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Decision models in pest management

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Introduction

Running a farm requires a major managerial effort on various levels of integration. We distinguish the level of the farm and that of the crop. On both levels the overall objective is to ensure a sufficiently large (or maximal) profit in the short term and survival of the farm operation in the long term.

Decisions at the farm level include the choice of crops to be grown, the selling, buying or storing of products and long-term investments in buildings, infrastructural changes or farming machinery. Market situation and expected commodity prices play an important role in decisions at this level. Ecological considerations also have to be taken into account to guarantee the stability and sustainability of the farm and to protect the environment. Constraints at this level consist of public regulations and private considerations on what is ecologically acceptable and sound. Decisions at the farm level set the constraints for decisions at the crop level.

At the crop level the farmer must decide on crop variety and density, and on the timing and methods of seed-bed preparation, planting and harvesting, fertilizer application and control of pests, diseases and weeds. Even in a relatively easy-to-manage crop like wheat this amounts to some 100 decisions from sowing until harvest. The majority of these decisions are based on experience and expectations, supplemented by insight supplied by agricultural research.

During the last decades quantitative knowledge about the consequences of particular decisions has grown tremendously, which has led to explicitize decision making and its rationale, rather than rely on the intuition and experience of the decision maker, farmer or adviser only. An important part of this complex decision making concerns crop protection. This part of farm management requires much biological knowledge and agronomical insight, which is increasing rapidly.

Expressed in labour or capital input, crop protection is a relatively small component of crop production. Crop protection measures, especially chemical control of harmful organisms, have a major effect on public concerns such as susceptibility of noxious organisms to pesticides and a clean environment. As such crop protection assumes an important place in agricultural management.

Since its introduction on a large scale half a century ago, chemical control has become a major component of crop protection measures. Decisions to spray occur at the end of a chain of decisions resulting in a certain crop in a certain field. No feedback exists with decisions on e.g. nitrogen fertilizer application which strongly affects the occurrence of economically damaging levels of pests and diseases. Crop protection has long been regarded as the carpet previous decision errors can be swept under. A decrease in the efficacy of chemicals due to resistance in target organisms and deleterious effects of pesticides on non-target organisms have led to a reconsideration of the aims of crop protection and its place in the decision hierarchy. Today the notion that a potentially high yielding crop can be devastated by a pest or disease and, on the other hand, that a crop with low yield expectation due to water and/or nutrient limitation cannot be made a high yielding one by spraying, are both accepted by researchers and,

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to a lesser extent, by farmers. Crop protection is developing into an integrated part of on-farm decision making in which various objectives such as maximum returns and minimal pesticide input have to be attained within the constraints dictated by the society and the environment.

In this article we will discuss the problems involved in pest management decisions and indicate how operations research may be employed to determine the best decision options.

Crop growth and production

Crop growth, or the increase in the quantity of dry matter, is expressed per plant in individual plants and on a per unit area basis in crops. The most important factors influencing plant growth are temperature, radiation, humidity, wind speed and CO_2 concentration in the air. When factors such as nutrients and water are abundant, and damaging factors such as pests, diseases and weeds are absent, the 'potential growth rate' is achieved. This rate is determined by the optical, geometrical physiological and phenological characteristics of the crop and the prevailing weather conditions. Computations confirmed by experimental observations have shown that under these circumstances production reaches values between 15 and 25 tonnes dry matter per hectare per growing season. In glasshouse crops potential yield levels may be reached because environmental factors such as temperature, CO_2-concentration and light intensity can be manipulated. However, the lack of detailed knowledge on the processes determining the growth of these crops limits the fine-tuning which is technically possible. Computerized systems for the control of glasshouse environments have been developed, to a large extent, from rules of thumb rather than by optimization procedures in which explanatory models of the effect of decisions are used.

In protected crops grown in glasshouses potential yield levels may be reached. This, however, is rarely on never achieved under field conditions. The difference between potential and actual yields is very large. More than 99% of the world's agriculture is carried out under conditions in which at least one growth factor is limiting. Water or nutrients or both are not at optimal levels, so that growth during parts or all of the growing season does not reach its potential level. A considerable part of the crop production in the world takes place at minimum yield levels of 800 kg grain equivalents per ha. In Table 1 four production levels are distinguished and some characteristic production values are given. For these computations a typical transpiration coefficient of 300 kg transpired water per kg dry matter produced, and minimum nitrogen and phosphorus levels of 1% and 0.05%, respectively, were assumed. The levels of production indicated in Table 1 are merely rules of thumb. In practice many other situations may be encountered.

Agricultural production in historical perspective

Agricultural production requires both an understanding of the biological processes involved

Table 1
Four production levels (after De Wit and Penning de Vries, 1982)

Production level (situation)	Limiting factor	Growth rate × period	Total dry matter production in a growing season, under Dutch conditions
1	radiation (growth rate) and temperature (length growing period and weather)	200 kg $ha^{-1}d^{-1} \times 100$ d =	20.000 kg ha^{-1}
2	water: e.g. 300 mm available transpiration coefficient 300 kg H_2O kg^{-1} dry matter	ca. 200 kg $ha^{-1}d^{-1} \times 50$ d =	10.000 kg ha^{-1}
3	nitrogen: e.g. 50 kg N ha^{-1} available. lower-limit nitrogen 1% N		5.000 kg ha^{-1}
4	phosphorus: e.g. 1.5 kg P ha^{-1} available. lower-limit phosphorus 0.05 % P		3.000 kg ha^{-1}

and use of external resources. External resources are needed on the farm level (water management, mechanization) as well as on the crop level (seeds, fertilizers, pesticides). Some farmers with 'green fingers' are able to reach high production levels without physiological and agronomical knowledge. Others, however, make wrong decisions, or time them wrongly. The development of the knowledge required to improve agricultural production, and the formulation of new perspectives, are the major tasks of agricultural research.

What has been achieved through a combined effort of research, education, extension and, last but not least, farmers' initiatives is illustrated by the increase in wheat production per unit area in the Netherlands since 1850 (Figure 1). There has been a continuous increase in yield, with a shift in the rate of increase at two points in time. The first point, at the beginning of this century, resulted from the introduction of new cultivars and artificial nitrogen fertilization. The second occurred just after World War 2 in the Netherlands, but also in other parts of Europe and the United States and can be characterized as an unrecognized green revolution. It was a consequence of advances in several areas. Plant breeders introduced short-straw cultivars developed by Heine during the second World War; nitrogen fertilization and its application were improved by plant nutritionists; herbicides (and later insecticides and fungicides) were introduced by crop protectionists.

The enormous increase in wheat yields was accompanied by an increase in labour productivity, due to mechanization, and increased use of the newly available fertilizers and biocides. Around 1900 the production of 1 tonne of wheat required 300 man-hours, whereas in intensive modern agriculture the same amount of wheat requires no more than 1.5 man-hours. The amount of pesticides used in wheat production in the Netherlands increased from a zero level in 1950 to an average of 3.5 sprayings ha^{-1} in 1985.

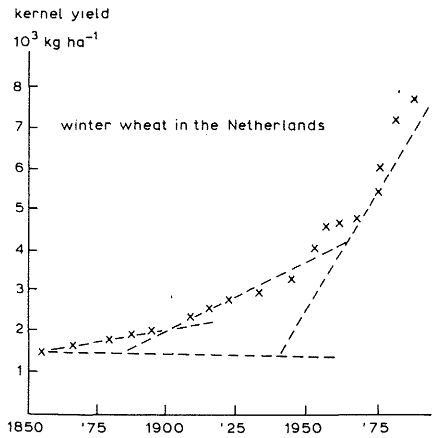

Figure 1. Average yield of winter wheat in kernels (kg dry matter per ha) for the Netherlands from 1850 to 1985 (after Rabbinge, 1986)

Growth reducing factors and pest management

Weather, crop characteristics and water and nutrient availability determine attainable yields, as indicated above. Actual crop yields may be lower due to pests, diseases, weeds and air pollutants. The effects of such growth reducing factors may vary considerably between crop production levels. At high yield levels the competitiveness of a crop relative to weeds is generally high, and control of weeds is relatively unimportant. In contrast, pests and diseases are usually more important at high than at low yield levels, because the improved condition of the crop and the micro-meteorological conditions prevailing in a dense crop render it favourable for pests and diseases.

Modern crop protection makes use of various techniques to control pests and diseases. Agronomic measures such as plant breeding and crop rotation form the basis, and these are supplemented by biological control methods, sophisticated techniques involving the use of sex phermonones and sterile males, and a variety of specific and general chemical compounds. To prevent the build-up of resistance in the target population, and to limit public costs associated with a deterioration of the environment, pesticides should be used only when other methods have failed. The decision criterion used in pest management is called the economic injury level (EIL). It is defined as the pest density or pathogen severity at which the costs of control equal the costs of the expected yield loss when no control measures are taken. Some time before this economic injury level is reached, control measures should be taken. The density or severity at which that should be done is called the action threshold. EILs vary with time during the growing season and, as argued above, with the state of the crop. EILs may be calculated by regression analysis of experimental data in which a relation between pest density or pathogen severity and yield loss is established. The drawback of regression analysis is that extrapolation outside the range of experimental conditions, e.g. water and nutrient supply, is not advisable. Simulation modelling, in which phenomena on the system level are explained by integration of descriptive knowledge on the process level, provides an alternative approach. The complexity of interactions between crops and pests makes simulation modelling a useful technique in the determination of dynamic economic injury levels; field experimentation alone is definitely not enough.

In most crops more than one pest or disease can be economically damaging at the same moment. The severity of damage and the possibilities for control vary among organisms. In a pest management model the effects of alternative decisions on the state of the system are described. These descriptions may result from regression analyses of experimental data or simulation studies. The objective function most commonly encountered is minimization of costs or maximization of profits. Dynamic programming has been found to be a suitable algorithm for determining optimal solutions in this type of pest management models (Shoemaker, 1973, 1981). The applicability of the optimal set of decisions generated by the model strongly depends on the quality of the biological information condensed in the transformation function.

Onstad and Rabbinge (1985) have shown how the EIL could be calculated with dynamic programming in a management model for cereal aphids and yellow rust in winter wheat. Using this technique, they identified the two discrete values of the state variables between which the decision changed from no treatment to biocide application (Figure 2). They also showed the power of dynamic programming by comparing the number of calculations required with the optimization algorithm to that required in exhaustive simulation of decisions.

There are however two important limitations to the use of dynamic programming in crop protection. Computation is feasible only when the number of state variables does not exceed 6 as a rule of thumb. Secondly, the damage function that relates yield loss to pest density must be capable of being calculated with a time step less than or equal to the length of a decision stage (e.g. daily or weekly basis). Both these problems can be overcome by lumping state variables and by simulation studies.

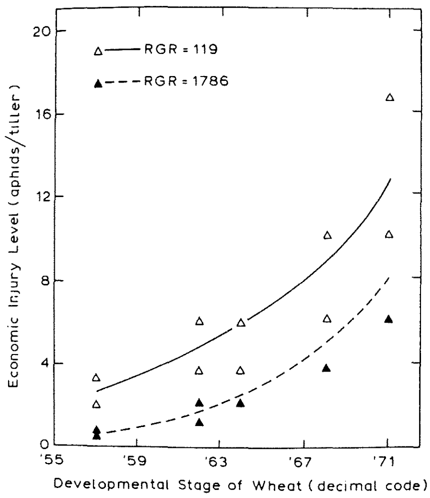

Figure 2. Economic injury level of cereal aphids on wheat as a function of developmental stage. EIL's are also influenced by assumed value of relative growth rate of aphid population. Dots represent ranges in which EIL's exist. Results are based on average conditions for the Netherlands

Future prospects

Dynamic programming seems to be the most appropriate method for optimizing decision making when decisions are mutually dependent and separated in time. Non-linear regression techniques may suit the same purpose but have seldom been used. Apart from static problems like storage of pesticides, linear programming does not apply to crop protection measures during the growing season. There is, however, a bright perspective for interactive, multiple-goal linear programming techniques when various, often conflicting aims, must be realized.

At present the use of operations research techniques in crop protection is limited to research. Cases studies are restricted to crops with one or two pests or diseases. No effort has been made to cover all crop protection aspects of a crop. But the number of publications of agronomists using optimization procedures seems to be increasing. The problems encountered are similar to those of the first decade of simulation modelling: most of the data collected to date are not suitable and the state of the art is still in its infancy. With more researchers becoming aware of the potential of these techniques, their development and application will increase.

Chemical control of pests and diseases was and will remain an important issue for optimization. Optimization procedures, combined with simulation models, may provide new insights into control possibilities. Not every disease can be controlled after it has invaded the crop. If no curative chemicals exist, spores have to be killed when they land on the crop and chemicals have to be applied preventively. This often results in a strategy where spraying is carried out after a fixed period of time has elapsed. Optimization procedures may be employed to identify weather conditions suitable for disease invasion: this is called 'negative prognosis'. Spraying when no disease is present can thus be prevented. In these systems the periods of risky weather are identified and the presence or absence of the disease is not considered. In other cases the disease may be controlled after it has infected the crop. With sufficient information available on the dynamics of crop, disease and chemicals, systems may then be developed based on cost-benefit analysis.

With sufficient biological information optimal strategies or tactics for explicitly defined objectives can be devised, possibly including an acceptable level of risk or a certain amount of yield loss. Where risk factors are involved, stochastic techniques may be used to fine-tune the decisions to reflect risk attitudes (Rossing, 1987). The decision maker would then be able to make his choice explicitly on the basis of calculated risks and costs, rather than by intuition, belief or conviction. However, the lack of suitable agronomical and biological information limits application of optimization techniques. Algorithms are available, but the facts and figures have still to be determined.

Operations research may contribute to agronomic research by indicating where gaps in our knowledge exist. It may also help to define in advance the desired level of certainty in decision making, for example by quantifying sample size, and sample frequency needed in monitoring, or by defining the minimum efficacy required of a pesticide or other control measures. These applications of optimization techniques are based on dynamic programming. The increased tendency to formulate more goals than profit maximization alone, will open a new field of application. Multiple goal planning techniques have been widely used in economic studies and are becoming more and more common in agricultural studies. They may be used at the regional level to optimize alternative ways of reaching various explicit objectives, such as an increase in the financial value of agricultural production, maintenance of employment in agriculture, nature conservation, minimization of environmental side effects and food production. Such analyses have been carried out in regional development studies in developing countries (Van Keulen and De Wit, 1987), or as a way to schedule infrastructural changes in developed countries (Bakker, 1986). Multi-objective programming has also been used to design policies for future development, for example the integration of agriculture and forestry (Mendoza et al., 1986). In these studies objectives and constraints are defined in advance. When the order or priority of objectives is an important part of the study, interactive methods are more appropriate (Spronk, 1981). Direct assessment by decision makers of optimal policies for interactively chosen objectives and constraints results in a consensus on the optimal policy. Conflicting objectives at the crop level such as short term maximization of profits, long term stability of production and minimization of pesticide and energy input may be brought into agreement using these interactive, multiobjective programming techniques.

The time scale for which policies are developed usually determines whether the programming exercise is tactical or strategic. Dynamic programming is a useful technique in tactical decision making for pest management during the growing season, whereas long-term farm management strategies, including levels of mechanization, fertilization, crop rotation and crop protection, should be designed using multi-objective linear programming techniques.

Conclusions

The prospects for the use of optimization techniques in pest management are bright. The increasing need for intelligent strategies for pest management which take into account the multiple objectives and constraints makes the use of optimization algorithms indispensable. These techniques may also play a major role in the research phase. Integration of such techniques with biological research, however, requires biologists with a mathematical nature or mathematicians with a biological feeling. The scarcity of these hybrids and the limited availability of sound quantitative data limit their present use.

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