insensitive mutations occur is, of course, only part of the problem. Increased rate of reproduction and frequency is dependent on the mode of fungicide use. At its simplest, the problem can be considered in terms of a treated (t.) and untreated (u.) fraction of the host crop, and a fungicide-sensitive (s.) and an insensitive (i.) fraction of the pathogen population. The reproductive rates can be ranked, at least initially, in the order of highest, sensitive pathogen on untreated crop (s.u.), insensitive pathogen on untreated crop (i.u.), insensitive pathogen on treated crop (i.t.), and lowest, sensitive pathogen on treated crop (s.t.) (the performance of the insensitive fraction on the untreated and treated crop (i.u./i.t.) may be reversed). The reasons for this standard ranking are simple: since the sensitive fraction of the pathogen population has a high rate of reproduction on the untreated host (s.u.), the introduction of an effective fungicide is necessary. Against this fungicide, the sensitive fraction fails more or less completely (s.t. = 0) and the insensitive fraction (i.u.) is so rare and unadapted that it is not easily detectable.

Increased use of the fungicide then has two effects. Reproduction of the sensitive fraction of the population (s.u.) becomes limited as the area treated increases. Conversely, there is an expansion in the area on which the insensitive fraction (i.t.) can increase without competition. The altered population sizes thus makes the insensitive fraction more frequent in relative terms even if there is no change in the basic reproductive rates of the two fractions. However, the increased population size of the insensitive fraction (i.u. + i.t.) also increases the probability that forms with improved reproduction rates will be selected. The overall course of events will therefore be determined by the interaction of the differences in rates of reproduction of the two population fractions on the untreated and on the treated crop areas, and of the relative areas of each.

Increasing the potential durability of fungicides

The major way to improve the potential durability of a fungicide is to restrict its exposure to the pathogen as far as is practically possible. This can be achieved in many ways, but not all are easily applicable or equally effective. Other papers in this meeting have dealt with design of pesticides themselves, techniques of application, and disease and pest monitoring to ensure efficiency of use. A simple way of restricting use is to apply the fungicide at a rate less than that recommended. Some argue that this is a dangerous procedure because it encourages the rapid development of partly insensitive strains of the target pathogen. Equally, however, it can be said to shorten the persistence of the compound and thus reduce selection for fungicide insensitivity. Unfortunately, it is impossible to predict for any one compound whether such a system would be advantageous or not. An alternative, which has not been considered but which may also be effective for systemic fungicides applied to seed, is to treat half of the seed lot at the full rate and then to mix it with untreated seed. Under this system, the pathogen would not be presented with a uniform medium until a late stage in the season when the fungicide concentration had declined to a minimum.

More sophisticated strategies that have recently attracted attention are the use of compounds with different modes of action either alternately or in mixtures. One example of effective mixing arose with the use of dodine and benomyl for the control of apple pathogens in New York State (Gilpatrick 1981). In one area each compound was used intensively by itself for a period and eventually became ineffective. In a different area both were used but only as a mixture and insensitivity to either compound has not yet become a problem. Currently, in Europe, mixtures of metalaxyl with dithiocarbamate fungicide appear to be more durable than the use of metalaxyl alone for the control of potato late blight. Unfortunately, for any combination of compounds, there is no simple generalization to indicate whether alternating or mixing is more effective for increasing their durability.

The concept of mixing fungicides at present only involves tank mixes of foliar sprays, but there are other possibilities. First, mixtures may be used in homogeneous or combined applications, in which mixed fungicides are applied to all of the seed to be sown, or as a tank mix to the whole crop when used as a foliar spray. Alternatively, mixtures may be used in heterogeneous or separated application, in which either seed lots are separately treated with different compounds and then mixed, or the nozzles of the spray system are so arranged that different plants receive different compounds. Again, it is not possible to predict whether homogeneous or heterogeneous mixtures would be more effective. However, if the components of a homogeneous mixture persist for different times, then the pathogen may eventually be exposed to a host population with a uniform fungicide treatment, thus causing intense selection for insensitivity to that compound. Heterogeneous mixtures, on the other hand, may effectively retain diversity of control for a longer period.

Increasing the potential durability of host varieties

The problem of host durability is analogous to that of fungicide durability, depending both on inherent characters of the varietal resistance, and on the way in which that resistance is exposed to pathogens. Although resistant varieties differ in durability, this feature cannot be predicted before the large-scale use of the variety (Johnson 1980). However, Johnson has developed the use of known sources of durable resistance, while in North American and Australian wheat breeding many resistance genes are bred into single varieties. Some strategies of use have been developed. For example, the National Institute of Agricultural Botany operates a system of minimum and desirable standards of disease resistance to prevent widespread use of highly disease-susceptible varieties. In this way, the build-up of large populations of particular pathogens is restrained. Schemes have also been introduced to assist diversification of resistant varieties of wheat and barley on the farm (Priestley & Wolfe 1979), to limit the exposure of any one host resistance source. The effects of diversification in reducing epidemic developments can be maximized by the use of multilines (Browning & Frey 1969) or of variety mixtures (Wolfe & Barrett 1980). The latter system is now undergoing commercial development and the total area of cereal mixtures has increased from about 11500 ha in 1980 to a projected 27000 ha or more for 1981, approaching 1% of all cereals in the U.K.

Variety mixtures commonly have three components, each of which differs from the other two in resistance characters of major and minor effect. Each component selects for its 'own' race of the pathogen which tends to be less well adapted to the other components. Spread of each of these races is therefore restricted by the presence of components to which they are less well adapted. The net effect is a total reduction in foliar disease of about one-half to two-thirds compared with the amount sustained by pure stands of the component varieties subjected to unrestricted spread of the race best adapted to each. The trade-off for this gain in disease control is increased selection for more complex races able to grow well on more than one component. To maintain both disease control and durability it is therefore necessary to introduce new components with different resistance characters and high yield, and to encourage frequent changes of mixture composition.

Table 1. Mean yields (tonnes per hectare) of groups of spring barley varieties with different levels of powdery mildew resistance and given different levels of fungicide (ethirimol) treatment, in western Europe

(After Slootmaker *et al.* (1975).)

area mildew risk	variety reaction	fungicide rate 0	$\frac{1}{3}$	1
low	resistant	5.3	5.3	5.3
	intermediate	4.9	4.9	4.9
	susceptible	4.5	4.9	4.9
high	resistant	4.6	4.8	4.9
	intermediate	4.1	4.6	4.8
	susceptible	3.2	3.9	4.4

Integration of fungicide use and host resistance

Fungicides and resistant host varieties are beset by the same problems of pathogen response to their use, and since the methods employed for reducing these problems are analogous, planned integration should benefit both control measures. This can be considered for conventional monocultures, and also in the development of mixed crop systems, concentrating particularly on recent work with powdery mildew of barley.

Conventional monoculture

Attention has been drawn several times to the way in which host resistance and fungicides can substitute for each other in disease control (Fry 1975; Slootmaker *et al.* 1975; Zadoks & Schein 1979). For example Slootmaker *et al.* (1975) noted the interaction of site, variety and fungicide level in the control of barley mildew in western Europe. Trials were carried out with a range of barley varieties, classified as resistant, intermediate or susceptible, untreated or treated with ethirimol at normal or one-third of normal field rates, and grown on sites previously regarded as 'low' or 'high' risk for mildew infection (table 1).

In the low-risk areas, fungicide treatment was of no value for resistant or intermediate varieties, and on the susceptible variety a low dose was as effective as the normal full dose. In the high-risk areas, the low dose of fungicide was almost as effective as the full dose only on the resistant varieties. The low dose applied to the intermediate varieties gave about two-thirds, and on the susceptible variety about one-half, of the yield increase obtained with the normal dose. Obviously, in consistently low-risk areas relatively little attention to mildew control is required. In the high-risk areas, however, either resistant varieties alone, or high levels of fungicide treatment on susceptible varieties, could be used, but at obvious risk to the durability of either the host on the one hand or the fungicide on the other. The choice can be widened by using varieties of intermediate resistance with low levels of fungicide. These can provide an economic

Table 2. Mean powdery mildew infection (percentage leaf cover) and yield of 4 three-variety mixtures of spring barley and their components grown as pure stands either unsprayed or sprayed with tridemorph

	pure stands		mixtures	
	unsprayed	sprayed	unsprayed	sprayed
infection (%)	19.1	9.2	9.9	4.1
relative	100	48	52	21
yield (t/ha)	4.6	5.1	5.1	5.2
relative	100	110	110	113

Table 3. Mean powdery mildew infection (percentage leaf cover) on spring barley varieties grown as pure stands (i.e. one component), and two and three component mixtures of those pure varieties, compared with the infection level when one of the components had been treated with ethirimol fungicide

number of variety components	powdery mildew infection	
	(%)	relative
1	8.8	100
2	6.0	68
3	5.0	57
3F	3.0	34

F, fungicide treatment on one component.

return, and potentially extended durability, since the pathogen is exposed to a greater diversity of disease control; selection for greater reproduction on treated resistant or intermediate varieties could only occur among pathogen recombinants able to overcome both the host resistance and the fungicide.

Exploitation of such a system requires definition of the risk level to be attached to a particular site, the provision of a range of varieties whose resistance levels can be monitored, and the range of different fungicides. The three elements can then be appropriately matched and diversified, to increase further the potential durability of host and fungicide. As an example, attempts to integrate the importance of various factors for infection of *Septoria nodorum* on winter wheat are being developed by Tyldesley & Thompson (1980) and others.

Mixed variety systems

Since variety mixtures of barley and wheat, and a number of the fungicides that are applied to them, are designed principally to control powdery mildew, it is not surprising that conventional fungicide treatment of a variety mixture is generally uneconomic.

The data in table 2 show that the effect of spraying on mildew level and yield is similar to the effect obtained by mixing varieties but with no chemical treatment. Spraying the mixture did produce a further reduction in the amount of disease, but the yield gain would not have justified the treatment. The system must therefore be modified to maintain the high yield, and to increase diversity, but at reduced cost; this necessitates a reduction in fungicide treatment.

Fungicides that are applied to the seed are more flexible in this respect because they can be

TABLE 4

variety component	year 1	year 2	year 3	year 4
A	+	+	+F	−
B	+	+F	−	+
C	+F	−	+	+
D	−	+	+	+F

F, fungicide treatment.

applied to any number of the components in a variety mixture. In the simplest case, a single fungicide can be applied to only one of the mixture components (table 3).

From table 3, the additional gain in disease control was obtained by treating the seed of a single barley variety in the mixture with ethirimol applied to seed at normal field rate. Any gain in yield is likely to be marginal at this level, but there is a useful reduction in the size of the pathogen population, and in the likelihood of pathogen response because of the 'double' resistance of the treated component. These advantages are achieved at approximately one-third of the cost of the recommended treatment rate; it is most unlikely that foliar spraying would be necessary. The largest gain should be made generally by treating the variety component that is potentially the most susceptible.

Diversification can be further increased by treating single, but different, components of different variety mixtures with different fungicides, which could easily be introduced in the programmed system shown in table 4. In each of 4 years a different grouping of three of the four host components is exposed, and a different variety is treated. The cycle of fungicide applications is arranged so that each variety is treated in the last of its consecutive three years of exposure.

Further complications could be introduced by treating different components of the same mixture with different fungicides. However, the additional gain would be minimal and would necessitate a reduction in the dose rate of each fungicide applied, to minimize cost. Since the number of compounds available is limited, diversity and cost efficiency may best be achieved by integrating the use of single compounds with different variety mixtures.

An alternative approach is to treat a proportion of the seed of a variety mixture with the fungicide, and then to mix that with untreated seed. The cost of treatment is again reduced, but now the number of components in the mixture is doubled. For example, for a three variety mixture so treated, there would be in effect three varieties multiplied by two fungicide treatments, giving six components. The effect of diverification on restricting epidemic development would be maximized, at low cost, but the potential for pathogen response would be limited by the amount of mutation and recombination required to produce a pathogen phenotype capable of rapid reproduction on such a diverse medium. Again, there are no management problems for the grower: a variety mixture partly treated in this way could be obtained 'off the shelf', and

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subsequent spraying is unlikely to be required. If it were, then spray timing would be simplified by the slow rate of epidemic increase.

To increase potential durability by the suggested partial fungicide treatment of all components it is arguable, for any particular combination of host varieties and fungicides, whether this would be as effective as doubling the number of host components. Initially, the fungicide-sensitive fraction of the pathogen population would be severely restricted on treated plants, whereas insensitive forms of the pathogen would be able to grow on both treated and untreated plants. The relative importance of this advantage to the pathogen would depend on the susceptibility of alternative varietal components and their selection against pathogen genotypes from other components. In practice, because of the limited numbers of varieties diverse in their disease resistance and similar in harvest maturity, they would probably be better deployed among a range of changing mixtures than in a single mixture of many components.

Table 5. Yields of a three-component mixture of spring barley varieties untreated or treated in various ways with ethirimol fungicide applied to the seed

fungicide treatment	yield t/ha	effective number of components
1. all seed × normal rate (N)	5.15a†	3
2. $\frac{1}{3}$ seed × N; $\frac{2}{3}$ seed × 0 N‡	4.98 ab	6
3. all seed × $\frac{1}{3}$ N	4.87 b	3
4. one var. × N; two vars × 0 N	4.87 b	3
5. all seed × 0 N	4.85 b	3

† Values with the same letter are not significantly different.
‡ 0 N, untreated.

Various methods of partial treatment with ethirimol of variety mixtures of spring barley are compared in table 5 for their effects on final yield. The largest improvement in yield was obtained, as expected, by normal treatment of all seed in the mixture. However, the cost of such a treatment is relatively high, and the mixture is uniform with respect to fungicide treatment. Treating only one-third of all seed at the normal rate provided a yield not significantly less than that obtained with the full treatment, but at a reduced cost and with increased diversity. The other treatments gave yields similar to the untreated mixture. It should be pointed out, however, that if one of the three variety components is markedly more disease susceptible than the other two, it may prove more efficient to treat only that component, and to leave the other two untreated.

Foliar sprays are less flexible in that they cannot be applied to a specific component in a variety mixture. They can, however, be sprayed as either homogeneous or heterogeneous mixtures, as defined above. At the simplest level, this would mean a single spray chemical applied at a reduced rate on the whole crop, or alternatively, applied at the normal rate but on only part of the crop area, for example, by blocking off alternate nozzles on the spray line.

More complex systems run into practical difficulties. For homogeneous mixtures of different compounds, presumably with each applied at a low rate to save cost, it is necessary to ensure that the chemicals are compatible and that a true mixture does emerge from each nozzle. To obtain a heterogeneous mixture would require rather complex modification of conventional spray equipment. A much simpler system could be developed by using modern low-volume equipment in which alternate sprayer units were fed from a cartridge of pre-diluted fungicide. Such systems are obviously more complex and more expensive than those suggested for seed treatment, but they at least offer the option of delaying the treatment decision until the disease pattern for the season has become established.

Summary

Some fungicides and disease resistant host varieties are inherently more durable than others, but this character can only be determined retrospectively after large-scale exposure to the pathogen. Potential durability can be increased by limiting the exposure of each fungicide or variety, which implies diversification between several or many control measures. Since there is some disadvantage to the pathogen in overcoming each of the control measures, and the disadvantages compound multiplicatively, then greater durability is more likely to be attained by minimizing the exposure of each control measure and maximizing the diversification of all.

The objectives of using disease control measures should therefore be:

(*a*) to minimize disease development, and thus population growth of the pathogen;

(*b*) to limit pathogen response so that the applied measures are durable;

(*c*) to cost as little as possible;

(*d*) to have minimal undesirable side effects in the environment.

An example of integrated control that fulfils all of the stated objectives is the cultivation of a mixture of host varieties with different disease resistance factors in which a proportion of the plants develop randomly in the crop from fungicide-treated seed, and the remainder from untreated seed.

Some of the suggestions made are less practical than others, and the list of possibilities is by no means exhaustive, particularly if consideration is given to other crops and other pests and diseases. The important point, however, is that by relatively little modification to existing technology, a large improvement in disease control, yield stability and potential durability of control is both possible, and necessary.

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Discussion

M. J. Jeger (*East Malling Research Station, Maidstone, Kent, U.K.*). Dr Wolfe made the comment that approaches combining varietal resistance with fungicide treatment can lead to a more efficient and durable usage of both. Does he think that we have adequate information – on the nature of the varieties' resistance, on the mode of action of the fungicide – to make the most of their interactions? For example, if a variety expresses partial resistance to a pathogen largely by restricting sporulation, should this be *reinforced* by an anti-sporulant fungicide or *complemented* by a fungicide that prevents infection. Would the latter diversified 'attack' be in accord with the rationale of diversification by means of crop heterogeneity?

M. S. Wolfe. I doubt if we do have adequate information to make the most of the interactions in the manner suggested, though the questioner himself is more competent than I to propose possible combinations. Certainly this approach represents valuable diversification and is an area worth further investigation. There is a practical problem in that we would need to operate with the tools currently available: it is unrealistic to contemplate varieties specially bred and fungicides specially designed for this purpose.

A related point is that there is evidence that the pathogen populations selected by particular fungicides are altered in their pathogenicity towards certain resistant varieties. It may therefore become possible to recognize certain variety–fungicide combinations that are more effective, and potentially more durable, than others.

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