THE CHALLENGE OF CROP DISEASE MANAGEMENT

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Changing agricultural methods have generally increased the risk of crop losses from epidemic disease during the past quarter century. At the same time research in epidemiology, the genetics of crop/pathogen interactions, and related areas has opened up new avenues for improved control of crop diseases. This paper discusses some of the more significant advances and their use to limit the impact of disease. The integrating concept of crop disease management is considered to be the key to future progress. Means of implementing the practical management of diseases in commercial agriculture are discussed.

During the past decade the capacity of agriculture to feed the growing world population has been increasingly under strain (Buringh, van Heemst and Staring 1975; Buringh and van Heemst 1977). At the same time a technological revolution is altering the whole character of agriculture with mechanization of virtually all aspects of crop production and the development of high input/output cropping systems. These changes often involve intense cultivation, heavy fertilizer and pesticide application and where possible, irrigation. Such technological developments and the introduction of improved varieties of many crops have led to a dramatic increase in both the level and efficiency of agricultural production (Marshall 1977). However, they have been accompanied by greater risks of serious disease loss (Saari and Wilcoxson 1974; Marshall 1977). The narrow genetic base of many crops has caused concern. This genetic uniformity provides an ideal situation for an epidemic when a virulent pathogen is present and suitable weather conditions occur. Furthermore, the increased price of petroleum has made some control measures more expensive, particularly those using fuel and crop protection chemicals derived from petroleum. These developments demand a much closer examination of diseases and their control.

Impact of disease

Whilst the current impact of disease is generally recognized, some figures are relevant. Losses in Australasia have been estimated at 12.6% of total agricultural production (Cramer 1967). Based on this figure and available statistics, a reasonable projection of on-farm losses in 1980 would be approximately $650 million. Little precise data is available, but some estimates have been made for certain cereal diseases. For example, Watson (1974a) estimated that a wheat stem rust (*Puccinia graminis* Pers. f. sp. *graminis* Eriks. and E. Henn.) epidemic in southern Australia caused losses of about $300 million in 1973-74, Kuiper (personal communication) considers that speckled leaf blotch (*Mycosphaerella graminicola* (Fuckel) Schroeter, previously called *Septoria tritici* Rob. ex Desm.) is responsible for an average annual loss of $10 million in southern New South Wales and Rovira (personal communication) estimates annual losses of $30-100 million for take all (*Gaumannomyces graminis* (Sacc.) von Arx & Olivier var. *tritici* Walker) and $20-40 million for cereal cyst nematode (*Heterodera avenae* Woll.) throughout Australia.

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At present many diseases troublesome earlier in the century are under control. These are far too numerous to list, but particular Australian examples of problems once causing devastating losses on a wide scale are the cereal bunts and smuts (Kuiper 1978) and *Phytophthora citrophthora* (R.E. and E.H. Smith) Leonian and most virus diseases of citrus (Fraser and Broadbent 1979). Crop loss assessment studies are increasingly necessary to indicate research priorities for the remaining problems (James 1974).

Recognition of disease

It cannot be overemphasised that the recognition of diseases with marked or ambiguous symptoms is difficult and may be at odds with the experience of farmers and agriculturalists. While there are many instances where the effects of the disease have been accepted as the norm or erroneously identified, three examples will suffice here.

The destructive nature of speckled leaf blotch of wheat was recognized only when large yield increases were obtained following protection by fungicides (Kuiper 1976) and superior performance observed in the partially resistant variety Teal (Martin *et al.* 1976).

A number of relatively symptomless virus diseases of deciduous fruit trees can reduce yields by up to 80% or more (Allen, Dias and Davidson 1969; Posnette 1969; Saunier 1969).

The greening disease of citrus in India was thought to be due to poor nutrition. This disease wiped out large areas of the Indian citrus industry before the problem was correctly diagnosed as caused by a contagious pathogen (Fraser 1967).

Many local crops deserve closer scrutiny to see if any diseases are being overlooked. Lucerne is perhaps the first crop to warrant and receive such attention. Certain lucerne diseases have been investigated (Irwin 1974a & b, Rogers *et al.* 1978). However, other diseases previously at a low level may prove troublesome in the aphid-resistant varieties now used (Stovold and Drummond personal communication).

Present trends

Changes in cropping practices may alter the prevalence of certain diseases. For example, the stubble retention involved in reduced cultivation systems of wheat farming has apparently increased the amount of inoculum carryover. The change to such cropping has been accompanied by a greater incidence of yellow leaf spot (*Pyrenophora tritici-repentis* Died.) Drechsler) (Wong 1977), take all (Moore, personal communication) and other diseases (Boosalis and Cook 1973; Cook *et al.* in press).

Disease management

Disease management is a relatively new concept which derives from earlier developments in entomology (Apple and Smith 1976; Horsfall and Cowling 1977; Smith and Pimentel 1978; Zadoks and Schein 1979). The term "management" rather than control implies that diseases are part of the agroecosystem and must be dealt with on a long term basis, utilizing knowledge of their interactions within that system. It also conveys the concept that diseases are to be kept at levels below that of economic impact and not necessarily be eliminated entirely.

Disease management involves the integration of all the traditional means of control (exclusion, eradication, protection, avoidance and therapy). It has four main aims: increased productivity; greater stability of production; reduced costs and pesticide usage hence less environmental pollution.

Whilst all the various forms of control may be integrated in disease management, those that tend to show most promise are: the strategic use of biologically active chemicals; the manipulation of the crop/pathogen genetic system; biological control and the manipulation of cropping systems.

We believe that the concept of disease managment is a real advance in crop protection and provides a sound basis for the planning of research and systems aimed at minimizing crop losses. More ecologically acceptable crop protection methods should be forthcoming.

The remainder of this review will concentrate on recent developments in these fields. Examples given will serve to illustrate the principles of disease management and indicate future trends.

DISEASE MANAGEMENT BY FUNGICIDES

The principles of chemical control of aerially dispersed fungal plant pathogens have remained virtually unchanged for the last 100 years. The aim has generally been to protect the susceptible crop from infection by coating it with an appropriate fungicide before the pathogen arrives. Control has relied on routine spraying to maintain the protective coat throughout the period of crop susceptibility. This approach may become very expensive if the period of susceptibility is long. Also, in practice, it is impossible to maintain adequate protection without unrealistically short periods between applications. There are a number of reasons -

1. Crops grow rapidly at times - new and unprotected leaves appear within a few days of a fungicide application.

2. The ability of a fungicide to control a specific disease changes from the moment it is applied to a crop. It is usually most active for a period after application then gradually becomes less so over a period of days until no activity remains. Few fungicides remain active beyond about two weeks after application.

3. Rapid dilution of fungicide deposits can occur simply by growth and expansion of treated tissues or through the action of rain or dew.

There are other good reasons for seeking better methods. In this age of environmental concern, use of chemicals such as fungicides should be kept to a minimum. Routine applications are often excessive being applied whether.

needed or not in dry weather with little disease risk. More precise methods of evaluating the level of disease risk should have many advantages. In addition, certain new groups of fungicides have selected out forms of particular pathogens which are insensitive to the chemicals (Dekker 1976, Kable and Jeffery 1979). Replacement by another chemical or the use of particular mixtures or sequences may be necessary.

Development of more rational and efficient control systems has been attempted for many years. A number of operational disease management systems exist based on epidemiological concepts (Berger 1977; Krause and Massie 1975; Young *et al.* 1978). So far, this approach has not revolutionised plant disease control but there has been steady progress. These systems seek to pinpoint times of danger when disease epidemics are likely to develop and to recommend appropriate responses in terms of control measures. The following example shows the potential value of forecasting. In 1973/74 (a wet season) grape growers throughout eastern Australia applied six or more routine sprays to control downy mildew. Despite this, in many cases, the disease was severe due to inappropriate timing. If a disease management system had existed six sprays timed accurately by epidemiological criteria, may have given good control. In 1974/75 (a dry season in N.S.W.), growers applied the same number of routine sprays and there was no disease; a management system might have indicated that one or two sprays were sufficient.

Some recent advances in science will facilitate the development and implementation of disease management systems: 1) The development of quantitative epidemiology and the computer modelling of epidemics (Analytis 1973; Schrum 1975; Van der Plank 1963, 1975; Waggoner 1974; Waggoner and Horsfall 1969; Waggoner *et al.* 1972). 2) The advent of fungicides which have systemic and curative properties opens up new and more flexible control options than were available with protectant materials (Marsh 1977). An omitted spray need not necessarily be disastrous. 3) Increase in availability of computers and microcomputers makes possible the management of disease on an individual farm and field basis e.g. the BLITECAST system described later in this paper (Jones *et al.* 1980; Krause *et al.* 1975). 4) The use of earth satellites either for data transmission or monitoring may also increase our capacity for disease surveillance and reduce its cost (Anon. 1975a; Suits and Safin 1972).

Ideally, disease management systems should operate in conjunction with a range of other management sub-systems within a comprehensive programme aimed at minimising the effects of all the major factors which adversely influence crop protection. *viz.* insect pests, poor nutrition etc. (Anon. 1975b; Bird 1978; Croft *et al.* 1976). In reality we are yet far from achieving such comprehensive systems, although a start has been made in Michigan with which we will deal later in this paper.

Most disease forecasting systems have been constructed from field observations of epidemics. First the factors influencing epidemic development were noted and measured over a period of years. Principally these were weather conditions: rainfall, dew and consequent duration of leaf wetness, periods of high humidity and concurrent temperatures. The prior abundance of the pathogen and the state of susceptibility of the crop were sometimes considered. The second step was to identify critical combinations or levels or accumulated durations of these factors which give rise to an immediate threat of disease. These states are expressed in simple algebraic terms which can then be used for prediction. These expressions integrate factors which favour disease outbreaks, hence are anlogues of epidemic progress. After field testing and suitable modification, they are then applied in agricultural practice.

There are other approaches to disease prediction which require an understanding of the interactions between meteorological conditions, and pathogen and host processes. One is statistical: the relationships of weather factors to disease development are characterised by statistical analysis, often by multiple regression techniques (Butt and Royle 1974). Then these relationships are applied to predict disease outbreaks or the projected rate of disease development. Another approach is to use the systems analysis method. This involves subdividing the epidemic into components of the disease cycle, individually modelling the responses of each to environmental factors, then re-synthesising the epidemic system by linking these paths. Field, glasshouse and laboratory data are used to construct the various components. This is essentially simulation of epidemics. When actual current field data are fed into a simulation model, it should provide information on epidemic progress, thus forming a basis for the planning of control measures.

It is only eleven years since publication of the first comprehensive computer model of a crop disease epidemic. Called EPIDEM, it simulated the development of the early blight pathogen on tomatoes (Waggoner and Horsfall 1969). Since then the same group has developed a simulator of southern corn leaf blight called EPIMAY (Waggoner *et al.* 1972). Schrum (1975) described a generalised simulator called EPIDEMIC which has the potential to be adapted to many different host/pathogen interactions and he demonstrated its use with the stripe rust disease of wheat.

It is our feeling that such models will be valuable in developing disease management systems, although until now they have been little used for this purpose. Recently, data from EPIDEM has been incorporated into FAST, an experimental management system for the control of tomato early blight by Madden *et al.* (1977).

Disease management systems in operation

Some systems in current use are described below. They exhibit a diversity of methods and objectives. The art of disease management is in its infancy hence none of the systems described approach the ideal yet their use is to be preferred to the alternative of routine application of protective fungicides.

Single disease systems

Research in the U.S.A. over a period of 30 years culminated in the development at The Pennsylvania State University in the early 1970's of a computer-based forecasting system for potato late blight (*Phytophthora infestans* (Mont.) d By.), (Krause *et al.* 1975). Called BLITECAST, it uses rainfall, humidity and temperature data to estimate the level of disease risk at any point during the growing season. The system determines the date for the first fungicide application, and then sets the intervals between spray applications. BLITECAST has operated successfully from the Pennsylvania State University for several years. Hundreds of farmers throughout the north-east United States subscribe to it.

Another computerised system is used in Germany for prediction of late blight (Burckhardt and Freitag 1969; Schrödter and Ullrich 1967). It differs from BLITECAST in that it is a negative prognosis: the aim is to indicate to farmers when the disease is not likely to occur. There are 80 recording stations in different localities throughout Germany and hourly readings of weather parameters are taken and processed to derive the prognosis.

A forecasting system for hop downy mildew (*Pseudoperonospora humuli* (Miy. & Tak.) Wilson) has been developed which is based on multiple regression analysis of data obtained in the field (Royle 1973, 1975). Rain-induced wetness is the most important variable affecting disease incidence. As yet the method has not been applied on a commercial basis.

A computer-based management system for control of early blight of tomato (*Alternaria solani* (Ell. & G. Martin) Sor.) called FAST gave satisfactory control with three sprays where the conventional programme required six (Madden *et al.* 1977).

The need to apply a fungicidal spray for the control of eyespot lodging in wheat (*Pseudocercosporella herpotrichoides* (Fron.) Deighton) is evaluated by a mathematical-statistical method developed in West Germany (Fehrmann and Schrödter 1971, 1972; Schrödter and Fehrmann 1971a, 1971b, 1974). If an epidemic is forecast, a single spray is applied at a time indicated by the model.

Outbreaks of barley powdery mildew (*Erysiphe graminis* D.C. ex Mérat f. sp. *hordei* Em. Marchal) are forecast in England using data on temperature, sunshine, rainfall and windspeed, together with a field assessment of current mildew incidence, the concentration of mildew conidia in the air, and frequency of infection on trap plants (Polley and King 1973; Jenkins and Storey 1975).

Other cereal diseases for which forecasting and management systems are under development in the United Kingdom are barley brown rust (*Puccinia hordei* Otth.), barley leaf blotch (*Rhynchosporium secalis* (Oud.) J.J. Davis) and glume blotch of wheat (*Septoria nodorum* Berk.) (Cook 1977a; King and Polley 1976; Polley 1971; Polley and Clarkson 1978; Ryan and Clare 1975).

Systems for control of several diseases

When a crop is subject to several serious diseases a need exists for a single system which will integrate the necessary control measures so that losses from all diseases, costs, and environmental hazards arising from pesticide application are minimized.

We know of only one system of this type. Currently under development at The Pennsylvania State University, it is directed at controlling six major diseases of apples and considers factors such as varietal susceptibility, previous history of disease, tree shape, size and density, sprayer capacity, current weather conditions, fungicide efficacy, etc. (Kable *et al.*1978). The computerized system is expected to provide farmers with individual spray programmes for each of their plantings which will optimise control and reduce costs, while taking into consideration the special circumstances and requirements of each planting. It will provide advice similar to that which might be given by a highly skilled and widely experienced scientist or extension specialist, but will be generally accessible at any time. This system will relieve farmers of complex decision making in disease control and provide them with straightforward specific recommendations.

Crop culture systems

The next logical step in crop management beyond the integrated control of all diseases are systems which embrace all or most of the management decisions necessary in raising a particular crop. In addition to disease control, these decisions may include those relating to the control of insect pests, nematodes, and the need for weed control. Such an all-embracing system has been attempted, to our knowledge, at only one place: Michigan State University (Anon. 1975b; Croft *et al.* 1976; Bird 1978). The term "Integrated Pest Management" is applied to the project there, but it deals with broader issues than insect pest control. Management practices utilized include several methods of biological control, cultural practices (intercropping, crop rotation etc.), resistant varieties and use of pesticides. It involves the use of historical records, data from research, monitoring of the crop environment, and regular crop inspections to record stage of growth, and incidence of diseases, insect pests, nematodes and weeds. The Michigan project covers seven crops: lucerne, sugar beets, small grains, asparagus, carrots, onions, and potatoes. The management systems for these crops are computerized and are accessible to farmers, extension workers and scientists at all times. The systems provide several types of service: pest alerts, monitoring summaries, prediction, control recommendations and historical data.

The Michigan system has been designed with future improvement in mind. Its most impressive aspect is its structure which will permit the addition of better disease management models as they are developed. Currently the system consists mainly of insect pest management models. Increased research in disease and weed management is needed if the Michigan project is to fulfil its promise of complete and economical crop care.

Getting disease management to work on the farm

The development of new and improved disease control programmes and management systems does not necessarily mean that they will be used by farmers. Two things are necessary for new knowledge to be put into practice. First, the benefits of the new practices must reach the attention of the appropriate section of the farming community. Second, the new technology must be easily accessible to, and easily used by farmers, i.e. there must exist what could be termed a delivery system for the new practices. A variety of methods have been employed in the past to provide farmers with the means and knowledge to carry out recommended disease control practices.

1. Spray calendars, leaflets and books containing descriptions of practices. These are the traditional means of conveying disease control information to farmers. Spray calendars are the total delivery system; all the useful information currently available is contained in them, but few farmers are able to use them effectively. Some farmers do not have an adequate educational background to interpret the information. Others, particularly those whose native tongue is not English simply have trouble reading them.

Even if a farmer has the ability to use these guides, he will be discouraged by the time needed to read, understand, and interpret them. Spray calendars are becoming more complex and weighty with every revision. For example, the main spray calendar for fruit crops in N.S.W. is now 108 pages long (Johnson *et al.* 1979). A similar publication in Pennsylvania recommends 200 different fungicide mixtures for disease control in spring (Anon. 1977). The merit of each mixture depends upon the diseases present, level of disease risk as estimated subjectively, weather etc. The situation becomes even more complex when necessary insecticide applications are considered. Farmers are busy people - we doubt if many have the time to read and analyse the information in spray calendars sufficiently to get the best results in terms of disease control on their own orchards.

2. Calculation sheets or cards. These may be designed to aid in determining the correct timing of sprays (e.g. grapevine downy mildew), or to indicate the level of risk from disease (e.g. apple scab) (Kable 1978). They are simple to use, but farmers using them need some instruction. The purpose of these aids is very specific; they are partial delivery systems. They fulfil the needs of only a small part of the crop protection programme. Total cost of a card calculator plus thermometer for use in identifying apple scab weather would probably be less than $10. The consistent operation of such equipment is required. It is common experience that many farmers begin well on such a programme, but neglect it when other demands become pressing.

3. Mechanical devices. Modified meteorological instruments have been designed which give a direct indication of the risk of infection (Weltzien and Studt 1974). Partial delivery systems, their purpose and limitations, are similar to those of the card calculator approach, but the meteorological measurements are likely to be more accurate, and are made automatically day and night. However the cost is higher ($250-$500).

4. Electronic devices. Instruments with varying degrees of electronic sophistication have been designed to carry out exactly the same task as the card calculator or mechanical device for indicating the occurrence of infection (Richter and Haussermann 1975; Smith *et al.* 1977). They are more precise, easier to operate, and simpler to interpret, but cost more initially and would doubtless be more difficult and costly to maintain.

5. Computer-based systems. With computers, it is possible to combine the breadth of the spray calendar and the specificity of the on-farm device to provide farmers with disease management systems which will make the most appropriate and economic responses to particular on-farm situations (Krause *et al.* 1975; Kable 1978). We believe that computer systems have many advantages and will be used increasingly for disease management in the future, but they do have one major limitation at present, and that is cost.

DISEASE MANAGEMENT BY GENETIC MEANS

Resistance breeding plays an important role in progressive agriculture (Thurston 1977; Russell 1978). In many situations the use of resistant varieties is the only practical or possible means of producing satisfactory crops. This applies particularly to pasture plants, cereals and other field and fodder crops, which are grown under extensive cropping systems permitting little choice of control measures. In addition, resistant varieties are often the only means of avoiding losses from certain virus and persistent soil-borne diseases in a range of crops. When the resistance confers a high degree of protection, resistant varieties require no effort by the farmer and add nothing to his cost of production. Of course, breeding such varieties does have a cost at the national or industry level, but this is recovered quickly by the increased quality, quantity and stability of the production.

Availability and stability of resistance

Diseases may be grouped according to the availability and stability of the resistance.

For one group of diseases, the resistance is readily available and stable. Once incorporated, a minimum of effort is needed to maintain it in later varietal releases. Examples include flag smut (*Urocystis agropyri* (Preuss) Schroet.) (McIntosh 1968) and milo disease (*Periconia circinata* Mangin (Sacc.)) of sorghum (Tarr 1962).

For a second group, either no suitable source of resistance has been located or the resistance has not yet been transferred to commercial cultivars. Higher degrees of resistance to certain of the fungal root diseases of cereals would be most valuable (Butler 1961; Purss 1966; Scott and Hollins 1978). Resistance to cereal cyst nematode in wheat was only recently located (O'Brien and Fisher 1974), and varieties with this resistance have not been released yet.

For the third group of diseases, the pathogens are variable, often producing new races capable of causing severe damage to previously resistant cultivars. This instability of resistance commonly occurs in rusts, powdery mildews and downy mildews. Such a series of new races of the wheat stem rust fungus developed in the 1940's on Eureka and Gabo, each with only a single gene for resistance (Watson 1974b). For this group a continuing programme of research and testing of breeding material is necessary to maintain the protection.

Thus the stability or durability (Scott *et al.* 1978) of the resistance is of vital importance and this is established only after its widespread exposure in time and space. Means for improving the durability with a minimum of time and resources would be of great value in planning use of disease resistances. Some relevant generalizations may be derived from systems in which considerable experience is available over a period of years, particularly with the cereal rusts and potato late blight. Four such generalizations are discussed here.

1. One of the earliest trends to emerge was that resistance to variable pathogens is generally short-lived when based on single genes (Watson 1970a, 1974b). However, certain genes have proved to be of particular value because of their durability. For example, races of the wheat stem rust fungus able to overcome the resistance conferred by *Sr 2* (Hare 1976) and *Sr 26* (McIntosh 1978) occur rarely if at all. On the other hand, races with virulence for *Sr 15* appear relatively frequently (Luig and Watson 1970). Generally genes need to be "protected" by being used in appropriate combinations (Watson 1970b). Wheat varieties with such multiple resistances in the one genotype have kept losses from stem rust at a low level in the northern wheat belt of Eastern Australia for many years. The use of this

strategy has been expanded to other areas of Australia in the National Rust Control Programme, instituted in 1975 (Watson 1974b). Nevertheless, this approach has not been as widely adopted in other crops, possibly because of the considerable expertise, background information, resources and sustained effort needed.

2. Some misconceptions have arisen in extrapolating from one disease system to another. One of the most misleading concerns the prediction that resistance expressed as slower and more limited development is the more stable and thus desirable form rather than that occurring as complete freedom from disease (Van der Plank 1963; Robinson 1976). The slow development or rate-limiting form of resistance certainly has been a more successful strategy for controlling potato late blight. The use of major genes (the *R* series) was not satisfactory because of the extensive variation in the fungus (Russell 1978). Nevertheless, this rate-limiting resistance has not been appropriate in all systems. For example, at one time at the Plant Breeding Institute, Cambridge, U.K., progeny with the major genes (the *Yr* series) against wheat stripe rust were discarded and those with the rate-limiting resistance were retained. However, a new variant able to overcome this latter form of resistance was recorded a short time later (Johnson and Taylor 1972). Similar reports of new aggressive variants have been made in other systems (Clifford 1975; Parlevliet 1975; Habgood 1976).

3. Another prediction is that races of the pathogen which have accumulated genes for virulence are less fitted to survive in populations than simple races with few virulences (Van der Plank 1963). Again this concept, called stabilizing selection applies in some instances but not in others (Brown 1975). In the wheat stem rust system the Australian data to 1958 supported stabilizing selection (Watson 1958) although the Canadian results did not (Osoro and Green 1976). Where stabilizing selection does operate the use of some mixture of host genotypes and/or regional gene deployment may be useful.

4. One unfortunate misconception is that there are associations between genes controlling resistance and certain undesirable features, particularly low yield. While such associations have occurred in a few instances, these are the exception rather than the rule. One convincing illustration is that many of the high yielding green revolution wheats combine several genes for stem rust resistance (Watson 1974b). Any problems associated with genes for disease resistance are most likely to occur when the genes are first incorporated into commercial types. Such disadvantages are often overcome with further hybridization and selection. Two examples in the wheat stem rust system are relevant in Australia as they concern two widely effective genes in current use. Plants carrying the gene *Sr 2* may show a false black chaff condition which is thought to reduce yields when fully expressed. Fortunately in certain genetic backgrounds and environments there is such limited expression that no problem exists (Hare personal communication). Secondly there have been suggestions that *Sr 26* is associated with difficult threshing and slightly lower yields. While Eagle and Kite may be difficult to thresh, the most recent release carrying this gene, Avocet, threshes readily (Martin and Fisher personal communication). The tests necessary to investigate yield have not been made.

Strategies for use of disease resistance

There is a range of strategies available for obtaining a satisfactory degree of stable resistance:-

1. Within a homogeneous variety

   (a) Several genes of major effect. This may be suitable if the changes in virulence occur relatively slowly and mostly in single step units as in the wheat stem rust system in Australia (Watson 1970a).

   (b) The use of rate-limiting resistance. There is potential for improving this by intercrossing and testing. Such an approach has been successfully used for the control of both *Puccinia polysora* Underw. and *P. sorghi* Schw. on maize in several geographic regions (Van der Plank 1963; Hooker 1967). Another classic example is in the potato late blight system mentioned earlier in this review.

   (c) A combination of (a) and (b) using the sib-selection method proposed by McIndoe (1949). This method does not appear to have been put into practice.

2. Within a heterogeneous population

   (a) Multilines. A multiline is a mixture of lines which are phenotypically similar except that each carries a single but different gene for resistance. Two strategies have been adopted with multilines (Marshall 1977).

      * The "clean crop" approach, in which all component lines are resistant to all prevalent races of the pathogen. Any resistant component which becomes susceptible is replaced by another. This has been developed by CIMMYT for the control of the wheat rusts (stem rust, leaf rust, and stripe rust (*Puccinia striiformis* Westend) (Breth 1976). While this approach reduces the risk of catastrophic disease loss, it has a serious long term defect. Because genes are used singly in the mixture, they may be frittered away. One can argue that such genes would have a longer effective life if used in combination.

      * The "dirty crop" approach, in which none of the lines in the mixture is resistant to all known races. Such multilines may be affected by disease but to a lesser extent than are plantings of the component lines singly. This has been advocated and exploited by Frey and coworkers for the control of crown rust (*Puccinia coronata* Corda) of oats (Frey *et al*. 1977).

   (b) Varietal mixtures. A varietal mixture includes lines which differ phenotypically as well as in disease resistances. This system has been trialed recently in the United Kingdom by Wolfe and Barrett (1977) for the control of barley powdery mildew. They propose an ordered rotation of the resistances. In each year, three of four components would be released in a mixture and the three in use would be rotated annually. Seed treatment with a specific fungicide could be similarly used in rotation so that the chemical was applied only to the variety that was in the third year of field exposure. Continuous disruptive selection would thus be applied to the pathogen population. Selection of forms of the pathogen insensitive to the fungicide may also be minimized in this way. While the breeding effort in varietal mixtures is less than that needed to produce multilines, management and marketing problems may be envisaged. The "dirty crop" approach would appear to be of most value where no suitable resistance genes are readily available as with barley powdery mildew.

Genetic vulnerability and the use of diversity

The use of a few varieties on a large scale has made crops vulnerable to serious losses from disease. The widespread and severe damage ($1000 million loss) caused by the southern corn leaf blight (*Drechslera maydis* (Nisikado) Subram. & Jain)) epidemic in the U.S.A. during 1970 was a dramatic illustration of this. The entire United States maize crop was based on T cytoplasm, used because its male sterility facilitated the production of hybrids. A new race of the pathogen well adapted to this cytoplasm appeared and the weather was favourable. This problem has now been overcome, but it prompted an appraisal of the genetic basis of major crops in the U.S.A. (Committee on Genetic Vulnerability of Major Crops 1972).

Recent developments enable us to be optimistic about alleviating problems raised earlier in this review. The developments of general application are:

Greater knowledge of sources of resistance and better availability of germplasm (Frankel and Hawkes 1975).

Better methods for creating epidemics both in the field and greenhouse. Thus potential sources of resistance and hybrid populations can be screened, both in breeding programmes and for research. Disease is necessary in every generation, otherwise progress in selection made in one year with heavy selection pressure may be lost in a subsequent season in which the disease is absent or at a low level.

Disease screening nurseries distributed internationally. These have often been co-ordinated by the international crop research centres (Thurston 1977).

Better international communication and seed exchange.

Developments of more specific application are:

For improving the durability of resistance, the present understanding of the genetics of variability in the host and pathogen and its application in breeding are of particular benefit (Watson 1970b; Flor 1971; Day 1974; McIntosh 1976; Scott *et al.* 1978).

Experience has been gained with stability of certain resistances in both time and space.

There has been co-operation between workers in different countries in matters such as selection of international sets of differential host testers. This assists in application of experience in one geographic region to other areas.

For certain diseases where no genes of major effect have been located, some progress has been made by the accumulation of genes of small effects from several sources. This is an even longer term venture than most breeding operations.

When deciding strategies for the use of disease resistance, all the options outlined above need to be considered for the disease involved. The approach should be tailored for the situation, as a strategy suitable for one disease may be quite inappropriate for another. The importance of sustained research and breeding over a period of many years cannot be overemphasized.

BIOLOGICAL CONTROL AND MANIPULATIONS OF CROPPING SYSTEMS

Biological control may be defined as "the reduction of ... disease-producing activities of a pathogen ... by one or more organisms, accomplished naturally or through manipulation of the environment, host or antagonists" (Baker and Cook 1974).

Again, there are many examples which may be used to illustrate developments in this most promising field, but only three will be given.

1. Root rot (*Phytophthora cinnamomi* Rands) of avocado has been controlled in certain avocado groves on particular red basaltic soils in northern N.S.W. and south eastern Queensland by the manipulation of the environment. By applying fowl manure and dolomite and by incorporating cover crops of *Dolichos lablab* L., maize and New Zealand blue lupin to these groves, some farmers have maintained soil physical, chemical and microbiological properties similar to those in nearby rainforest. It would appear that the replacement of the natural vegetation with crops such as avocado has caused drastic changes in the soil, making it more favourable for the establishment of the root rot fungus (Broadbent and Baker 1974).

2. Control of the crown gall pathogen affecting stone fruit and roses (*Agrobacterium radiobacter* (Beijerinck and van Delden) Conn 1942, biotype 2) has been obtained commercially by inoculating seeds, seedlings or cuttings with a non-pathogenic biotype (strain 84) of the same species (Htay and Kerr 1974, Moore and Warren 1979). The non-pathogenic strain produces a highly specific antibiotic effective only against biotype 2.

3. A more general farming systems approach is being adopted in several programmes aiming to reduce losses from cereal root disease. Considerable research has been carried out in this area, yet for a variety of reasons widespread and serious losses still occur. Losses from these diseases may be reduced by improving soil fertility with organic matter, nitrogen and phosphate, and by rotations in which the levels of disease in the soil are

reduced by growing non-host crops, especially legumes in the years between wheat crops. (Garrett 1948; Butler 1961; Rovira and Ridge in press).

This review has detailed some of the advances which have occurred recently in disease management. These advances however do not mean that the threat of loss from epidemic disease has diminished. In fact, there is some evidence that diseases of agricultural crops in many developed countries, e.g. the U.S.A., have increased in recent years (Council on Environmental Quality, 1972). As indicated at the beginning of this review, increased disease can be a consequence of technological advances in crop production and resultant greater vulnerability of the agroecosystem. The lack of progress in the limitation of disease also suggests poor application of new disease control technology.

However, there is reason for real optimism as shown above. Many new concepts and methods to aid disease management have been developed during the past 20 years. It is our view that disease management is now at a watershed position: in the years to come more intensive application of modern knowledge and further progress will result in more effective limitation of crop disease. Nevertheless, for this to occur there must be increased input of resources for research, development and extension. This is especially so if Australia is to reap the benefit of overseas advances. Our unique climate often precludes the direct application of overseas results.

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