Crop losses in crop physiological and crop ecological terms and their implication for pest management

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1. INTRODUCTION

Plant protection is developing more and more into a science which develops and designs pest and disease management systems for different cropping situations. Modern monitoring, prediction methods and data handling techniques have been introduced and help users, farmers and extension officers in decision making by giving advices and recommendations for the specific conditions in individual fields. The necessity to tune control measures to the specific conditions of an individual field is greatest in high-input modern agriculture, whereas general recommendations may suffice in low-input agriculture.

This paper discusses the value of plant protection measures at different crop production levels and considers the possibilities and the need for sophisticated pest and disease management systems.

Each pest and disease management system comprises three important aspects: monitoring, forecasting of population densities, and damage assessment. These aspects will be discussed for tactical and strategic systems.

2. PRODUCTION LEVELS AND PLANT PROTECTION

Plant pathologists often pay much attention to the biology of pest and disease organisms which cause yield losses, and implicitly assume that the crop is a constant substrate: they neglect its interaction with the pest or disease. Thus the effect of production level on the pathogen, and vice versa, are usually not considered. However, the nature of the relation between crop and pest and disease organisms may vary considerably between production levels; crop losses, both qualitatively and quantitatively, may depend also on the way crop growth is affected. In a detailed study on crop losses due to cereal aphids, Rabbinge et al. 1984 demonstrate that the effect of a similar aphid load on the plant depends strongly on production level. Yield loss (kg kernels/ha) was correlated with the maximum aphid density per tiller, normally reached at crop development stage milky ripe (decimal code 77). At a production level of about 5000 kg of wheat ha^{-1}, a peak density of 15 aphids $tiller^{-1}$ causes a yield depression of about 250 kg ha^{-1}; whereas the same population density at a yield level of 7500 kg ha^{-1} causes a yield loss of 800 kg ha^{-1}. In the analysis of this damage relation, it was demonstrated that the major reason for the progressive damage relation was the relative importance of indirect effects on yield loss. The major reason for the considerable damage at higher yield levels is the effect of honeydew on photosynthetic rate and promotion of leaf senescence (Rabbinge et al., 1981). The effects are caused by the sealing of stomata, the depression of the activity of photosynthetic active enzymes, and the promotion of senescence.

This example demonstrates the importance of defining the yield or production level at which the pathogen-crop relation is studied. In an effort to define in advance the expected yield de Wit (1982) distinguishes four types of crop production.

Production situation 1. Comprises the potential production level reached in conditions with ample plant nutrients and soil water all the time. The growth rate of the crop in these conditions is determined by weather conditions and amounts to 150-350 kg ha^{-1} day^{-1} of dry matter when the canopy fully covers the soil. In these conditions the absorbed radiation is often the factor limiting the growth rate during the growing season. In fact, this is quite a common situation in cool climates. Major elements in this class of system are the dry weights of leaves, stems, reproductive or storage organs and of roots, and the surfaces of photosynthesizing tissues; major processes are CO_2-assimilation, maintenance and growth, assimilate distribution and leaf area development. A situation with plant growth at this production level can be created in field and laboratory experiments while it is approached in practice in glasshouses and in the very intensive production of sugar-beet, potato and wheat on some Western European farms.

Production situation 2. Growth is limited by water shortage at least part of the time, but when sufficient water is available the growth rate increases up to the maximum rate set by the weather. Such situations can be created experimentally by fertilization in temperate climates and in semi-arid zones; it is approached in practice in non-irrigated but intensively fertilized field, such as many Dutch pastures. The extra elements of this class of system are the water balances of the plant and soil; crucial processes are transpiration and its coupling to CO_2-assimilation and loss or gain of water by the soil through evaporation, drainage and runoff. The heat balance of the canopy needs consideration in detailed analyses at this production level, because of its relation to the water balance.

Production situation 3. Growth is limited by shortage of nitrogen (N) at least part of the time, and by water or weather conditions for the remainder of the growth period. This is quite a common situation in agricultural systems using little fertilizer, and is also normal in nature. Even with ample fertilization, N shortage commonly develops in crops at the end of the growing season. Important elements in these systems are the various forms of N in the soil and in the plant; important processes are the transformations of nitrogenous compounds in the soil to forms less or more available to plants, leaching, denitrification, N absorption by roots, the response of growth to N availability and redistribution of N within the plant from old organs to growing ones.

Production situation 4. Growth is limited by the low availability of phosphorus (P) or by other minerals like potassium (K) at least part of the time, and by N, water or weather for the remainder of the growth period. Lack of P is particularly interesting because of its relation to the metabolism of N. Growth rates are typically only 10-15 kg ha^{-1} d^{-1} of dry matter during a growing season of 100 days or less. This situation occurs often in heavily exploited areas where no fertilizer is used: in many of the poorest parts of the world. Important elements of this class of system are the P or mineral contents of the soils and of the plants; important processes are their transformation into organic and inorganic forms of differing availabilities, absorption of minerals by roots, and the response of plant growth to their absolute availabilities. The availability of P relative to that of N is also important.

It is rare to find cases that fit exactly into one of these four production situations, but it is a very practical simplification of a study to reduce specific cases to one of them. It focuses attention on the dynamics of the principal environmental factor and on the plant's response. Other environmental factors can then be neglected, because they do not determine the growth rate; or rather, it is the growth rate that sets the rate of absorption or efficiency of utilization of the non-limiting factor. If, for example, plant growth is limited by the availability of N, there is little use in studying CO_2-assimilation or transpiration to understand the current growth rate. All emphasis should then be on N availability, the N balance and the response of the plants to N.

Plant diseases and pests are often not specific to certain production levels, but their epidemiological characteristics may differ considerably and, consequently, their effects on yield may be different (Zadoks and Schein, 1979). Generally crops growing under good conditions are a good substrate for population growth of pests and disease organisms. Pathogens on poor crops show a much slower population increase. Modern crop cultivation in Western Europe is such that crops stay rich in nitrogen until maturation and form an excellent food source for pest and disease organisms. High growth rates and long growing periods result in high pathogen densities. Poor crops, due to nitrogen shortage, are less suitable for population growth of pests and diseases.

3. YIELD DETERMINING AND YIELD REDUCING FACTORS

Potential yields of crops (production situation 1) are determined by crop physiological characteristics and incoming radiation. For different locations potential yields are computed using simplified crop growth models (Sibma, 1977; de Wit, 1965). There are clear differences in total dry matter attainable at different geographical locations even when environmental conditions are optimal. Attainable yields are considerably lower and much more variable when water or nutrients are not abundant: at production situations 2, 3 and 4. In these cases, which are more common than production situation 1, attainable yields can be computed with crop growth models which take into account lack of resources (Penning de Vries & van Laar, 1982; van Keulen, 1975). Actual yields are a fraction of attainable yields and the size of this fraction depends on yield reduction due, for example, to pest and disease organisms. When attainable yields approach potential yield, yield reduction due to pests and diseases can be considerable. Yield variation is then large only if yield reducing factors are active and important. In some crops, e.g. wheat, it has become clear during the last decades that pests and diseases may form the major yield-reducing factors; and a trend towards preventive overspraying started in these crops in the early eighties in parts of Western Europe (Zadoks, 1980). However, in fields with low yield expectation, due to inappropriate agronomic measures or poor production conditions (e.g. soil condition or water management) spraying activity should be limited. A poor crop can't become a rich crop through increased spraying activity. A pesticide will not increase yield potential, but only protect it against pests and diseases. Pest and disease management should there be tailored to the yield expectation and prospects of pest and disease development.

4. CROP MANAGEMENT

Farmers producing at whatever production situation are not interested in one-disease management systems. Even at the high production levels of Western European agriculture, where pests and disease are major factors for yield reduction, pests and disease control is considered relativity unimportant. Crop protection may involve up to 20% of their time and expenditure (Zadoks, 1980) but farmers don't see it as a first priority. They have to deal with a crop situation in which several choices have to be made. The varieties they choose, the crop husbandry practices they apply, and the weather they experience affect crop growth and pests and diseases differentially. Control measures, when chemical have often plural effects, e.g. triadimefon gives good protection of wheat against Puccinia striiformis and Erysiphe graminis and fair protection against Puccinia recondita and Septoria tritici. These characteristics determine the farmers acceptance of pest and disease management systems aiming at cost reduction and reduction of pesticide use through monitoring, yield loss, forecasts and calculating risks. Further progress and implementation of pest and disease management is possible only if it fits well into crop husbandry as a total. This means that variety choice, fertilizer application and water management should be involved: complete crop management systems should be designed and developed in which disease and pest-control (preventive or curative) are an important part.

This does not hold for all production situations. In conditions of water and/or nutrient shortage, pests and diseases are relatively unimportant. Of course plaques of locusts or an explosion of blight may occur, and should be prevented, but in such cases pest and disease management is not usually last minute work and can be decided by selection of different alternative strategies.

5. STRATEGIC AND TACTICAL MANAGEMENT METHODS

Pest and disease management in practice is different for different crop situations. Strategic or tactical methods may be used. Strategic methods are based in long term approaches, often have a general validity and indicate the consequences of certain pest and disease control policies. The choice of variety, production situation, regional characteristics etc. may come into strategic systems. Tactical methods are used in the short turn in the individual field. They are based on the stimuli of the moment and need to be applied frequently during the growing season. The pest- or disease-manager, in many cases the farmer, wants to make a decision on whether to treat or not, and prefers to decide on the basis of calculated alternatives. Strategic methods offer him different policies and the consequences thereof, they can be used at different production levels and are not field specific. Tactical methods on the other hand are tailored to a specific option and the specific needs of their users. Unfortunately very few, if any, pest and disease management systems use tactical methods. Apparently, knowledge and techniques are not yet sufficiently advanced to develop such methods. An example of a tactical pest and disease management system is the EPIPRE-system. This system was developed for winter wheat growing at high production levels. It originates from elaborate and accurate simulation models which were used to increase insight into the epidemiology of the different cereal diseases and pests. Simplification of these comprehensive models has resulted in summary models and decision rules which are at present used in this computer-based supervised control system.

Some explicit criteria may help in the development of these tactical pest and disease management systems. First of all the system should be simple so that the practical recommendations are simple. Counting schemes or spraying criteria should be not too complicated. As an illustration I may quote our own work in EPIPRE. In this project the criterion for spraying against cereal aphids was formerly set, for a certain yield expectation, at 15 aphids per ear. The counting activity required to determine this density was so laborious yet often so inaccurate that another easier and more reliable method was urgently needed. To meet the requirement of simplicity we now determine the percentage of infested tillers by inspecting 100 tillers. This procedure is possible, since when aphid numbers are less than 15 per tiller, there is a linear relationship between the logit value of tillers infested and the logarithm of average number of aphids per tiller (Figure 1). When higher densities are present the proportion of tillers with more than 10 aphids per tiller is determined as there is a linear relation between the logit values of percentage of tillers with more than 10 aphids and the average aphid density, thus average density is again determined by a reliable and simple sampling technique. The next criterion is that the pest and disease management systems have a sound biological basis. A system that is based purely on empirical data may prove reliable for some consecutive years but may be unreliable when conditions change.

For this reason, biological knowledge on for example, the rates of development, reproduction and mortality of the pathogen should be combined with knowledge on its relation with its host plant and its natural enemies. It seems self-evident that a pest and disease management system should also be reliable, but very often the absence of well defined experiments to test the value of the recommendations makes independent judgement impossible. Thus, pest and disease management systems should be tested thoroughly in experiments in different regions and under various conditions before it is introduced into practice. Participation in a management system should not require time-consuming monitoring and observation by the user, since then the cost/benefit ratio of the system is too great and its use is limited. For this reason, simple, low-labour-consuming monitoring techniques and short decision processes, simple decision rules and fast communication between user and the extension service or other advisers should be guaranteed.

A warning and monitoring system should not be considered as a separate crop management activity, but must be compatible with other management activities since a combination of activities and observations limits costs and makes its use more attractive. For this reason, pest and disease systems should be designed such that activities can be easily combined. Since biological systems are subject to change and our knowledge of them is still growing, the criteria for spraying, the observation techniques and the control measures may change with increasing insight into the crop system and the prevailing pests and diseases. To guarantee a rapid adaptation of the system to this increased insight there should be close connection with research teams or, even better, these development experiments should be done by the supervisors of the system. The final decision to introduce the crop management system should be based on a cost/benefit analysis with appropriate consideration of the environment. The costs of running the system should, therefore, be as low as possible; this is promoted when a complete crop protection and management system is offered. The basis of the decision to introduce sophisticated pest and disease systems will be different for each situation.

Strategic methods do not obey these criteria and have a much wider application. They should result in some alternative policies and help in that way to decide which objectives can reached. Both, strategic and tactical methods include three main features: monitoring; forecasting; assessment of damage levels.

6. MONITORING

The simplest monitoring method is to make direct observations of the harmful organism at regular intervals. Although that method may give a good impression of how the pest or disease develops, its costs are high. Too often a farmer is asked to inspect his field, frequently without his understanding of what he is observing. Systems like that are in use in many crops but will probably evolve into one of the more advanced approaches discussed below.

A system in which some field observations are replaced by suction, pheromone or other trapping methods is available in some crops and for some specific insects. The reliability of those methods is low but sufficient to warn the farmers to start inspection of their fields, and in some cases even to recommend spraying. Methods using suction traps or pheromone traps have to be complemented with field observations, since these traps measure only activity, which is not always correlated with actual density of the harmful organism. An extension of the suction trap or pheromone trap system is the phenological recording system. The suction trap and pheromone trap catches are then combined with calculations of when and at what rate the pest population will develop so that warnings may be given in advance. The development rate of the harmful organism is assumed to be linearly related to the temperature above a development threshold. The actual development stage of the pest can be expressed as a temperature sum. In many cases, however, it has not been established whether development really is a linear and instantaneous reaction to temperature. However the wide application of physiological time and temperature sums in warning and forecasting systems indicates that these systems can be useful. Although the biological basis for these systems is narrow, they still form the most developed monitoring system for classical pest control. The system can be run without use of computers or other sophisticated technological equipment and needs only a low input of biological knowledge. Other examples of systems in which early observations of the harmful organisms are combined with field sampling are in use in integrated control of fruit orchards. Another modern system of early observations of pests and diseases involves the use of satellite observations. Examples of use of satellites are found in locust control, and the observations of cloud patterns to predict outbreaks of stemrust in India. The high expectations of many plant pathologists in the 1960s and early 1970s for early detection of diseases and pests by remote sensing methods is now somewhat reduced by the disappointingly low resolution of the instruments, the considerable technical difficulties, and the high costs. The next decade may show better prospects for these monitoring methods but at present their value seems to be very limited. More laborious and technically less sophisticated methods seem to have a better chance for success.

7. FORECASTS

Forecasts in strategic methods are most appropriate for diseases which occur sporadically (Bourke, 1970), whereas in tactical methods disease forecasting is necessary for both sporadically and regularly occurring diseases and pests. The epidemiology of a disease provides a guide for developing forecasts. Comprehensive simulation models may result after sensitivity analysis and simplification in summary models and decision rules which may be used in pest and disease forecasting. Although forecasts have been developed for dozens of diseases, only very few are widely used. Practical examples include apple scab caused by Venturia inaequalis and Stewart's wilt of maize (caused by Erwinia stewartii).

Many growers in the Northeastern United States use forecasts of these pathogens.

Potato late blight (caused by Phytophtera infestans) is probably the most intensively studied plant disease. However, accurate forecasts based on monitoring are still not available. Late blight forecasts were until very recently based exclusively on weather variables. A method of forecasting using host resistance, fungicide effect and weather for scheduling

TABLE 1

Criteria for a tactical pest and disease management system

Simple Monitoring, sampling and decision rules for actions (control measures) should be not too complicated.
Sound biological basis Warnings and recommendations should be based on knowledge of the population dynamics of the pest or disease organism and its effect on the host plant.
Reliable The advices should be based on accurate knowledge of the effect of actions and the decisions should be tested thoroughly.
Labour extensive Participation in the pest and disease management system should not require much monitoring, sampling and communication time.
Compatible The sampling activities and the control measures should be compatible with other crop management activities.
Iterative improvement There should be a continuous recording of some observations and an evaluation of the results so that iterative improvement of the system is possible.
Costs per unit of product Costs to run the system should be in accordance with the value of the crop and the severity of the pest disease, so that a relatively high investment in pest and disease management is avoided.

fungicide applications has been developed by Fry et al. 1983 and is applied in some areas of New York State. This step foreward will probably lead to appropriate tactical disease management systems.

8. INJURY, DAMAGE LEVELS, ACTION THRESHOLDS

The concept of the economic injury levels, or damage threshold, which is required in pest and disease management is defined as the lowest population density that causes economic damage justifying the cost of control measures. When the damage threshold is known and the disease or pest is present, the farmer must know when and how to act; thus we must also define an action threshold which occurs earlier than the damage threshold.

Appropriate control measures should be applied at such a time that the increase of the pest or disease is delayed and the damage threshold is not reached. Knowledge of the effect of spraying has to be combined with detailed knowledge of the development rate of the harmful organism. The

action threshold presumes such knowledge and also presumes that sufficient time exists for control measures to be applied and to take effect before the population reaches the economic injury level.
In ornamental crops, for example, the economic injury is so low that the former criteria of clean and spotless crops are still in use, thus making warning systems impossible. Frequent and close monitoring is needed. The same holds for many short season vegetable crops.

In modern highly productive agriculture the same silly action threshold will lead to preventive overspraying and cause unnecessary costs for the farmer, increasing chances of pesticide resistance, and environmental effects which can be avoided if appropriate injury levels are defined. EPIPRE uses calculated risks, whose accuracy may be improved by appropriate stochastic elements in the forecasting models (Onstad et al., 1984). In this way farmers have the opportunity to choose between risks.

9. CENTRALIZED OR DECENTRALIZED SYSTEMS

Current simple and static supervised pest and disease management systems are all completely decentralized. Written recommendations are used by the farmers and the extension officers. Most computerized management systems, however are still completely centralized. Communication between user and computer is by mail (EPIPRE), by phone (BLITECAST) or by visiting consultant carrying a microcomputer that can interact with the mainframe computer (APPLESCAB).

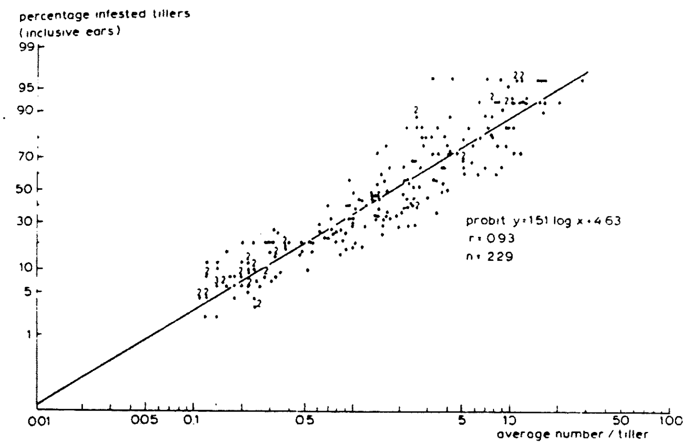
Decentralized computer systems will be implemented before 1990. Some simple computing facilities are now used in the potato leaf blight forecaster BLITECASTER, and the next step will be the installation of the on-the-farm microcomputers which run not only farm administration programs but also crop protection or even total crop management programs. Of course, these micros can be connected with sensors placed in the field. Thus the farmer will expand his diagnostic equipment and feel more independent.

10. SHORT TERM, MEDIUM TERM AND LONG TERM FORECASTING

Both, tactical and strategic methods discussed above have been considered in the context of farmer decision making and are meant for the short term. Norton and Way (1984) distinguish this short term prediction from medium and long term prediction methods.

Robust strategies with population models as used for example, in potato cyst nematode control, are presented by Norton, 1976 and Jones, 1973. Improvement of these models using more detailed explanatory models will lead to medium term strategies for control comprising crop rotation schedules and chemical control methods. Longterm forecasting cannot in the near future improve decisions on the control of either endogeneous or exogeneous pests or diseases. However, the consequences for different strategies may be considerable in the long run. Present day agriculture may become a risky affair if pesticide usage continues to increase since this will probably lead to both plant genetic resistance erosion and unsolvable problems of pesticide resistance in pests and diseases. To prevent this development societal constraints should be formulated which may lead to the development of ecologically sound control measures.

Tc develop sound longterm forecasting methods feasible short term forecast and pest and disease management have to be available and should be developed. Thus short term control systems may be incorporated into longterm pest and disease management.



Average number M. dirhodum, R. padi and S. avenae per tiller versus percentage infested tillers.

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