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A Quarter Century of Diseas

Fashion governs the design of science as well as the design of dress. Fashion in dressing up and fashion in science reflect, each in its own way, an attitude to life, but in science, far more than in dress, new technologies affect the design.

The topic of disease warning is obviously subject to fashions. The topic is "in" and not yet riding the crest of the wave. The interest of the public at large mainly roots in environmental concerns, and the renewed interest of the farming sector sprouts from economic concerns. The scientific community received new stimuli from technological innovations. The chemical industry created new opportunities. Systems theory provided a new paradigm, literally changing the design of our science. Changes in agricultural practice rapidly outdate existing knowledge. Within this broad pattern of change, however, the three basic ingredients of disease warning have not altered.

Terminology is rather loose. "Forecast" and "prediction" can be used as synonyms (Webster's and Oxford dictionaries). Both deal with something future; they make a statement ante factum. Confusingly, the forecast of future disease outbreak is often based on the observation of a past critical period. With respect to infection, such a forecast is post factum; with respect to outbreak, it is ante factum. Sometimes the word "detection" is used for the post factum statement of infection. To avoid terminological traps, and to emphasize that the message to the farmers is more important than the technical origin of that message, the term "disease warning" will be used here.

Basic Ingredients

There are but three basic ingredients of disease warning: the crop, the disease, and the weather.

Few warning systems use the crop as an only input. If so, crop phenology data are mainly used in strategic warnings in the sense of "start treating the potato crop against late blight when the green line stage is reached." In a broader sense, crop data are used in recent "risk assessment" schemes (Table 1). As these are strategic rather than tactical, they will not be discussed here. Also, weather-based strategic forecasts, such as S. Nagarajan's "Indian stem rust rules" or the stripe rust forecast for the U.S. Pacific Northwest developed by S. M. Coakley and R. F. Line, will not be discussed.

Table 1. Items in a "risk assessment" scheme for strategic use in protecting wheat against various diseases[a]

Item	Maximum score
Previous crop	3
Variety	3
Sowing date	2
Local disease risk	3
Cultivation	2
Land grade	3
Susceptibility of soil to drought	1
Nitrogen usage	2
Crop density	1
Total	20
Decision threshold	⩾10

[a] Kelly (3).

Warning systems using disease as a basic ingredient are rare. In many cases, it is too late to intervene when disease becomes manifest. This is particularly true for explosive diseases such as those caused by peronosporaceous fungi like downy mildew of vine (*Plasmopara viticola*) and potato late blight (*Phytophthora infestans*).

As a single input, and for tactical usage, weather is the only basic ingredient frequently used per se. Infection periods were studied around 1910 in Hungary for *Plasmopara viticola* and around 1920 in the Netherlands for *Phytophthora infestans*. Van Everdingen's (1) postulation of the Dutch rules for potato late blight in 1926 was a breakthrough. He launched the concept of "critical period." Another milestone was the declaration of W. D. Mills's periods for apple scab in 1944. In addition, Mills introduced a novelty by proposing three different risk levels.

Critical Periods

The critical period approach has been highly productive, but it is post factum, warning that something did happen rather than predicting that something would happen. The great popularity of the critical period approach is probably due to its accurately timing the onset of a spray program with preventive fungicides against downy mildews, or, in other words, its strategic value in the control of peronosporaceous fungi.

Dissatisfaction with notification post factum led to intensive research. The Dutch scientist G. A. de Weille (6) studied the behavior of *Phytophthora infestans* in detail and described it in a "biological model." He defined the micrometeorological requirements of the fungus in a "meteorological model," which he translated into a "synoptic model." Weather fronts carrying blight weather could be identified up to 18 hours before arrival. In 1964, de Weille produced real predictions with tactical value.

In the United Kingdom, the inspired guidance of the unconventional meteorologist Lionel P. Smith made itself felt. Several nonperonosporaceous agents were studied and their fascinating life histories were reduced to a few simple weather screen measurements (Table 2). Though all of these studies could be applied in situ, most were intended for use in regional forecasts.

The Problem of Context

Two meritorious epidemiologists, J. M. Hirst from the United Kingdom and R. D. Schein from the United States, assisted by A. J. P. Oort from the Netherlands, convened the first international meeting of epidemiologists in 1963, as part of the Third International Congress of Biometeorology, in the French city of Pau. There, an interesting debate arose between de Weille, who claimed his warning system for potato late blight to be universally applicable, and P. M. A. Bourke from Ireland, who had developed a different but equally functional warning system for his

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Warning, 1958—1983

country. Bourke illustrated his reasoning by Venn diagrams, reproduced here with some modifications (Fig. 1).

The complete reality of a managed pathosystem, here potato late blight, is represented by a circular surface (Fig. 1). Reality is so complex that it cannot be comprehended by a single human mind. Nor is that necessary. For practical purposes, only those elements of reality are needed that are relevant to the purpose of disease warning at a particular time in history, in a particular place, and under specific technical constraints. At least three completely independent blight warning systems were developed:

1. A system based on the idea that a new treatment is needed when protection by the latest treatment has eroded through heavy rains;

2. A system based on the idea that a critical period appears when a frontal system carrying a rain zone is blocked in its course by a stationary high-pressure area;

3. A family of systems, much interrelated, based on detailed weather screen observations. Among these are systems using A. Beaumont's periods, L. P. Smith's rules, R. A. Hyre's rules, and J. R. Wallin's index points. Common to all systems of the family is detailed knowledge of the fungus, but none of them is universal, not even de Weille's system. Each system was developed in its own context. The climatic component of context may be continental or Atlantic, with overhead irrigation, tropical showers, or Nordic haziness. The problem of context is a very real one, but contexts are difficult to define. The realization that different people work in different contexts, where phenomena may have different appearances, was already one step forward.

Table 2. Some typical weather-only plant disease warning systems

Host	Pathogen	Senior author	Year
Barley	*Erysiphe graminis*	R. W. Polley	1973
Wheat	*Septoria* spp.	R. J. Cook	1977
Wheat	*Septoria nodorum*	J. B. Tyldesley	1980

Table 3. Various disease warning systems with mixed ingredients

Host	Pathogen	Senior author	Year
Wheat	*Pseudocercosporella herpotrichoides*	H. Fehrmann	1972
Peanut	*Cercospora arachidicola*	D. H. Smith	1974
Pear	*Erwinia amylovora*	S. V. Thomson	1977
Tomato	*Alternaria solani*	L. Madden	1978
Hops	*Pseudoperonospora humuli*	H. T. Kremheller	1979
Cherry	*Coccomyces hiemalis*	S. P. Eisensmith	1981
Wheat	*Septoria nodorum*	G. Englert	1983

Table 4. Some index value systems for plant disease warning

Host	Pathogen	Senior author	Year
Potato	*Phytophthora infestans*	W. E. MacHardy	1979
Wheat	*Pseudocercosporella herpotrichoides*	L. Lescar	1981
Wheat	*Septoria* spp.	R. J. Cook	1977
Wheat	Various diseases	J. R. Kelly	1982

Disease Monitoring

Not all diseases hop from one critical period to the next. Some proceed slowly but steadily. K. S. Chester, E. C. Large, J. E. van der Plank, and I all stressed the importance of disease progress curves. Their parameters can be used to predict future infection and, more specifically, whether that infection will pass the damage threshold. In such diseases, the rate of disease progress is relatively independent from the weather, once the rate has been set. F. H. Rijsdijk (*unpublished*) found that yellow stripe rust (*Puccinia striiformis*) on wheat is relatively independent of weather, since it derives up to one-half of its disease progress from lesion growth.

Warning systems using disease as their sole ingredient are not popular, probably because they require disease monitoring in the field. Possibly, phytopathologists are waiting for automated disease monitoring systems, ignoring farmers' experience and insight. Entomologists, less fussy than phytopathologists, rely heavily on field monitoring. Exception must be made for specially planned pilot plots ("late blight gardens") used in potato late blight warnings. The German PHYTPROG system, dating from about 1970, emphasizes negative prognosis; as long as pilot plots remain free from disease, no treatments are recommended.

Mixed Systems

The reduction of manyfold and intricate biological phenomena to just a few meteorological observations at the weather screen level, as seen in extreme weather-oriented warning systems, does no justice to the complexity of nature. In many cases, and certainly in field-specific forecasting, a mix of basic ingredients is needed (Table 3).

Planting dates and developmental stages are used to mark the beginning and the end of the period during which forecasts are applicable. G. Englert et al combined development stages and critical periods to warn against glume blotch of wheat (*Septoria nodorum*). A warning system for eyespot in wheat (*Pseudocercosporella herpotrichoides*) based on work by H. Fehrmann and H. Schrödter also takes into account crop rotation, soil type, fertilizer aspects, and weeds. Topography is an item in spray decisions on *Septoria* spp. in wheat in Great Britain. All these items fall within the gross category "crop," as does varietal resistance. In weather-oriented warning systems, varietal resistance does not fit; it is added rather as an afterthought. In the painstaking work by F. Rapilly on eyespot of wheat, varietal resistance was fully incorporated. Varietal resistance is part and parcel of a British *Septoria* forecasting system.

Delivery

Phytopathologists developing forecasting systems should think of delivery to farmers living in a complex society.

1. Whatever the crop, farmers usually face more than one and often many harmful agents. The new broad-spectrum fungicides and the avalanche of pesticide mixtures have killed the farmer's interest in single-agent systems.

2. Farmers have several options, among which are a fixed calendar spray schedule and a flexible approach that utilizes integrated disease and pest management.

3. Farmers can follow their own wisdom or the recommendations of competent pesticide salesmen, extension officers, private consultants, or spray contractors. They can apply treatments themselves or contract to have treatments applied. The cash flow per hectare of crop affects the farmer's decision, as does his own attitude toward risk, which he may avoid or accept.

Delivery methods cover a range from the collective to the individual. An original and effective mode of collective delivery, once practiced in northern Italy, is that of ringing the church bells to let farmers treat their vines against downy mildew. With increasing organization and technology came delivery by mail, radio, pay phone, and public and pay TV. In these cases, the message delivered is statewide, regional, or local, but always collective. Such a message is, by necessity, general and risk-avoiding. It easily leads to overtreatment of a majority of fields. Its opposite is the personal message, issued by the visiting pesticide salesman, extension officer, or private consultant. The personal message must be paid in one way or another, but being personal and tailored to the farmer's needs, it can often compete with a collective message. When the personal message is not only personal but also decidedly field-specific, it may really optimize pesticide usage.

Modern technology has added a new dimension to centralized disease warning systems, allowing these to become field-specific. The farmer specifies input data from an individual field, and the system responds by a recommendation for that field specifically. BLITECAST (4) was the first system in this operating mode, geared to a single disease (potato late blight), using a central computer, with on-line delivery by phone. BLITECAST is a fine example of a forecasting system completely remodeled for on-the-farm delivery of a field-specific message. This remodeling required a considerable effort on the part of the phytopathologist.

Decentralization has been attained by providing the farmer with equipment, such as leaf wetness recorders in the control of apple scab, or some kind of do-it-yourself kit. The farmer has to answer successive questions by jotting down some figures and adding these up to an index value (Table 4). When the index value surpasses a given threshold, the farmer has to treat. Such self-help kits often give allowance to the farmer's degree of risk avoidance. BLITECAST has developed either way, a self-help kit with a form, an overlay, and caliper on the one hand, and a sophisticated black box placed in the potato field on the other

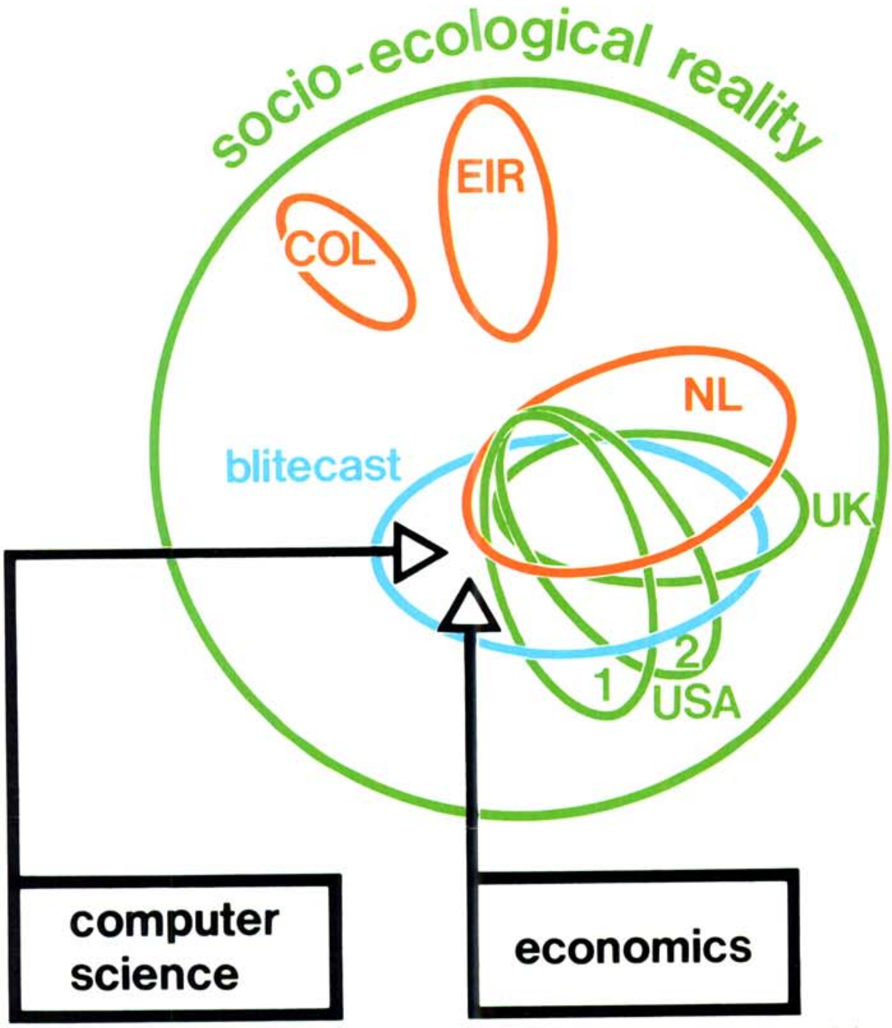

Fig. 1. Symbolic representation of the managed pathosystem potato late blight. Management systems are indicated as ovals, taking into regard only part of the complete reality covered by the circle. Two recent inputs are mentioned in quadrangles.

Table 5. Some highlights in plant disease warning

Year	Senior author	Characteristic
1926	E. van Everdingen	Critical periods
1944	W. D. Mills	Risk levels
1953	J. Grainger	Mechanical forecaster
1964	G. A. de Weille	Biological + meteorological + synoptic models
1966	J. Ullrich	Negative forecast PHYTPROG
1967	J. Grainger	Transportable analog computer
1975	R. A. Krause	Central computer BLITECAST
1978	D. R. MacKenzie	On-site microprocessor Blitecaster
1981	J. C. Zadoks	Multiagent system with on-line economic calculation EPIPRE

hand. The black box, called Blitecaster, contains a microprocessor that warns the farmer when to treat the potatoes, when he presses a button on the front of the instrument. On-site microprocessors are being used in the control of apple scab (*Venturia inaequalis*) and cherry leaf spot (*Coccomyces hiemalis*). John Grainger, the pioneer from Great Britain, merits special mention, as he published his analog computer for crop loss forecasting in 1967 (2), after having developed a mechanical contraption, the "Auchincruive potato late blight forecaster," in 1953.

The European scene witnesses an increasing pressure on farmers and phytopathologists to reduce fungicide application. Pesticides still are a favorite issue in political debate. Phytopathologists and extension officers are picking up the message. The farming community in some countries is beginning to hear the message, either because the farmer's wife does not like her husband to be exposed to pesticides or because the farmer lost money due to fungicide-resistant strains of plant pathogens. Public needs to maintain common property values, such as health of people and animals, cleanliness of the environment, and a stock of plant pathogens not resistant to fungicides, and private needs to receive a maximum return on every dollar spent on the farm can be reconciled in part by means of field-specific forecasting systems.

Most forecasting systems take it for granted that treatments pay. The assumption may be correct for peronosporaceous diseases of an explosive nature, but it is not necessarily correct for diseases of the slow-and-steady type. Financial aspects are seldom mentioned in disease warning studies, and action thresholds are rarely established. A noteworthy exception is the British 1977 *Septoria* system, which explicitly mentions treatment costs and expected yield and which is, of course, field-specific. The truism that returns on expenses in disease control increase with increasing yield level is often neglected.

EPIPRE

A recent warning system that combines many requirements is EPIPRE (5,7), an integrated disease and pest management system for wheat encompassing six fungal diseases and all aphid pests. EPIPRE is a centralized, computer-operated, field-specific system based on postcard interchange with the participating farmers, with a turnover time of 3–4 days. Farmers pay a participation fee.

EPIPRE integrates two basic ingredients of forecasting: the crop and the disease. EPIPRE excludes the unpredictable weather as a basic ingredient. For the crop, cultivar and varietal resistance, sowing date, soil type, nitrogen status, and developmental stage are relevant. The developmental stage is used as a tactical input, among other things for calculating the date at which a new field observation has to be made (forecast period). For the diseases and pests, EPIPRE requires the participating farmers to do their own monitoring. For the time being, the disease and pest observations have integrated all weather effects up to the date of monitoring. A novelty provided by EPIPRE is its financial justification, with an on-line calculation of the added value (expressed in kg/ha^{-1}) for every action, including the decision not to act. Another novelty is an algorithm indicating the possible appearance of fungal strains resistant to fungicides.

For the farmers, the comparative advantage of EPIPRE is its educational value. They gain in professional competence and they certainly do not lose money. For the authorities, the comparative advantage of EPIPRE is its considerable reduction of pesticide usage. During political debates in the Netherlands Parliament, EPIPRE was cited repeatedly by the Dutch minister of agriculture. An environmental protection threshold can be incorporated, as has been done in Switzerland.

Though EPIPRE was developed within a Dutch context, it soon spread throughout Europe. It has been implemented now in Belgium, the Netherlands, and Sweden, whereas France, Switzerland, and the United Kingdom test EPIPRE using the Wageningen computer. The EPIPRE system is certainly not universal, but the underlying philosophy seems to be widely applicable.

Epilogue

The farming world is a complex world indeed. The topic of tactical disease warning was portrayed against this background of complexity. To picture a quarter century of disease warning packed with new developments, a coarse brush is needed. With apologies to those not mentioned, a few points are highlighted in Table 5. New needs and new possibilities for disease forecasting will challenge another generation of plant pathologists. I do expect disease forecasting to increase its comparative advantage when it integrates with crop management.

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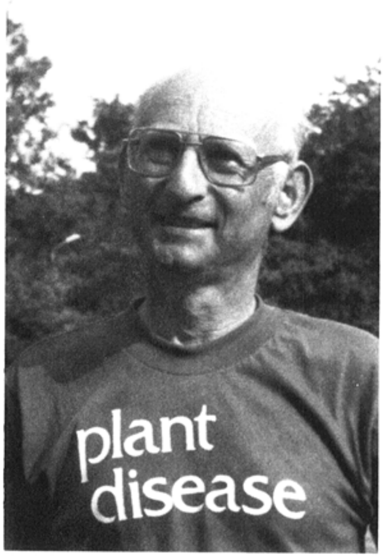

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Dr. Zadoks was born (1929) and bred in Amsterdam, the Netherlands, where he completed his studies in biology at the Municipal University. He started his professional career as a research scientist (1956) at the Research Institute for Plant Protection (IPO) at Wageningen, then (1961) shifted over to the Department of Phytopathology at the Agricultural University, Wageningen, where he is now a full professor of plant pathology. He spent one 3-year term as a dean, responsible for all teaching and research at the university. At present he is president of the National Science Foundation for Biology in the Netherlands and a member of the FAO/UNEP Panel of Experts on Integrated Pest Control. He specializes in epidemiology and has completed several missions to the tropics. He has published some 150 research papers, and with Richard D. Schein he wrote the 1979 book *Epidemiology and Plant Disease Management*. He became an APS member in appreciation of the new journal Plant Disease.