Crop disease management with fungicides - an overview of its origins, progress, current status and future development using modelling and climate data

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Summary

This paper reviews future directions, priorities and needs for strategic crop disease management with fungicides. The subject is examined in the context of its historical development within the science of plant pathology, its relationships to non-chemical methods of crop disease control and its economic significance to agriculture. Problems confronting contemporary chemical disease control are discussed and the use of strategic disease management methods to minimize or overcome them are suggested. Examples of strategic disease management systems are cited, their data requirements examined and means of implementating them are discussed.

The current status of this field worldwide and in Australia is considered, as are requirements for its future development, including discussion on the scope of research, staffing, funding, interdisciplinary research (including meteorological inputs) and international co-operation.

Introduction

Most cultivated crops are subject to fungal diseases. Fungi are the most important group of organisms pathogenic to plants and there are generally several fungal pathogens which attack a particular crop. For most crops there are one or a few pathogens which are most damaging while others may be of minor or sporadic significance.

In temperate climates the severity of particular diseases tends to be extremely variable in time and space. This variability, while influenced by several factors, is most strongly affected by weather. There may be less variability in disease incidence in some crops in the tropics where climatic variability is less than in temperate regions. While some of the observations made in this paper may be relevant to tropical crops, they are directed principally at disease management in temperate cropping systems.

A wide range of practices have been developed to control crop disease. Principles such as protection, eradication, therapy, exclusion, avoidance and altered resistance can be involved. However, while the methodologies of disease control are very diverse, they can be classed as either culturally-, biologically-, genetically-, or chemically-based.

In this paper the term "disease management" is used rather than the traditional term of "disease control". There has been growing usage of the term "disease management" since the mid 1970s: it follows the introduction of "pest management" and "Integrated Pest Management" (IPM) in the related discipline of entomology. There is merit in the change: "management" implies the rational use of measures to achieve goals, in both a biological sense (i.e. the manipulation of pathogen populations) and in terms of economics (i.e. improved efficiency of crop production), while "control" suggests the complete or near complete elimination of a pest or pathogen, something which is usually biologically unrealistic. "Disease management" also focuses on dynamics of the crop/pathogen interaction, an approach that is more likely to be successful than concentration on the pathogen, the approach engendered by the term "control".

How do farmers cope with diseases in their crops, given the uncertainty as to when and where disease outbreaks may occur? This paper addresses this question by describing in general terms the present overall approach in agriculture and horticulture to disease management using fungicides. Discussions are concentrated on above-ground fungal diseases but there is some mention of the management of bacterial and soil born diseases where appropriate. The present situation is set in the context of its historical development and its strengths and weaknesses are examined. Directions for future development and improvement in crop disease management by fungicides are drawn from this evaluation.

Chemical *versus* genetic *versus* biological control

All types of disease management practice have a role in the overall management of crop disease. No one type alone will give effective control in every disease situation. Concern over adverse effects of pesticides has led some of the environmentally concerned in the wider community to suggest that chemical pest and disease control methods can or should be replaced with "natural", biological or genetic methods. This suggestion is impractical.

Genetic manipulation is not a universal panacea for crop diseases. Superficially it might seem to be so, particularly when compared with the pesticide option, however it has its limitations and hazards, some of them being common with those of pesticides. 1) Often suitable disease resistance genes have not been discovered. 2) Disease resistance genes, introduced into a crop by plant breeding or other genetic manipulation may be accompanied by closely linked undesirable characteristics. 3) It is also commonly thought that plant genetic manipulation provides permanent disease resistance. While there has been considerable success in some cereal breeding programs using multiple genes for resistance, it should be recognized that ongoing evolutionary processes in pathogen populations can, and often do, result in a return to crop susceptibility. 4) Plant breeding for disease resistance has not been a viable option for perennial crops with a long juvenile period. It is possible that genetic engineering methods may provide practical disease resistance for perennial crops in the future, but this remains to be seen. 5) The high cost of breeding and genetic improvement programs is another limitation of genetic control of crop diseases.

Biological control is also appealing, however it has limitations. 1) Research and development costs are considerable. 2) Biocontrol agents may constitute health risks to human or animal consumers. Many biocontrol agents achieve disease control through antibiosis. The potential hazards of naturally occurring antibiotic compounds, which often have broad-spectrum biological activity, need to be evaluated in the same way as those posed by man-made chemicals. There are some reported successes in the biocontrol of crop diseases but there are many more preliminary reports in the literature indicating promising results which have not been followed by further developments. This field has promise, but due to lack of funding it is much less developed than that of chemical control agents. In the last few years the growth of environmental concerns has seen some of the larger agrochemical companies commence bio-control research programs. This should give the field the impetus it needs to develop rapidly in the immediate future.

In summary, while there are many good reasons for using genetic manipulation and biological control agents to manage crop diseases, these approaches have limitations and cannot be the exclusive basis of crop disease management. For agricultural productivity to remain at its present level, or increase, all the currently available types of disease control measures must continue to be employed. This does not preclude further improvement of these measures with replacement of practices causing environmental concern. It is also desirable that as broad a range of disease management options as possible be available so that measures which fail due to pesticide resistance, pathogen evolution, biological imbalance, etc., can be quickly replaced, avoiding catastrophic crop losses. It is important therefore to identify future directions for disease management using fungicides which will be practical, safe and efficient.

The threat from crop diseases

Potential

Plant pathogens take an extremely heavy toll in the absence of counter measures imposed by man. Estimates of losses in major crops of the United States of America (Anon. 1979, Anon. 1980) if all types of pesticide were not used range between 45% and 100%. Losses would be less if only the use of fungicides was suspended, however it is certain that they would still be very substantial.

Why would losses be so high in the absence of pesticide use? In simple terms the cause is agriculture, the basis of human civilization. The growing of crops brings together large quantities of genetically uniform plant tissues. This spatial aggregation provides ideal conditions for the growth and spread of virulent pathogens. Environments not modified by human activity have great genetic diversity in space which hinders the population growth of pathogens and their spread.

Actual

Data on the real impact of crop diseases on farmers or the general economy is limited. One comprehensive study of which I am aware (Cramer 1967) attempted to determine total losses in agriculture due to diseases, pests and weeds. On the world scene he estimated production losses of about one third from all causes. A more recent estimate by the U.S. Office of Technology Assessment agrees. Even with modern effective crop protection programs at least one third of the world's potential food harvest is lost (Anon. 1980).

Cramer (1967) estimated that crop diseases reduced overall agricultural production in the Oceania region, which included Australia, by 12.6% p.a.. The gross value of crops (not including crops and pastures for green feed or silage) in Australia in 1986/87 was approximately $7,738 million (Castles, 1989) giving a monetary loss of $1116 million from crop diseases in that season using Cramer's percentage loss estimate. The costs of control measures used against crop diseases are additional.

Examining a major Australian crop, Watson (1974) estimated that losses from the Australian wheat stem rust epidemic in the 1973-74 season were about $300 million. Brennan and Murray (1988) recently estimated Australia-wide losses from all wheat diseases to average about $400 million annually.

Losses are not easily predictable or evenly distributed across crops and between seasons. If that was the case, farmers could plan measures to prevent the losses. Often, however, losses are quite extreme in some crops while other crops remain unaffected in a particular season, period, or sequence of seasons. This sporadic pattern of loss has an adverse effect on farmers' incomes and on their ability to manage their farm businesses. A grape bunch rot epidemic occurred during the 1986/87 growing season which resulted in a 10% crop loss ($20 million) to the N.S.W. grape industry. Three seasons later in 1989/90 the losses from another severe bunch rot epidemic were double this figure. Such losses occur with a frequency of one season in every three, but the grape industry has never been fully prepared or forewarned of the impending epidemics, so effective counter measures are not taken (Nair, personal communication).

The occurrence of epidemics which are sporadic in time and space affects farmers and the wider community in a number of ways. 1) There are the direct losses incurred. With many sporadic epidemics, these losses can amount to 100% of the crop to individual farmers in a particular season. While most farmers are not entirely dependant on one crop or variety, epidemics in their major plantings can seriously affect their incomes. 2) The longer term effects of severe epidemics, particularly in perennial crops, are often overlooked. For example a severe epidemic of rust of French prunes has a long-term debilitating effect on the trees, and hence on future productivity (Kable 1990). In many crops the build-up of disease in epidemics causes elevated disease risk in subsequent seasons due to higher initial frequencies of disease causing organisms. 3) Economic dislocation may result from major fluctuations in yield and quality caused by epidemics. This is also evident in the prune industry. For example production of prunes from the Young district of N.S.W. dropped to about 10% of normal because of a severe rust epidemic in the 1983-84 season. Total production was about 90 tonnes of dried fruit, whereas in normal seasons production is about 1000 tonnes. Additionally, the quality of fruit produced on rust affected trees was very much reduced due to low sugar content.

Not only do wild fluctuations in productivity and quality affect the particular industry involved, they are deleterious to associated marketing, processing and service industries. Fluctuations caused by epidemics undermine confidence within the economic network derived from the particular agricultural product and are disruptive to the establishment of long term trade stability.

Sporadic and heavy crop losses due to disease also discourage farmers from continuing to cultivate affected crops. This is particularly damaging for new types of crops, retarding development of expertise in them.

Why is present day crop disease management unsatisfactory?

The preceding sections indicate that, despite a century of scientific plant pathology, the levels of crop disease control achieved in agriculture leave a lot to be desired. There is considerable scope for improvements which will result in greater and more economically efficient agricultural production.

Poor and variable crop disease control can be attributed to several causes: 1) Some farmers fail to follow recommended control procedures either due to lack of awareness, knowledge, time, equipment, other necessary resources, inappropriate day-to-day management priorities or excessive cost of control measures. 2) Other farmers apparently carry out recommended control measures, but these fail for (a) operational reasons (e.g. incorrectly calibrated spraying equipment) or (b) because the recommended control measures are, in themselves, inappropriate or not sufficiently flexible to counteract all disease threat situations.

Remedies for causes 1 and 2a the within the scope of agricultural extension, but technical inadequacies (2b) are the responsibility of the science of plant pathology. An objective of this paper is to indicate how disease losses from cause 2b can be minimized or eliminated by strategic disease management systems developed through interdisciplinary research and development in plant pathology, meteorology and the application of computer science. However, before doing so we need to understand the current status and methods of crop disease management with fungicides.

Historical development of crop disease management with fungicides

The current situation is best appreciated when seen in the context of its historical development. Before the mid-19th century there was some use of fungicides in agriculture, mainly sulphur and copper compounds, but the prevailing inadequate understanding of the nature of disease precluded the rational development of control measures.

Because of this crop diseases had major and frequent impact on human existence in earlier times, precipitating famine, war, disease and major migrations (Large 1940, Carefoot and Sprott 1969). A relatively recent example is the Irish famine of the 1840s. While political factors exacerbated the situation, the famine was the result of the destruction of the Irish staple crop, the potato, in several successive seasons by the fungal pathogen *Phytophthora infestans*. The potato blight resulted in the death of about one million people in Ireland during and following the famine and contributed to the emigration of an estimated 0.5 million, thereby significantly affecting the development of Australia, the U.S.A. and other countries.

A major step forward occurred in the second half of the 19th century with the demonstration by Louis Pasteur and Anton De Bary of the validity of the germ theory of disease. Before then many considered the fungi observed on diseased plants did not cause disease, but were a consequence of it. Because of this view there was no point to measures directed against these fungi, and little or no motivation for the development of control measures.

The next major conceptional advance accompanied the discovery of Bordeaux mixture just over 100 years ago. In his classic paper Millardet (1885) perceived "that a practical treatment of mildew ought to have for its objective not the killing of the parasite in the leaves ... but of preventing its development by covering ... the surface of the leaves with ... substances capable of making the spores lose their vitality or ... of impeding their germination". This concept was the basis for all the developments in protective fungicide usage which followed. It could be argued that scientific crop disease management dates from

October 1885. Millardet's discovery and his concept of fungicidal protection were important steps in the rise of the modern science of plant pathology, which had its beginnings following the Irish and European potato blight epidemics of the 1840's some 40 years earlier.

With time research into the use of protectant fungicides grew and a number of inorganic compounds, mainly copper- and sulphur-based, were used against a wide range of crop diseases.

The first organic protectant fungicides, the dithiocarbamates, were discovered in the 1930s. It was soon recognized, that for many applications, they caused less toxicity to crops and were more effective than inorganic fungicides, hence their use increased rapidly. Following World War 2 the agrochemical industry grew rapidly and new organic fungicides were introduced into agriculture with increasing frequency.

Initially most of these were protectants, but from about 1970 onwards extremely active fungicides which could penetrate plant tissues to a varying extent and which were capable of curative action began to appear. Up to this time curative disease control using chemicals had been the almost exclusive province of human and veterinary medicine: only a few crop disease situations had existed where limited curative control was feasible. The advent of curative fungicides should be viewed as a major milestone in crop disease management comparable with Millardet's discovery of Bordeaux mixture and formulation of the principle of protective disease control some 85 years previously.

A significant feature of many of the modern fungicides is that they are very specific in their action, often affecting only one biochemical process or cellular site in the target pathogen. By contrast, the older protectant fungicides acted on many processes or sites. A consequence of this specificity of action in modern fungicides has been increasing problems caused by pathogens developing resistance to them. Fungicide resistance had not been a significant economic problem prior to 1970 when most fungicides in use had multi-site action.

In most developed countries the use of fungicides and other pesticides in agriculture has been regulated by government since early this century. Factors considered in registration are effectiveness against target diseases, safety to target crops and safety to humans, animals and the environment.

An important trend which accelerated during the 1980s is community concern about the health and environmental impact of pesticides. This has resulted in the de-registration and restriction, or removal from the market of a number of fungicides. Inorganic fungicides containing mercury or cadmium now have very limited uses and some organic fungicides are no longer available (e.g. captan) or their future availability is extremely doubtful (e.g. some dithiocarbamate fungicides).

Parallel to the development over the past century of the chemical armoury against crop disease there has been a steady growth in understanding how and when to use fungicides in cropping. This has come from increasing knowledge of the etiology and epidemiology of diseases, of their seasonal occurrence in crops, of varying crop susceptibility and of the behaviour of persistence of fungicides on crops. Some of this knowledge has come from scientific observation and research and some from farmer experience.

Scientists and agricultural advisors around the world, generally in publicly funded organizations, but also in the agrochemical industry have collated this knowledge in the form of spray guides and calendars. These documents have formed the main basis of advice to farmers on how to control crop diseases for at least the last half century. Spray calendars describe appropriate disease control measures for crops based on date and crop growth stage. They list fungicides which are known to be active against each disease of a crop, indicate the concentrations required, and suggest timing in relation to crop development and frequency of application. In most calendars a wide range of other related information is also supplied.

Problems of crop disease management today

Spray calendars

Spray calendar recommendations tend to be general and are designed to cover all eventualities. They are not meant to be followed as a recipe. If this is done and all possible control measures used, the cost would be prohibitive. In 1991 spray calendars are still the main basis for crop disease management, however, because of their nature they have certain limitations.

They can only give farmers very general advice on the influence on disease of epidemiological factors and climatic variables prevailing in specific crop situations. Spray calendars are encyclopaedias of methods and remedies. They are designed to cover all possible needs and situations and to act as a source for reference by farmers. Many farmers do not have the time, experience, or expertize needed to carefully evaluate all the options available to them for disease control and then to make the right choice from among the many offered in spray calendars.

Spray calendars are a passive medium. They do not alert farmers to impending risk from diseases. The consequence of this is that diseases often cause serious damage before they are noticed by farmers. This results in a fluctuating awareness of the risk of disease. In the aftermath of severe epidemics, there is a high awareness. However, as years go by in which there was little or no damage by a disease in question, the level of farmer awareness declines, and with this comes a reduction in the use of counter measures. When conditions once again favour the disease there are unnecessarily heavy losses. This cycle also leads to a fatalistic attitude among farmers that, while they are able to control diseases in most years, it is impossible to control them in epidemic years when conditions are highly favourable.

Improved disease management systems should be more specific. What is needed is information relevant to a particular crop, its particular growth stage, the time of season and level of disease threat. This approach may not necessarily result in reduced pesticide usage in all circumstances, but should match the level of disease threat with an appropriate and measured response in terms of pesticide application. For example, in a season very favourable to diseases, more pesticide applications might be made than would be indicated by a spray calendar but the outcome would be minimal losses. On the other hand, fewer pesticide applications than recommended in the relevant spray calendar would be applied in seasons of low disease threat, with once again, the outcome being minimal disease.

Uncertainty, loss of fungicides and costs

As discussed above, severe losses from crop disease still occur in agriculture despite over 100 years of scientific research and development. Resultant dislocation impacts on individual farmers and the wider economy. A feature of losses due to disease is their sporadic and unpredicted and/or unexpected occurrence. This uncertainty has additional adverse effects on planning and economic performance at the individual farmer, industry, wider community and national levels.

A major problem is the threat of loss of fungicides from the chemical armoury. There are two main influences at work. First, concern about the environmental impact of fungicides and their effects on health. Some fungicides have already been lost due to de-registration, others, some of the most effective and widely used, are currently under threat. Second, the range of fungicides available for particular disease management applications is being reduced by the development of fungicide resistance.

Another important problem is the cost/price squeeze on farmers over the past few decades. Increasingly the cost of fungicides is a significant factor in most agricultural production. The newer and more effective fungicides tend to be the more costly. Those being lost due to de-registration are often relatively low cost products.

Strategic disease management

Desirable features

It is obvious from the previous discussion that research and development in crop disease management should aim at incorporating the following features into future systems: 1) Elimination or at least minimization of epidemic losses of crop diseases. This should mean that sporadic and unexpected losses would not occur. 2) Chemical intervention to manage diseases in crop production should be strategic, aimed at: (a) maximum effectiveness at minimum cost; (b) reduced fungicide usage to minimize human/animal/environmental impact; (c) reduced fungicide usage to prevent or delay the development of fungicide resistance.

Disease management practices should provide a measured response to a measured risk of disease. This requires continuous monitoring throughout the development of a crop. To assess level of risk it may be necessary to monitor crop growth, the environment in which the crop is growing and the activity of pathogens.

Until fairly recently it was not practicable to attempt to provide such continuous monitoring and management information for the control of crop diseases. Among the reasons for this are: 1) Large amounts of information are involved and; 2) complex interactions occur in the build-up of crop diseases.

Use of epidemiological principles

Strategic disease management must be based on an understanding of the interactions between crop plants, plant pathogens and meteorological conditions: i.e. on basic epidemiological principles. For example, research has shown the dependance of plant pathogens on very specific meteorological conditions for each of the stages of their development. It was once said that "humid" weather favoured certain diseases. This is vague, and consequently does not give much help to growers wanting to know when disease outbreaks may occur. Information must have greater precision. e.g. many diseases are now known to require free water (rain, dew, fog, etc.) on plant surfaces before the crucial infection stage of the disease cycle can occur. Furthermore, infection is dependant upon plant surfaces being wet for time periods in excess of a minimum which varies with prevailing temperatures. Strategic application of knowledge of this type to the management of specific diseases can lead to the identification of disease risk events and the use of appropriate and efficient management measures.

There has, in fact, been a thread of epidemiological principles running through the fabric of disease management since early this century, however up to the present, its potential has not been fully realized. Epidemiologically-based disease control was used, for example, by Müller (1913) when he developed an infection calendar for downy mildew of grapes. His research defined the meteorological criteria for infection by the causal fungal pathogen, *Plasmopara viticola*, and its latent period. He recommended the application of fungicides towards the end of latent periods so that maximum levels of toxic deposits were present on plant surfaces to provide protection just prior to the dispersal of a new generation of infective spores. His system has been used to some extent in Europe for grapevine downy mildew control up to the present time.

Epidemiological principles have also been used in the control of apple scab (caused by the fungus *Venturia inaequalis*). In this case development of concepts started when Keitt and Jones (1926) defined duration of leaf wetness/temperature relationships for infection by the pathogen. These data were further refined through orchard observations during the 1920s and 1930s in New York state, U.S.A. by W.D. Mills, who eventually published the well known Mills Table describing the apple scab infection/environmental relationships (Mills 1944, Mills and La Plante 1951). In mid-century apple scab was practically unique among crop diseases because it could be controlled in a curative fashion by available fungicides. The Mills Table therefore was used by some apple growers in some areas as a guide for the application of curative fungicides. Nevertheless overall fungicide programs used by apple growers for the management of apple scab were then, and still are, largely based on routine protective fungicide applications as described in spray calendars. This is the situation for crop disease management in general.

Implementation of strategic disease management systems has been retarded in the past because of difficulties in obtaining good meteorological data in or near crop sites. The use of meteorological instrumentation was limited due to labour and capital costs and inefficient data collection and processing capability.

Knowledge of crop growth and physiology and of pathogen etiology and epidemiology is needed for the development of rationally based disease management systems. The last few decades have seen major advances in these fields. In particular, the development of quantitative epidemiology during the past 30 years has helped in the understanding of the dynamics of epidemic development. Also progress in the development of methods for the assessment of crop losses due to disease has facilitated more accurate measurement of the level of disease present in crops, hence better estimates of the economic risk from diseases.

The question of cost is important in the collection of biological data. The gathering of information on crop growth and disease incidence is labour intensive. Data of this sort may require regular visits to crops by trained personnel. The collection of such data may add to the cost of disease management systems. Many existing disease management systems circumvent this difficulty by being largely dependant on meteorological criteria while making estimates of crop growth and disease incidence.

Availability of fungicides with required activity against target pathogens

Once periods of risk from diseases have been identified, for example, when pathogen inoculum is available and conditions favouring infection have prevailed during a period of host susceptibility, then counter measures must be taken. An effective fungicide must be applied. Here again the past 20-30 years have seen an expansion in the number of fungicides available with a variety of performance characteristics. Also the advent of systemic and curative fungicides since 1970 has given more flexibility in controlling diseases. In some instances after-infection treatments can eliminate pathogens from within plant tissues. This was generally not possible before 1970.

Data acquisition, data analysis and communication of disease management information to farmers

Developments in electronics during the past decade have resulted in the availability of relatively inexpensive microcomputers and data loggers. The use of data loggers as meteorological stations and modern electronic communication systems has the potential to overcome the remaining constraints on implementation of strategic disease management systems.

There are several ways in which crop disease management information can be provided to the farming community. One approach is to provide information through a centralized system to all farmers growing particular crops within a region. Pioneers of this approach were entomologists and plant pathologists at Michigan State University, U.S.A.. In the 1970s they established agricultural weather stations throughout the state of Michigan with reports being sent daily to a central co-ordinating unit on the University campus (Anon. 1975a, Bird *et al.* 1976). Initially these stations had mechanical instruments housed in Stevenson screens in orchards or fields. Later automatic electronic equipment was used. Ultimately in an experimental program in collaboration with NASA they tested automatic stations which collected weather data every few seconds. This was followed by data transmission to a geostationary satellite for storage and later re-transmission to a ground station from which information was transferred by telephone line to a computer on the University campus. The data were then processed and timely disease management information was placed on an automatic answering phone from which it could be readily accessed by interested farmers (Anon. 1975b).

The Michigan State University research group moved away from centralized systems to provision of systems that can be operated directly by individual farmers. They introduced the Michigan State University Disease Predictor, an instrument which was developed initially to identify infection periods of the apple scab fungus (Jones *et al.* 1980, 1984). This instrument takes environmental information and processes it according to the Mills table to provide an indication as to whether or not scab infections have occurred. The microelectronic chip at the heart of this instrument can be programmed to provide management information for other diseases, pests and operational needs when appropriate models are available.

Whatever the physical means of getting information and disease management messages to farmers, it is important that the information provided addresses the needs of farmers. 1) In developing disease management systems it should be recognized that all operational decisions should ultimately be made by the individual farmer. Each farm is a unique business operation with its own specific requirements. The role of the disease management system is to provide the farmer with as much background information as possible on which to identify problems and make the best strategic and tactical disease management decisions. 2) While the factors influencing disease outbreaks are many and complex, the choices open to farmers in dealing with crop diseases are relatively few. From the farmers' perspective, therefore, systems should present simple information specifically aimed at facilitating the decision making processes outlined in Figure 1. Systems which look at disease management in this way will have a much better chance of adoption by farmers than those which do not. This does not preclude the use of complex data within the disease management models provided that the models indicate relatively simple and specific management choices for farmers. Nevertheless the detailed data used by management models should be available for examination by users in cases where decision making is not straightforward, hence requiring personal judgment and also for validation purposes by system designers.

The ultimate goal - holistic crop disease management

Management strategies employed on crops should be integrated so that the complete set of risk factors likely to affect a particular crop are taken into account and comprehensive counter measures are taken. We cannot simply aim at controlling a single disease. Integrated strategies must be developed to counter all diseases, both major and minor. An integrated approach cannot be developed, however, without having first created the individual components. Management strategies should initially be developed for the major diseases of a crop and then modified and integrated to provide adequate protection against all diseases. Once disease management strategies have been developed, they may be further integrated with those developed for insect pests and other crop management needs.

Integration of disease management strategies should also embrace cultural, genetic and biological methods where appropriate. Integrated programs should be operationally compatible with existing simple management strategies for minor diseases, management strategies for pests and weeds and general crop management practices.

Crop disease management systems - development from 1960 to the present

Beginnings

Interest in the development of strategic disease management systems has gradually accelerated over the past 30 years. Initial impetus to this movement was given by publication of Vanderplank's treatise on quantitative epidemiology (Vanderplank 1963) and the expansion of computing resources which occurred during the 1960s. Plant pathologists began to realize that quantitative or semi-quantitative evaluation of risk of crop disease had become a real possibility.

The Decision Process

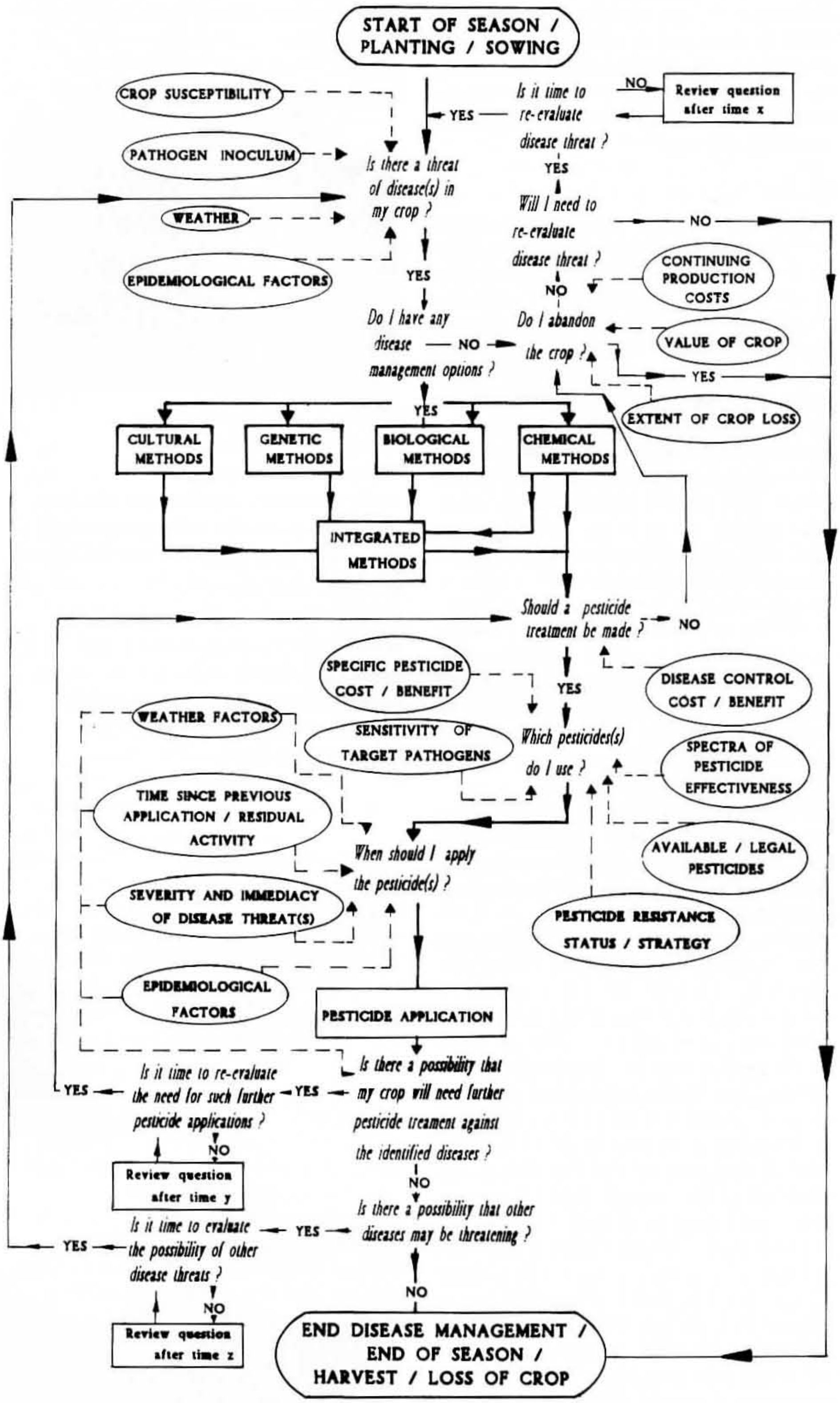

Figure 1. A generalized flow diagram of the decision process which farmers must follow for crop disease management. Issues (questions) which require decisions by farmers are in italics. Factors affecting decisions are enclosed in ovals. This diagram is not definitive: depending upon circumstances other pathways and variables may be involved

An important milestone was the publication of the first crop disease simulator, EPIDEM (Waggoner and Horsfall 1969). This was not used in practical prediction of disease, but demonstrated the potential of mathematical modelling in epidemiology, and by extension, in disease management. Other simulators followed during the 1970s (Kranz *et al.* 1973, Shrum 1975, Waggoner *et al.* 1972) and the development of strategic disease management systems accelerated.

The world scene

Examples of strategic disease management or forecasting systems developed in overseas countries include systems for use against diseases of wheat (Zadoks 1981); potatoes (Pscheidt and Stevenson 1986, Mackenzie 1981, Krause *et al.* 1975); tomatoes (Jardine and Stephens 1987, Madden *et al.* 1978); apples (Zwet *et al.* 1988, Lalancette and Hickey 1986); cherries (Eisensmith and Jones 1981); soybeans (Stuckey *et al.* 1984); maize (Castor *et al.* 1975); peanuts (Johnson *et al.* 1986); grapes (Ellis *et al.* 1986, Lalancette *et al.* 1988, Bourdier 1986, Roussel 1982, Sall 1980); rice (Kim *et al.* 1988); turfgrasses (Danneberger *et al.* 1984); tobacco (Nesmith 1984); and celery (Berger 1970).

Australia

Strategic systems for the management of apple scab have been operative in Australia since the 1950s. These used mechanical instrumentation located in apple orchards (Hutton 1961). The risk of disease was calculated manually and farmers were advised by various media. More recently electronic instruments which automatically calculate disease risk have replaced mechanical instruments in some districts (Penrose *et al.* 1985).

In the early 1970s a system for the management of the brown rot of stone fruits was introduced in N.S.W. (Richens *et al.* 1975). Based on epidemiological research (Kable 1972) this system predicts outbreaks of the disease from synoptic weather forecasts.

During the 1980s a computerized system was introduced in N.S.W. for control of rust of French prunes (Kable *et al.* 1989, 1990b, 1991). Devices located in orchards measure micrometeorological parameters (Figure 2) and from these measurements identify rust infection events and estimate their likely severity. This information is readily accessible to horticultural advisors or orchardists from office-based computers via permanently installed telephone lines (Figure 3). A seasonal outlook indicating the likely severity and time of occurrence of rust epidemics is also calculated by this system. Horticultural advisors provide orchardists with up-to-date information and advice derived from this system through answer phones, radio, television and the press. A prototype of this system was first field tested in 1984 (Kable and Ellison 1984). Following further research and development, it was finally launched for general use by orchardists at the beginning of the 1988-89 growing season (Slack *et al.* 1988).

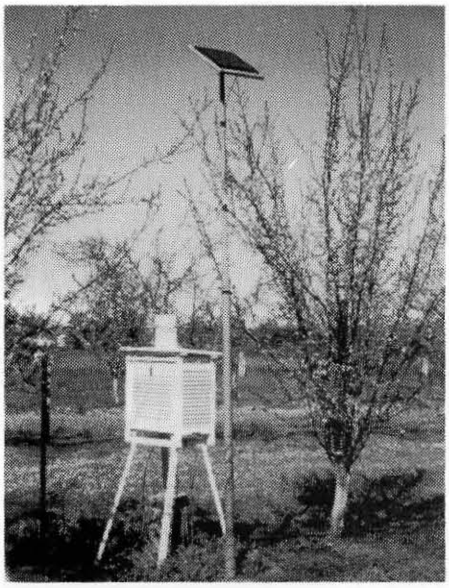

Figure 2. A Prune Rust Infection Predictor (PRIP) located in a prune orchard near Young, N.S.W. The PRIP monitors weather parameters, identifies potential infection periods of the prune rust fungus (*Tranzschelia discolor*) and measures the severity of infection periods. It requires little maintenance, using power supplied by solar cells and its data can be accessed readily through a permanent telephone connection. (Photo: P.F. Kable).

Systems have been developed in Australia to predict the likely severity of stripe rust of wheat, and whether or not spraying for control is an economic proposition (Brown and Holmes 1983, Murray and Ellison 1988). Another Australian system identifies infection periods of mango anthracnose (Peak *et al.* 1986).

A system for the management of downy mildew of grapes has also been under development during the 1980s in South Australia, with anticipated introduction for general grower use within the next one or two seasons (Magarey *et al.* 1983, Magarey and Weir 1988, Magarey *et al.* 1990, 1991). Work is also proceeding on the bunch rot disease of grapes in N.S.W. Investigations, which are still at a relatively early stage, are aimed at defining the epidemiology of this disease (Nair and Nadtotchei 1987, Nair *et al.* 1987, Nair *et al.* 1988, Nair 1990). Research is also in progress into the strategic management of grapevine powdery mildew (Emmett *et al.* 1990). This work is attempting to build upon the model of Sall (1980) with incorporation of specific information relevant to the Australian grape growing regions.

A role for Expert Systems

In the last 5 years there has been a realization that Expert Systems could be very useful in the delivery of specific disease management systems to farmers (Caristi *et al.* 1987, Cooley 1988, Latin *et al.* 1987, 1988, Sands *et al.* 1986). Expert Systems are a development in computer science in which the knowledge of

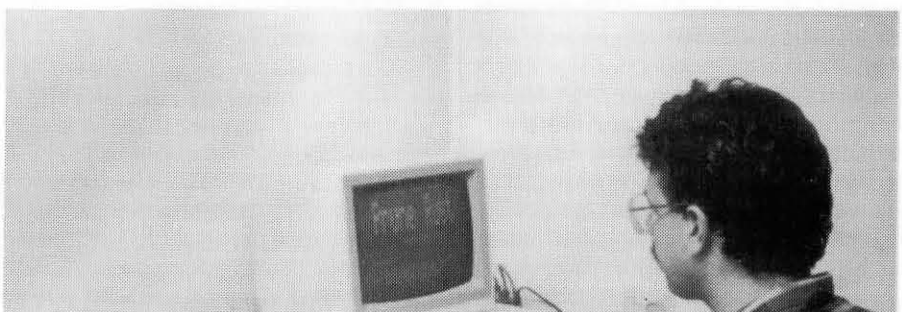

Figure 3. A personal computer being used to obtain potential infection period data from a remote Prune Rust Infection Predictor (PRIP). Horticultural advisors access PRIP units located in orchards via telephone connections. Software developed for the application allows the advisors to evaluate the potential rust infection and to obtain a prognosis of likely seasonal severity of the disease. This permits rapid issuing of warnings to farmers. (Photo: L. Turton).

experts is made available to the non-expert through easily used interactive computer programs.

Success and acceptance in agriculture

Most disease management systems which have been successfully used in agriculture have been based on relatively simple models. They describe crucial steps in the disease process, or integrate either empirically, or in a biologically meaningful way, the processes giving rise to epidemics.

Grower acceptance of strategic disease management systems has been variable. For example BLITECAST, a system for scheduling fungicide treatments against the late blight disease of potatoes (Krause *et al.* 1975), was provided as a commercial service by the Pennsylvania State University in the 1970s but failed to be viable. Similarly, in Australia the cotton pest management system SIRATAC (Peacock 1980) experienced acceptance and usage problems (Anon. 1989) and failed after commercialization.

Following the development of pyrethroid resistance in *Helicoverpa armigera* on cotton and other crops in north-west N.S.W. and Queensland a resistance management strategy was implemented (Forrester 1990). This included managed usage of all insecticides applied to *H. armigera* susceptible crops. It has been in operation since 1983 and is adhered to almost completely by growers. EPIPRE, a system for identification and control of wheat pests and diseases developed in the Netherlands is being provided successfully on a commercial basis throughout northern Europe (Zadoks 1981, Rabbinge and Rusdijk 1983). Grower acceptance will depend upon a range of technical and socio-economic factors. The orientation of system design to meet farmers decision making needs, as discussed above (Figure 1) will increase the likelihood of system acceptance and use by growers.

Strategic disease management systems in Australia - the future

It is my view that crop disease control in Australian agriculture must, in the immediate future, become dominated by strategic disease management practices. The foregoing discussion, in terms of economic performance, efficiency, and crop, animal, human and environmental safety demands it.

As discussed, much research has been carried out in relevant areas and many models and systems have been developed. Nevertheless, applications in practical agriculture have been limited. One constraint has been concern about accuracy of models and the need for their validation in commercial agriculture. I believe that this, together with structural problems in public sector agricultural service organizations has inordinately limited progress. In view of the urgent need for strategic disease management these constraints must be overcome. Organizational constraints need to be addressed by public sector management or through commercialization, preferably by the primary industries involved. The needs of validation can be reduced by, for example, using very simple uncoupled models such as the Mills Table for apple scab, or the temperature/duration of leaf wetness algorithms for prune rust infection. The disease risk evaluations of such systems given to farmers need to be qualified, but are still of great strategic value.

Research and development

An understanding of the epidemiology of a crop disease and derivation of quantitative relationships between driving variables (meteorological and biological factors etc.) and outcomes (e.g. epidemic severity and magnitude of crop loss) require a substantial research base. The amount of research needed will depend on the extent of existing knowledge and the intrinsic complexity of the crop/pathogen interactions. Costs are therefore difficult to estimate, but experience and observation suggest that a minimum of 3 man-years of research effort is required for the simplest project.

Obtaining the research base is just the beginning: information distribution systems are required to get the strategic disease management advice to farmers. This phase requires the collaboration of researchers and agricultural advisors at several levels from policy formulation to hands-on installation of equipment, making field observations, processing field data and providing growers with timely strategic advice. Capital and operating costs are involved, some of which are recurrent for as long as the service is provided. Decisions must be made as to whether these costs are to be born by government or by grower organizations.

Information gathering and distribution in modern strategic disease management systems is, for the sake of efficiency, based on computer and communications technologies. The computer programming required for a strategic disease management system may, from my experience, require 0.5 to 1.0 man-years for initial development and continuing inputs will be needed for up-dating and debugging.

In summary, the costs of developing strategic disease management systems are high. Policy makers and granting agencies must realize this and provide funds accordingly. They should not be deterred by the costs because the *status quo* is becoming increasingly untenable on grounds of excessive pesticide use, and inefficient, variable and costly disease control.

Organizational requirements

Disease management research and development is multi-disciplinary. Expertise required includes plant pathology, especially the epidemiology sub-discipline, meteorology (macro- and micro-), plant and crop physiology, mathematical modelling, biometrics, computer and communications science, agricultural extension, etc. No one person can embrace all these areas and skills, so a team approach is required. Teams can be made up of individuals scattered in various locations. However, it is desirable for efficient operation that at least a core group of workers should be located together. This could be achieved and maintained through the establishment of centres of excellence for crop disease management research.

An attempt to develop a team approach has been made by scientists in N.S.W., Victoria and South Australia working on the management of grapevine diseases in Australia. Their goal is holistic management of diseases in grapes. Research and development of management systems for the major diseases have been apportioned among the group (Kable *et al.* 1990a). Up to two meetings per year are scheduled to discuss progress and plan future research and development. All participants expect to assist in evaluation of research and management models produced by the principal investigators. This group nevertheless will require supplementation with experts in a range of associated fields because at present it is composed principally of plant pathologists.

Meteorological requirements

Weather factors are major determinants of crop disease. They influence the likelihood of epidemics and their severity. Measurement of meteorological variables is therefore essential to strategic disease management systems. To be useful in crop disease management, meteorological measurements must be accurate, appropriate and accessible.

In the past, measurements made by the Australian Bureau of Meteorology (BOM) whilst fulfilling the criterion of accuracy have often been unsuitable for use in disease management because they were not appropriate or easily accessible. Most existing disease management models require meteorological measurements within crops. Measurements taken by the BOM for aviation or general forecasting purposes at sites remote from crops have often been inappropriate. The failure to measure particular parameters or to take measurements at suitable frequencies for disease management purposes has also been a problem. Some of the parameters of particular importance to disease management are not standard meteorological parameters measured by the BOM, or are measured at only a few sites (e.g. duration of crop foliage wetness, soil temperature).

Difficulty in obtaining BOM data quickly has also been a barrier to its use in disease management in the past. Strategic disease management requires quick response times. If a danger period is identified then growers must be provided with that information in as short a time as possible. The time scale over which significant crop disease processes can develop is measured in hours. Response times must be of the same order or quicker. Because of the barriers to the effective use of BOM data, scientists working on disease management have tended to by-pass the BOM and to set up meteorological monitoring in crops which meets the data requirements of their systems.

Standard meteorological forecasts have sometimes been used to predict diseases. The only Australian example is a system for forecasting epidemics of the brown rot disease of stone fruit which involves the use of BOM synoptic data and close collaboration between agricultural advisors and the BOM forecasters (Kable 1972, Richens *et al.*, 1975). Recently a system has been developed in the U.S.A. which uses forecasts of precipitation probability in the prediction of *Botrytis* leaf blight of onions (Vincelli and Lorbeer 1988). Research using mesoscale weather forecasts to predict crop disease one day in the future for areas as small as 1 km^2 has been reported (Royer *et al.* 1989). This area of study seems to hold considerable promise for useful disease management applications.

The meteorological network of the BOM is a major national resource which could be used more effectively to meet needs in agriculture and, specifically, in the context of this paper, strategic disease management. The creation in 1986 of the National Committee on Agrometeorology (NCA) to advise the BOM and Standing Committee on Agriculture (SCA) on this subject has produced progress in this direction.

An important initiative of NCA is a proposal to establish a network of "agrometeorological benchmark sites" strategically located in agricultural regions throughout Australia. The establishment of 177 meteorological stations measuring meteorological parameters of agricultural and general significance is proposed. It is expected that most, if not all of these stations will be automated, will record parameters with sufficient frequency to be useful in modelling, and will provide rapid data access. The NCA has recognized the importance of duration of crop foliage (leaf) wetness for the disease management, however the lack of standardization in the measurement of this parameter presents difficulties for its immediate inclusion as a parameter measured at sites in the network. Means of providing important, but non-standard data such as leaf wetness and soil temperature remain under consideration by NCA. The benchmark sites network will be of some use for crop disease management, but it is likely that the majority of systems will continue to require their own meteorological measurements within crops. It is possible that future research will establish good relationships between standard measurements made at benchmark sites and micro-meteorological conditions, including foliage wetness within crops in the same general locality. If this is achieved then the benchmark sites may become more useful for strategic disease management. Advances in the interpretation of satellite data and synoptic forecasts might also reduce the need for in-crop micro-meteorological monitoring.

Setting priorities

The potential range of diseases which could be managed by strategic systems is large. Almost any disease, the epidemiology of which is weather driven and hence is sporadic in occurrence and for which fungicides are used is a candidate. There is considerable scope for work on a number of vegetable diseases (e.g. grey mould of tomatoes) against which current fungicide use appears to be excessive, resulting in unnecessary residues and fungicide resistance.

Higher value intensive horticultural or agricultural crops have obvious scope for more flexible disease management. Systems could also be developed for broad-acre crops where use of fungicides is economically feasible. Research and development priorities in Australia will depend upon the perceived or relative impact of diseases and the availability of funding.

Mechanisms for implementation and maintenance of strategic disease management systems need to be developed and improved. A major concern of researchers in this field is that, after completing the necessary research and development, a system which might be extremely valuable to a particular agricultural industry may not be implemented. Alternatively it may fall into disuse for lack of necessary mechanisms and/or personnel to ensure its regular reactivation with the cropping cycle. Development of systems starts with advisory/research interaction in problem definition, then major research inputs followed by close advisory/research interaction at the implementation stage. Ultimately system maintenance and updating should be managed through advisory services with research inputs as necessary to address changes in cropping methods, technology, the target diseases, etc.

International co-operation

The movement towards strategic disease management arose through the international scientific community. If Australia is to maintain pace with the rest of the world in this area then international exchange and co-operation between Australian scientists and their overseas counterparts must be encouraged. This means funding of involvement by Australian scientists in international research projects and for scientific exchange visits. This type of co-operation can result in quicker implementation and considerable savings in research and development costs. Systems developed in co-operative international programs may be adaptable to Australian conditions with very little additional work. For example the introduction and use of Reuter-Stokes Apple Scab Predictors in N.S.W. from 1983 onwards resulted in part from international contacts and co-operation (Penrose *et al.* 1985, Penrose 1989). Costs were minimal when one considers the cost of independently developing systems of this type.

It seems likely, too, that countries which are our agricultural trading competitors will in the future set new standards for pesticide residues on their agricultural products, based on lower levels achievable through the use of strategic disease and pest management. Possibly as a first step in this direction fresh fruit and vegetables for sale in supermarkets in France are being labelled as to pesticide history and country of origin (personal observation). It is essential that Australia meet this challenge and match or exceed required reductions in pesticide residues. Given adequate research inputs and our relatively dry climate, use of strategic management systems should enable Australia to do better than most of its international competitors.

The maintenance of international scientific links in strategic disease management is also important in view of the worldwide trend towards commercialization of agricultural management aids. If Australia does not participate in the development of disease management systems or have tangible links with the relevant groups of scientists in other countries, it is likely to be excluded from participation and use of such systems or be required to pay for them on a fully commercial basis. This could be disadvantageous on the basis of both cost and relevance of systems to Australian conditions and. Maintenance of Australian public sector science involvement in international research on crop disease management is also essential to provide Australian farmers with comprehensive and objective information. Disease management systems developed in the private sector (e.g. by multinational agricultural chemical companies) may promote products of the developing company. Farmers using them may not be made aware of their full range of management options.

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