COMPUTER-METHODOLOGY FOR DESIGNING PEST SAMPLING AND MONITORING PROGRAMS

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Abstract

This paper evaluates two distinct enterprises: (1) an ongoing attempt to produce an introductory book plus accompanying software tools on sampling and monitoring in pest management; and (2) application of the modelling approaches discussed in that book to the design of monitoring methods for European Red Mite in North America.

1. Introduction

Monitoring of pests over part of a growing season is often required to schedule interventions (biological, chemical or other) at the right time. To minimise sampling effort in monitoring programs, risks of a too late detection of damaging outbreaks must be balanced against the labour costs of frequent intensive monitoring. We developed a structured, simulation-based approach to design monitoring programs, which allows for a much wider exploration of management options than is possible in field-based studies, and which complements and supports an empirical approach by practitioners. In the simulations, the performance of candidate monitoring approaches is calculated by 'applying' them to computer generated stochastic population trajectories which are representative for pest dynamics in the field. The results of those simulations are summarised in a set of performance indicators. Such indicators include the probability of intervening, the number of samples in time and the size of those samples, as well as the damage caused by the pest and its density when the necessity of an intervention is 'detected'. Prototype monitoring programs with desirable performance in the simulations are tested in the field. The simulation approach has been successfully used to design monitoring programs for European red mite in apples under North East American conditions. By simulation we discovered possibilities to use higher actions thresholds, smaller sample sizes and longer sampling intervals than practitioners thought were feasible. Hence, the number of interventions and sampling effort could be reduced, with savings in costs while conserving natural enemies. The associated (small) risks were calculated. The methodology is widely applicable. User-friendly software tools are under development.

While our research focuses on the relatively unexplored area of monitoring, we work at the same time on a book and accompanying set of software tools that has a wider perspective. The book and software tools include basic sampling methods for decision making in pest management. These software tools are primarily aimed at researchers, to develop prototype sampling and monitoring protocols, and at students who want to become proficient in decision making for pest management. Therefore, researchers and

Proc. 5th Int. Symp. on Comp. Mod.
Eds. Wagenmakers, Van der Werf and Blaise
Acta Hort. 499, ISHS 1999 - IOBC/WPRS Bulletin

well-informed extension specialists are the 'users' of the methodology. The end-users are the people who use the resulting protocols for practical surveillance in the field, such as scouts and growers. Our work gives therefore decision support at two levels: (1) the level of the scout in the field; and (2) the level of the designer (pest extension specialist) of sampling and monitoring protocols. When we address questions on decision support, we will most often answer them from the viewpoint of the extension officer.

Our work on sampling and monitoring cannot be easily classified as 'Research' or 'Decision Support' oriented; it can be viewed either way, and either way gives interesting and different perspectives on the usefulness of the approach. We therefore answer both questionnaires. We will first address the list of questions asked in the framework of Decision Support Systems (DSS). Further below, we address the questions asked in the framework of Research Models.

2. The DSS outlook

2.1. Problem context

From whom does the initial idea for this DSS originate? Cornell University (New York State) has responsibilities for research, education as well as extension. The New York State Agricultural Experiment Station, which resorts under Cornell University, specialises in research and extension in horticultural crops, including fruits (apples and grapes) and vegetables. Growers influence the programs of the station, as members of the planning boards. Integrated Pest Management is a major work area within the Department of Entomology, and work on sampling is an inextricable part of IPM.

To which problem is the DSS expected to be an answer/solution? The software tools are meant to allow researchers (and well-educated extension specialists) to design tailored sampling solutions for specific pest problems. The software allows integrating information on pest distribution, action threshold, and desired performance of the sampling method, acceptable and unacceptable risks, and sampling effort into a practically feasible sampling design.

Who is the 'problem owner'? There are problems and problem owners at two levels. At the one level the problem is how to set up a reliable and feasible sampling or monitoring scheme for use in practice under a variety of conditions. Here a researcher or extension specialist is the problem owner. At the crop level, the scout or grower is the problem owner. His problem is to take a correct management decision. He has to match effort and risk. Scouts and growers are generally not that interested in how a protocol is developed, only that it meets certain requirements of time and precision and even these are only vaguely understood and expressed.

Is the problem 'permanent' or 'once only'? Sampling is a recurring problem (or business) for a scout or pest management advisor. The design of a practical sampling method is in a sense a unique undertaking, because the sampling protocol, once developed, may be further developed in practice. However, as value judgements and perceptions change, the expectations about the performance of a sampling method may change, and hence it may require to be 'redesigned'.

2.2. Strategy

How is DSS expected to contribute to problem solving? The concept behind the DSS is that sampling may be simulated as a stochastic process. By repeating the simulations many times, an overview can be made of the 'overall performance' of the method by giving the distributions for a set of performance indicators. The performance depends upon the design parameters of the sampling method, e.g. the 'type' of protocol (e.g. fixed sample size, sequential sampling), the maximum sample size one is willing to collect, a threshold density, the distribution of the pest over sampling units, etc. Performance indicators are first of all the *operating characteristic (OC)* and *average sample number (ASN)* functions, which give – as a function of true pest density – the probability of *not intervening* and the *average number of sample units* that must be collected before a decision is taken. Measures of risk and effort can be derived from those primary performance functions. The main contribution to problem solving is that a clear link is provided between desired performance, biological properties of the pest (e.g. its distribution) and the sample plan parameters.

Which stages of learning, decision making or problem solving should be supported? The methodology supports the design process of sample plans, i.e. the initial steps towards formalising a decision process for the grower or pest consultant. Researchers and extension specialists, who use the design tools, are the main target group for learning. Secondly, the end-users, using tested sampling approaches under field conditions, have a learning experience, partly because the sampling and monitoring guidelines are provided with up to date information on the biology of pests and pictures of their life stages and injuries.

What is the input required and output furnished by DSS? At the design stage, required inputs are action thresholds for pest density, information describing the distribution of the pest over sample units, and desired performance (sample number and OC function). Under field conditions, the only information that is required is a chart or table with decision criteria and sample observations.

2.3. Means

Why has DSS been chosen as a tool to help solve the problem? The relationship between the parameters of a sampling protocol and its performance can be derived using statistical theory and stochastic simulation approaches which are too complex to 'write on the back of an envelope' and solve in a short-cut kind of way. Mathematical tools are needed to perform the underlying mathematical analyses and calculations. With the advance of modern fast personal computers and sophisticated mathematical software with a friendly user-interface, the stage is now set to provide the mathematical and simulation technologies to users.

What other and/or competing means are available to users? The main alternative to using the proposed structured approach to designing sampling plans is to proceed by trial and error, and evolve methods in practice. Such an approach is not basically unsound, but entails the risk that sub-optimal solutions are the end product and that implicit or hidden objectives guide the process. Moreover, the resulting product may not be easily transported to different conditions, because the boundaries within which they are valid may be unclear. At the other hand, the design process on the computer can result in a theoretically optimal product, which is practically not feasible or incompatible with other practices or grower's objectives. Therefore, field evaluations and computer explorations are complementary rather than competitive. An asset of the design approach using computer tools is that all the objectives and constraints are made clear in the process. This promotes awareness among researchers, consultants and other practitioners. For instance, when we made simulation analyses of thresholds for monitoring and control of red mite in apples, we realised during the simulations that one of our restrictions was that mite density should never be above 15 mites per leaf at the time an intervention was scheduled, because the age structure and persistence of such high density populations would hamper effective control. This restriction was 'built into' existing thresholds, but at first we did not consider this and based our threshold calculations only on damage relationships. Hence, we became more aware of the multi-faceted nature of the decision problem.

What is the added value of the DSS vis-à-vis other means? The computer simulation approach offers a sound theoretical underpinning, and allows running fast and cheap tests of alternative approaches that would be impossible to execute in the field.

How complex are the models on which the DSS is based? The statistical and stochastic models that are used are simple in a mathematical sense. Few variables and parameters are considered.

Are concept and operation of the model easy to understand for users? The details of the methods will be difficult to understand for users without a good grounding in mathematical statistics; however, the global results of the software tools should be accessible for interpretation. Nevertheless, the outcomes of simulations of sampling processes can be counter-intuitive and not so easy to understand. This gives in fact a strong argument for running such simulations! It shows the need for learning.

2.4. Targeting

Who are the prospective users of the DSS? Researchers with a task in extension.

Which sub-categories of users exist? Students of pest management courses at universities.

2.5. Organisation

What training activities have been carried out to make users familiar with the DSS? The software tools will be included in university courses on decision making in pest management.

What other support services are available to users in working with DSS? None.

How much money must users invest for gaining access to appropriate hardware and software? The situation on the soft- and hardware market is rapidly changing. As of June 1999, the expectation is that the tools (MathCad electronic books) will be placed on the World Wide Web at no cost, or a low service charge. MathCad, a sort of sophisticated mathematical spreadsheet program, is required to read those electronic books and run simulations. A powerful demo version of MathCad is available on the Web free of charge (www.mathsoft.com). MathCad runs under Windows95 on Wintel PCs.

On whose co-operation does the success of the DSS crucially depend? Success depends on the need of users to explore the theoretical performance of proposed sampling methodologies, and the ease of use and accessibility of the software. In addition, effective communication of the availability of the software is required.

What activities are carried out to assess whether or not the DSS must be updated? The DSS as we are developing it, is a set of tools (incorporated in an electronic book in MathCad) to design and evaluate sampling protocols. Updating may be required on the basis of user response. Sampling protocols developed using the DSS, may require regular 'redesigning' as the position of sampling in the context of whole crop management changes.

Who is responsible for updating the DSS? The authors.

How often has the DSS been updated? The current development of the design tools as an integrated MathCad electronic book is an innovation upon earlier – more limited – tools, developed in FORTRAN (Nyrop and Binns, 1991; Nyrop and van der Werf, 1994).

Are there any bottlenecks in updating the technology? The main bottleneck will be research money (i.e. time) and maintenance of a critical number of competent staff at research institutions. Changing research priorities, away from agronomy at the field level, and short-term allocation of research funds appear to constitute a threat.

2.6. Development process

Who have been directly involved in the development of the DSS? The main proponents of the theoretical work relating to sampling are Binns and Nyrop with publications in this area for more than a decade. They worked closely in co-operation with specialists on the control of specific pest-crop problems. Many of the theoretical advances were included with little delay in the yearly Pest Management Recommendations by Cornell Co-operative Extension (Anon., 1998).

What software development method was used? We did not follow a specific software development method. The basic structure of each 'chapter' in the electronic book is: Introduction, Input Parameters, and Results. The software program MathCad provides an interface for combining text, mathematical simulations and graphical presentation of results in a single environment.

Did development start from scratch? Developments in MathCad started from scratch, but calculation and simulation methodologies were reprogrammed with guidance from statistical literature and existing FORTRAN code.

How long did the development process last? For the MathCad electronic book: three years (1996-1999); for the earlier tools in FORTRAN: decades; for the original statistical and mathematical theory: centuries.

How were prospective end-users involved in the development process? They were not involved in the development process, other than through informal personal contacts in the frame of Cornell Co-operative Extension. End-user feedback can be obtained by active soliciting, and it does not come voluntarily easily. Users of development tools, such as extension specialists are involved more directly, due to co-operation within the New York State Experiment Station, where the decision guides are both developed and communicated to practice.

What forms of user and/or market research have preceded the development process? There was no user or market research.

2.7. Experiences

How widely has the DSS been adopted by the prospective users? Numerous well-designed sampling plans are available to growers and scouts (Anon., 1998). The new environment for developing sampling and monitoring guides, a DSS for applied researchers and extension specialists, is not yet readily available. It is planned to be available in the course of 1999.

How long do users use the DSS? Do they continue to use it, or do they discontinue their use after a while? The information in the Cornell Cooperative extension package is being updated and upgraded continually and keeps up with the demands of the market. Agnello et al. (1994) report that about 35% of 35 growers who had been trained to use a mite monitoring protocol developed by Cornell Cooperative Extension, continued to use it without modification. Another 60% monitored mites, but modified the protocol, usually by taking fewer leaves when they thought they could already predict the outcome. The remaining 5% abandoned the scouting procedure.

What unexpected forms of use have occurred since the introduction of the DSS? None.

Has the DSS been formally or informally evaluated? An evaluation of the adoption of decision support tools for insect pest management in 1993 was reported by Agnello *et al.* (1994).

3. Research model outlook

3.1. Identification of model and author(s)

This paper is not about a single model, but rather about a methodology, a way of thinking, as well as about a set of new tools to put that methodology into practice. The methodology will be published as a book with an accompanying electronic version on the World Wide Web. The provisional title is: *Sampling and monitoring in crop protection; the theoretical basis for designing practical decision guides.*

When arthropod pests (insects, mites) occur in annual or perennial field crops, season long surveillance may be required. To check the state of the system, a grower (or scout or pest management advisor) needs to go into the crop, collect a sample, and make a decision on pest management on the information contained in that sample. We assume that some kind of corrective intervention is possible, otherwise sampling makes no sense. That corrective action may be a pesticide application; it may also be a natural enemy release or a cultural action. We therefore refuse to see sampling as the bandwagon of pesticide spraying (although for judicious pesticide use, sampling cannot be dispensed with!). Sampling through time is monitoring. We make distinction between sampling and monitoring because monitoring has a time dimension which sampling lacks, with important consequences for the underlying design methodology.

3.2. Purpose of the model

The purpose of the research on the theoretical underpinnings of sampling and monitoring in crop protection is to strengthen the justification and appropriateness of sampling approaches used in practice. A theoretical approach helps to clarify objectives and means of sampling for pest management and ascertain that the chosen sampling or monitoring protocol has the expected performance and is the optimal approach in view of the objectives of management. A theoretical approach contributes to reducing the reliance on pesticides for pest control by explicitising risks. Practitioners may be more willing to accept risks if these can be quantified. Risk acceptance helps to increase pest density action thresholds, which lowers pesticide usage, conserves natural enemies, and contributes therefore to a more ecologically sound practice of crop protection.

3.3. Application area of the model

The prime objective of research on sampling methodologies is to develop more effective and efficient protocols for end-users: scouts, pest management advisors and growers. These protocols take into account both the growers objectives of sampling cost and risk of pest damage as the more public objective of reduced intervention with chemical products and restoration and conservation of natural enemy communities. Improved insight in the workings of sampling methods is an additional benefit that helps in designing methods for other systems. The modelling tools are used to derive decision rules.

3.4. Structure of the model

As an example, we summarise the conceptual framework, which was used by Nyrop *et al.* (1994). The methodology for developing and evaluating monitoring methods comprises five steps (Fig. 1).

1. The first step is the construction of a set sampling plans that are used to determine whether intervention is necessary or not. If no intervention is necessary, the time at which the pest should be resampled is indicated. For red spider mite in apples (*Panonychus ulmi* Koch), Nyrop *et al.* (1994) used sampling schemes that decided between immediate intervention, resampling after one week and resampling after two weeks (Fig. 2).
2. Monte Carlo simulation of the performance of each of the sampling plans in terms of 1) the probability of taking one of the possible decisions, and 2) the average number of sample units required to reach a decision (Fig. 3). These two criteria are functions of the true pest density only, assuming that the variance of population density is a function of the mean density. Nyrop *et al.* (1994) represented the sampling distribution of red spider mites over leaves with a negative binomial distribution, using a power relationship between the variance and the mean to calculate the dispersion parameter k.

Calculation of the performance of a chain of sampling plans used over a season to monitor density through time. Performance is calculated by combining the performance criteria of the sampling plans (functions of density) with simulated or observed trajectories of density over time. The performance of a monitoring protocol for a given set of population trajectories is characterised by five criteria:

1. the probability of intervening
2. the cumulative pest density up till the moment of intervention
3. the density at the moment of intervention
4. the total number of sampling bouts scheduled
5. the total number of samples taken in all bouts.

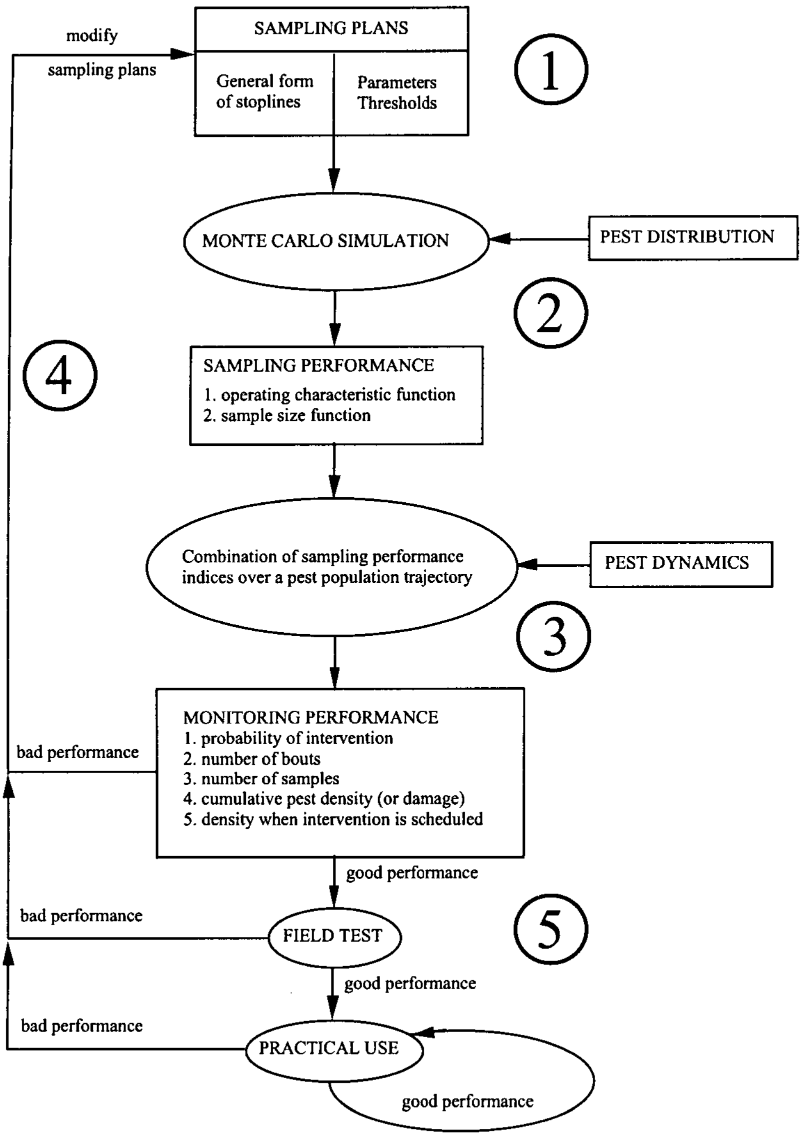

Figure 1 - Five steps in developing and evaluating a monitoring protocol

An example of simulated performance is given in Fig. 4. The overall performance depends on the performance of each of the sampling plans for given densities and on the population trajectorie(s). Monitoring protocols that have good performance for slowly growing pest populations (biological control!) might have bad performance for rapidly growing populations, and vice versa (Nyrop et al., 1994).

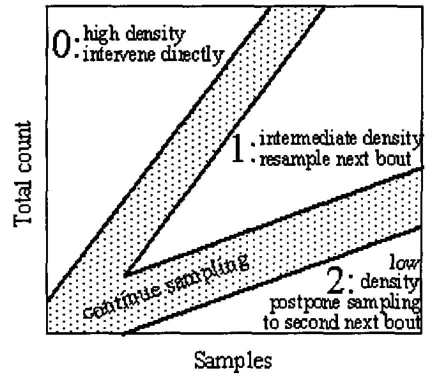

Figure 2 - Protocol for tripartite sequential classification. Leaves are inspected one by one. The cumulative number of 'positive' leaves (vertical axis) is plotted against the running total number of inspected leaves. As long as the point indicating the result of sampling is in the grey areas, sampling has to be continued. As soon as the point moves into one of the three white areas, the result of sampling is reliable enough to take a decision. The decisions are intervene (0), resample at next occasion (1), and resample at second next occasion (2).

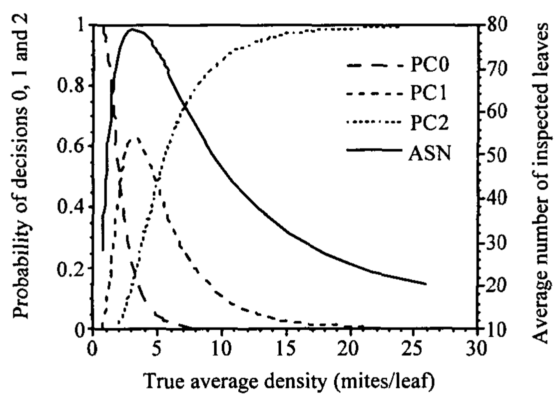

Figure 3 -Performance characteristics of a tripartite sequential classification sampling plan. Left axis: Probability of making one of three alternative Classifications: intervene (0) resample at next occasion (1), or resample at second next occasion (2). Right axis: ASN = average number of leaves inspected before taking a decision.

Next, the parameters of sampling plans constituting the monitoring protocol are varied, in order to identify the set of sampling plans that gives the most desirable performance. Thereby, the performance criteria are weighted by expert judgement.

The best monitoring protocol resulting from the iterative simulation process is tested in the field. If its favourable performance is confirmed, it can be extended to practice. The monitoring scheme developed by Nyrop *et al.* (1994) is currently recommended to and used by New York apple growers and field scouts (Anon., 1998).

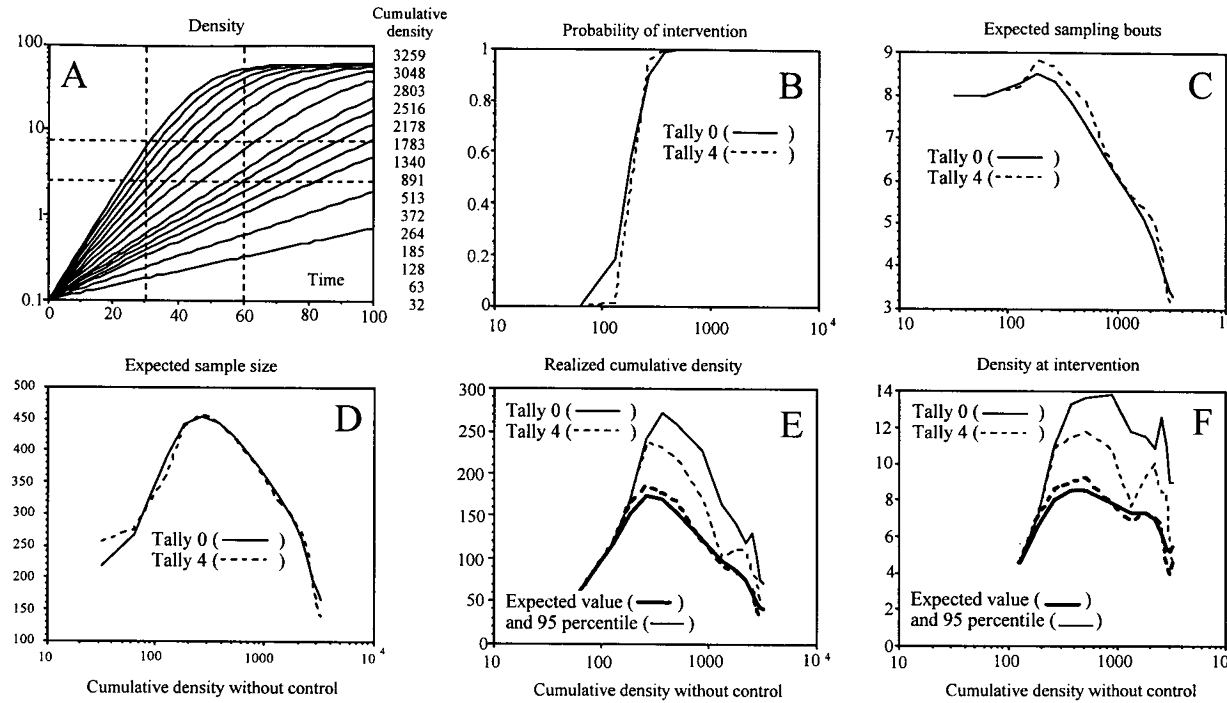

*Fig. 4: Simulated performance characteristics of two monitoring protocols, based on tripartite presence/absence classification, when monitoring mite populations over a period of 90 days. The comparison is made using logistic population trajectories with a maximum level of 50 mites/leaf and differing relative growth rates (A). Both protocols are based on critical densities of 2.5, 5 and 7.5. mites/leaf over the time periods 0-30, 31-60 and 61-90 days. Protocol 1 (**drawn lines**) is based on simple presence/absence monitoring (**tally 0**). Protocol 2 (**hatched lines**) is based on counting leaves with more than 4 mites/leaf (**tally 4**), which yields a more precise relationship between incidence and density, but is more laborious to execute in the field. The performance criteria are: (B) the probability of intervention, (C) the expected number of sampling bouts, (D) The expected total number of sample units, (E) the accumulated number of mite-days per leaf, and (F) mite density at the time of scheduled intervention. Performance criteria are quite similar for the two protocols, except for the 95th percentiles of density at intervention and cumulative mite density. These measures for 'risk' are higher for the less accurate presence/absence based monitoring method. Curves for the 95 percentiles are jagged due to the stochastic nature of the simulations.*

3.5. History of the model code and programming aspects

Versions, programming languages, computer platforms. Earlier versions of some of the software tools were developed in portable FORTRAN code, which could be compiled and executed on a range of computer platforms (including Macintosh computers, mainframes and IBM-compatible PCs). The current developments in MathCad run only under Windows95 on PCs. The existing FORTRAN code is directly available from the authors, while the newly developed MathCad electronic books will be published on the World Wide Web.

3.6. Sensitivity and uncertainty analysis

Sensitivity and uncertainty analysis, by way of simulation, is a main component of the design process (see above).

3.7. Evaluation of the model

Range of evaluation conditions. The only purely biological information that enters the model is the characterisation of dispersion among sample units. In theory, such dispersion may vary extensively depending upon local conditions, weather (rain showers), temperature, quality of the crop, pesticide applications, etc. The performance of sampling plans depends on the true distribution of the pest, and the sensitivity of the protocol to (un)expected deviations from an assumed 'nominal' dispersion model, should therefore always be investigated. The action threshold combines biological and economic information. In a strictly economic sense, the threshold should be decreased when the value of the crop is increased. Likewise, the threshold should increase when due to environmental conditions, there is less damage per unit pest.

Evaluation criteria. Performance indicators fall in two categories: (1) control quality, and (2) sampling effort. An optimal combination of performance indicators can only be determined by a personal evaluation.

Nature of evaluation. The calculation of performance indicators is strictly objective. On the contrary, the judgement of the appropriateness of optimality of a certain set of performance indicators is a strictly subjective value judgement. A bonus of this approach is that these subjective value judgements are brought to the forefront. Hence, following the theoretical design process towards sampling schemes promotes awareness of the 'true' objectives of the person developing the sampling protocol. Discussions with end-users may highlight what the end-user 'really wants'.

Conclusions of the evaluation: validity range. The framework for setting up and evaluating sampling and monitoring approaches is universally valid. For a specific pest problem, the validity range depends upon the variability of the biologically informed parameters of pest distribution and action threshold.

3.8. Usefulness of the modelling exercise

Were objectives reached? Yes. Sampling and monitoring protocols developed with the computer-methodology are included in the Cornell Pest Management Recommendations (Anon., 1998). They are used in practice and improve upon previous methodologies (e.g. Nyrop *et al.*, 1994; van der Werf *et al.*, 1997)

More appropriate approaches in retrospect. Empirical work in the field is an indispensable complement to the theoretical work, but not a substitute.

3.9. Future plans

A book and accompanying electronic book will be published in about a year after the Wageningen workshop.

3.10. Outlook

We expect demand for the book + electronic book at universities with courses in IPM throughout the world.

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