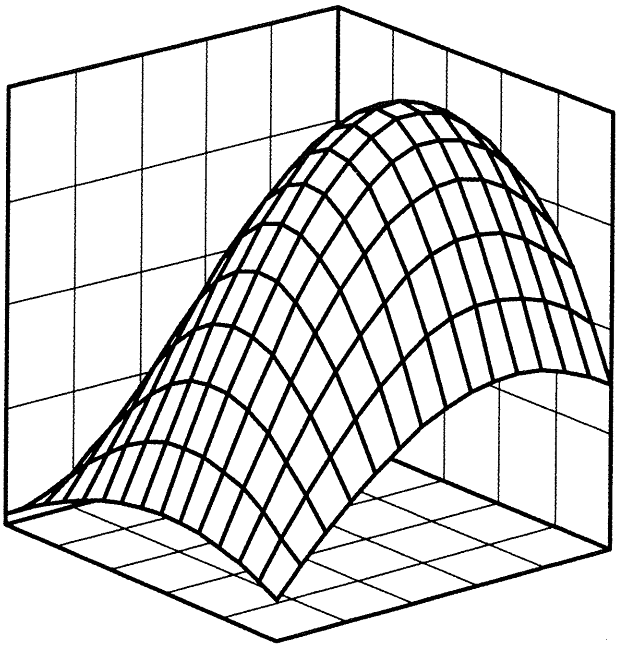
Model-based decision support in agriculture



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Model-based decision support in agriculture

Proceedings of the INRA-KCW workshop on decision support systems, Laon (France), October 1997

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Preface

In spring 1995, Dr. J. Boiffin and Prof. F.W.T. Penning de Vries proposed an exchange between scientists from I.N.R.A. and from Wageningen on the topic of Decision Support Systems in Agriculture. In a short period, this idea was elaborated and turned into a proposal for a meeting. The concrete results of the preparations of the meeting are before you. We hope and expect that this will be another step in the direction of full collaboration with the aim of mutual benefits from broader insights and experiences.

The meeting was held in Laon, on 22 and 23 October 1997. The aim of the meeting was to bring together approximately twenty Dutch and French scientists, who are actively involved in decision support for agriculture and to encourage a broad exchange and confrontation of ideas on related important issues. These include:

- is it pertinent to make a research investment now on decision support for cropping and farming systems?
- what kind of expertise is required to address it properly?
- can we identify categories of management problems that seem most crucial to focus on; what kinds of decision support tool should target on what kinds of user (farmers, extension services, researchers)?
- what kind of knowledge do we need to acquire and formalize in order to provide effective DSS-tools; what types of models are suitable, and particularly what kind of experimental work is required and feasible?
- what methodological approaches (statistical, operation research, control theory, artificial intelligence) are most appropriate for the different categories of DSS?
- what are the important methodological issues of DSS that need full attention?
- what kind of collaboration should be fostered between research teams involved in the subject, extension services and farmers, and how do we encourage that?

We trust that the participants of the workshop, and all other readers of this QASA-issue, will find this overview of the state of the art in DSS interesting and encouraging.

Alfred Stein
Hein ten Berge

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Section I

FIELD AND GREENHOUSE SCALE

DSS for climate control in greenhouses

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Abstract

In greenhouse cultivation the primary objective of climate control concerns control of crop growth. The decisions regarding operation of the control organs have to be taken so frequently that this task is automated. This raises the question of how to distribute responsibilities between the automated control system and the operator in a complex multi-objective, ill-defined environment. This problem touches subjects like model-based, intelligent control systems, interaction between grower and control system and the role of different time-scales.

1. Introduction

Modern greenhouses offer advanced opportunities to influence crop growth, by controlling the root and the aerial environment of the plants (Bakker *et al.*, 1995, Ch. 4). By manipulating the ventilators, the mixing valves of the heating system, the supply rate of CO_2, opening, or closing screens, controlling the concentration of ions in the nutrient solution and the watering intensity and frequency, optimal conditions for the production process may be achieved dynamically. Adjustments of the actuators may be made very frequently, typically every minute, enabling the system to deal with fast disturbances brought away by the variations in outdoor conditions. Obviously we are dealing with a highly advanced growing system, with a great potential for application of scientific principles regarding physical and plant physiological processes and of modern insights on decision support systems, to support the grower in the management of the production process.
Present climate control systems provide functions to automate the fast responses to disturbances caused by the weather, to adapt set-points to variations in radiation and to create the desired diurnal temperature pattern. Yet, correct setting of these systems is a problem for many growers. They often interfere in the settings of their system, even within one day, which may be interpreted as a sign of poor communication between grower and system and/or a lack in flexibility of the system. In fact, it should be realised that modern climate computers are provided with a great number of settings, often hundreds, which makes the operation of these systems difficult. The reasons for these inadequacies are the complexity of the job to be performed, the wide range of conditions (crops, countries) where the systems are used, and the differences in opinion of customers about the way climate should be controlled.
Apart form the user-unfriendly operation present control systems also lack flexibility in dealing with improved knowledge about the physical and physiological principles of the production process. In fact, the rules for adapting set-points to variations in the environment are too

simple (Challa, 1990). However, more flexible rules would put even higher demands on communication between grower and system and hence require more intelligent control systems.
The discussion about climate control and interaction between control system and grower reveals the rather fundamental problems that have to be solved to enable progress in the development of user-friendly, effective and intelligent control systems. The objective of this contribution is to analyse decision making in the context of climate control and to consider the role of the grower and of scientific knowledge, represented by models. To obtain a proper balance between these resources, the decisions involved in climate control will be considered in relation to the time domain and in relation to the need for interference of the grower.

2. Analysis

Climate control is a complex subject: we deal with a time critical process with multiple objectives (Challa & Van Straten, 1993), mostly not explicitly formulated, that are, at least partly, mutually conflicting (either as such, or in the process of realisation, due to the interdependency between different control measures), the greenhouse/crop system is ill-defined (complexity and variability of biological systems) and is subjected to disturbances (weather, pests and diseases, price formation), whereas the performance criteria are poorly defined (Figure 1).

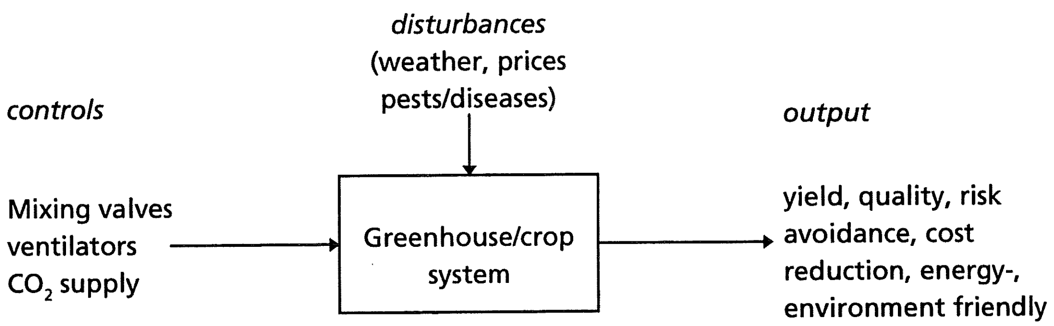

Figure 1. The greenhouse climate control situation: long-term targets are realised through operation of the actuators, while taking the effect of (fast) disturbances into account

To cope with this complexity, growers largely rely on their personal observations of the crop and of the crop environment (they even may use their nose to judge the situation), information from outside (weather forecast and price trends, occurrence of problems in other nurseries, etc.) and the personal judgement and experience to make the right decisions for setting the control system (Martin Clouaire *et al.*, 1996). Observation and judgement are thus all in one hand and in a way this facilitates the decision making process, since there is no need for explicit statements regarding the decision process. Yet, as pointed out before, the majority of the growers experience difficulties in setting the control system properly. The large number of, easily mutually conflicting, settings and the lack of transparency brought away by settings

that affect hard (technical) control tasks and crop performance simultaneously, contribute to this problem.
When we consider the control task in greenhouse production it can be noticed that the relation between actuators and production targets is not straightforward (Table 1). The disturbances brought about by the external climate conditions requires a fast response of the control system, which therefore has to be automated. There is, however, no one-to-one relationship between actuators and climate factors: if we consider temperature, VPD (water vapour pressure deficit of the air) and CO_2 concentration, it is obvious that there is a strong interaction between the control of these factors (Bot & Challa, 1991). These factors, moreover, are not clearly linked to production targets (Challa, 1990). Growers are hardly able to observe the response of their crop over a period of less than a couple of days and in that sense there is some parallel with the control of the mission of the "Pathfinder" at the surface of Mars, where the time required for the images to reach earth is too long to allow safe cruise for more than anything like 10 minutes. After this interval movement is stopped to evaluate the situation and to plan the next trajectory. Obviously this is not possible in greenhouse cultivation: the process continues as long as the culture lasts.

Table 1. Control actions affect climate factors, which in turn affect production processes and final targets. The relation between control actions and targets is obscured because of interactions, no observations on intermediate processes and complex relationship between these processes and the production targets

Actuators	⇒ Climate factors	⇒ Fast crop responses	⇒ Targets
mixing valves	temperature	photosynthesis	yield
ventilators	CO_2 pressure	crop development	product quality
CO_2 supply	VPD	transpiration	harvest time
		damage	crop quality
			expenses / risks
			emissions

The paradigm in our research group is that a good decision is a decision that satisfies the user (Challa *et al.*, 1994). Even if from a scientific point of view a better decision could be made than that chosen by the grower, science has to provide tools, or insights that would lead to a better decision, rather than overruling the user. When considering decisions in diurnal control, it is therefore necessary to settle responsibilities and information exchange between user and machine.
The interaction between grower and system normally should take place only once a day, requiring unattended operation under strongly varying and sometimes hard to predict weather conditions, while leaving full control over the production process with the grower and minimising information transfer from grower to system. A logical principle for separating responsibilities is, therefore, according to domain and to time scale: fast responses should be dealt with by the system autonomously, while the grower should take decisions regarding slow responses. This principle is even more imperative when it is realised that slow responses tend to be crop specific. Given the number of crops encountered in greenhouses, it would not be easy

to provide information able to deal with all, or even most species in a piece of standard software.
Decisions that do not interfere with decisions that should be taken by the grower and that concern domains that are not well known by growers, as a rule should be delegated to the system, like in a car, where the car driver should concentrate on the interaction with other traffic, rather than on technical performance, with the exception of a few, not automated operations. In this situation, the driver has full control over the car's performance while accepting many automated functions at the technical level.
In this context, fast responses are responses that, after one day, could lead to unrecoverable losses, whereas slow responses can be compensated after one day/night cycle, to accommodate the production targets better, for example leaf number, fruit set, plant height, or plant sturdiness. Unrecoverable events are first of all those that cause damage to the crop or the product. Their prevention has a high priority, because these events will cause losses. Also loss of photosynthesis, or growth due to unfavourable conditions cannot be compensated for and should be avoided.
Although this principle is simple, its practical implementation is not, because the same actuators control many, fast as well as slow processes, simultaneously. Moreover, the system requires a great deal of information to take the right decisions, which, in fact, need to be in line with the general policy of the grower. This has very much to do with priorities and risk assessment. Based on this discussion we may now consider a possible solution of model-based control and decision support systems.

3. Model-based decision support

Fast processes, generally not observed by the grower and hard to monitor, but playing an important role in the production process, are crop photosynthesis and transpiration and related carbon and water balance. These are rather generic process that can be modelled for a wide range of crops and that, moreover, interfere directly with the greenhouse climate. Modelling of these processes and those describing the physical behaviour of the greenhouse, together with the weather forecast, provide the basis for optimal control (Challa & Van Straten, 1993). This approach ensures that an optimal path is created for the dynamics of the greenhouse climate factors, provided that the optimisation criterion is formulated properly and in accordance with the intentions of the grower. In this criterion lies also the key to link long-term control, which proceeds under direct responsibility of the grower, with automated diurnal control.
The central issue in this criterion is crop photosynthesis, the motor of the production process. Radiation that is captured from the sun should be converted into chemical energy, enabling the crop to grow. If conditions are sub-optimal, radiative energy will be spilled, leading to loss in yield, that cannot be compensated for later. For optimal performance the value of sugars formed during photosynthesis needs to be evaluated economically (Challa & Heuvelink, 1993), to establish the right balance between inputs and outputs.
Although photosynthesis is an important process, it is clear that many other consideration should play a role in establishing the best control. These consideration should be incorporated in the optimisation criterion. What are these considerations and how could they be incorporated in this criterion? If we would follow the underlying philosophy consequently, we should add models for all the relevant processes and so expand the criterion to its full complexity. This approach, however, would create major problems: there are no, or no good models of many of the relevant processes, and those models may be quite crop specific.

Moreover, supplying and processing all the required information within a time-critical context would be difficult, if not impossible.
Alternatively, a solution may be found where hard or soft constraints, formulated in terms of an acceptable range for states, rates, or integrated rates per day or longer could complement the generic models that represent the hart of the system. These ranges may be formulated in terms of constraints, or expressed by a penalty function. This solution would give the grower full control over the production conditions and complies with the grower's experience. Without precautions, however, this solution would still leave us with a similar number of settings as in the traditional systems.
Models could play an important role in creating a user-friendly interface. The more we can prevent setting of constraints on the climatic factors and replace it by constraints on processes or states, the more transparent the system will be, because there is a more explicit interpretation. The formulation of constraints on daily integrals links the diurnal control with long-term objectives, while the grower does not have to bother with what situation requires what response, since general principles are settled that should work under a wide range of situations.
Setting of constraints is not an easy task, when so many, often conflicting, aspects are interfering and growers definitely would need support for such tasks. This is especially important since it has been shown that constraints play a major role in the performance of optimal control systems (Tap *et al.*, 1997). Models are an important tool to formulate and quantify constraints and to preview how a constraint, release of a constraint, or changing priority of it, would affect the daily performance. Models could provide important feed-back to the grower, showing the predicted diurnal course of climatic factors and the response of the crop, with the settings chosen in a particular situation, as well as the response to a change in settings. The use of constraints would also enable a gradual transition from traditional systems, because they enable set-point control. Growers could learn from broadening constraints, leaving more room for optimality. Using an intelligent controller, the information that needs to be provided by the user could be reduced, because we are dealing with principles, rather than cases.
A question that remains is how this general approach compares with an alternative like SERRISTE, where a DSS is used to facilitate setting of a conventional climate control system (Martin Clouaire, *et al.*,1993). It is not easy to judge what approach would be better, since it is a balance of benefit and effort. However, it may be anticipated that under conditions of major changes, a process based approach has at least the advantage that it should allow for more extrapolation and provides more opportunities for adaptation.

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Planning daily climate set-points for a greenhouse tomato production: the serriste system

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Abstract

SERRISTE is a decision support system that generates suitable daily climatic set-points for greenhouse tomatoes planted in autumn. Scientific and expert knowledge about climate management has been analyzed and formalized in terms of constraints. These constraints express the acceptable values for each variable and the linkage that the biological and physical processes imply between some of these variables. SERRISTE has been tested in the main tomato production areas of France and has demonstrated its ability to operate a greenhouse with the same results as local experts, but at a lower cost.

1. Introduction

The decision levels involved in the management of greenhouse crops can admittedly be separated into three hierarchically linked levels (Baille *et al.*, 1990). Level 0 is the most basic and deals with on-line control, *i.e.* set-point tracking. It is controlled by the level 1 decisions which aim at optimizing the current environment of the crop to maintain it along the path or production plan issued by level 2 decisions. Climate computers commonly found in high-technology greenhouses are in charge of level 0 and require a weekly if not daily update of the set-points. Determining the necessary environment of the crop given its current state and expected outside weather evolution is a difficult level 1 task which can involve conflicting goals and require a good knowledge of both biological and physical processes of the system at hand.

SERRISTE is a decision support system[1] which addresses the problem of finding daily set-points resulting in proper climatic conditions to obtain the desirable production from a greenhouse tomato crop planted in autumn on soil-less media. It has been designed for the main French production locations, namely the Mediterranean (south-east), the south-western and western (Brittany) areas. SERRISTE provides heating and ventilation set-points for temperature control,

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[1] *Strictly speaking, SERRISTE is a deciscion making system since it returns ready-to-apply solutions. It can nevertheless be called a decision support system because the grower is still involved in the decision process. Indeed, he has to, first, provide information about a subjective appraisal of the crop and situation dependent objectives and, second, decide whether or not to apply the set-points generated by the system.*

and minimum and maximum water vapor pressure deficit with the necessary ventilation set-point modifications required to respect these bounds. These set-points are compatible with most of the commercial greenhouse computers. For each day, three sets of such values are produced, to be applied in sequence during the daylight period, the night and the pre-dawn hours, thus accounting for the variations of the plant needs and of the problems to solve along the 24 hour period. The decisions made by SERRISTE aim at satisfying some production goals specified by the grower prior to the search of a solution, while also fulfilling other goals considered as ever present such as sparing expensive inputs. The variable goals include adjustment of the plant vigor, a state of the crop that the grower has to "measure" (evaluate) himself and the prevention of the occurrence of diseases.

In Chapter 2, the knowledge that SERRISTE is dealing with is presented. The principle of its representation and processing in the constraint-based framework is outlined in Chapter 3. A discussion on the development of the project concludes this paper.

2. Knowledge base

The goal of SERRISTE is to find the climate conditions and the associated control set-points which will, by their influence on the behavior of the crop, fulfill the goals at-hand. It operates on a daily basis, and produces a solution which is valid and self-consistent for this day. The necessary inputs are:

- the inside and outside climate of the previous day, which allows SERRISTE to determine how well fitted were the set-points calculated for this previous day and to take the necessary decisions to correct any deviations,
- the current state of the crop (plant vigor, occurrence of botrytis) and the goals for the day (increase or decrease the vigor, take preventive measures against diseases),
- the forecasted weather, defined by the expected irradiance, minimum and maximum temperatures and average wind speed.

Two types of objectives are taken into account by SERRISTE. The first one can be called "permanent", because it is always part of the reasoning. It includes general considerations on the balance between vegetative and reproductive functions of the plant, between assimilate supply and demand so far as growth is concerned. It also includes some goals that correspond to local customizations, as mentioned hereafter. The second type of objectives can be called "situation dependent" and encompasses correction of the vigor of the plants, if need be, or drastic enforcement of climatic measures to prevent the outbreak or the occurrence of diseases. These goals are specified by the grower himself.

The first step in the rationale is to adjust the average temperature to the forecasted irradiance and to the level of CO_2 enrichment. The underlying assumption is that CO_2 and irradiance will determine the total amount of carbohydrates produced during the daylight period and that the temperature is the main factor controlling the rates of respiration and growth which must be adjusted to the available pool of carbohydrates (Seginer *et al.*, 1994). The relationship used is linear but the coefficients depend on the location and on the combination of the date and of the plant age. The values are adapted from the results of previous experiments which showed that the optimal average temperature increases with the available irradiance. The value obtained by this relation is used to determine the set of acceptable values for the 24-hour average temperature, which is also adapted for the cultivar.

The average temperatures for the night and day periods are then defined, considering several rules. Of course, the weighted mean of these two values must lay in the set defined for the daily average. Moreover, sets of acceptable values are defined to maintain a proper balance between the vegetative and generative function of the tomato plant. The day/night temperature difference must also belong to a set with bounds depending on the location and the expected irradiance to balance the dark and light activity of the crop. Finally, the night temperature is split into "true" night and pre-dawn temperatures. The pre-dawn period covers the last hours of the night before sunrise; its length (from 1 to 3 hours) depends on the heating system type and on the age of the crop. Its goal is to prevent water condensation on the plants and to increase their temperature before the light period). Finally, an order relation exists between the three day night and pre-dawn temperatures.

These values are used to determine the corresponding ventilation and heating set-points. The difference between these two set-points for the daylight period increases with the forecasted irradiance but decreases if it is necessary to prevent the development of botrytis. In the mean time, the absolute value of the ventilation set-point decreases when the forecasted irradiance increases. Thus the ventilation set-point is closer to the desired average daily temperature when the light level increases and the heating set-point is smaller, because of the high heat load supplied by the natural radiation. When there are risks of disease development, the set-points are chosen such that they will imply low humidity levels, and thus the ventilation set-point is set closer to the heating one, so that we try to achieve drier conditions without using dehumidification (simultaneous heating and ventilation) because of its high cost. A set-point for the soil temperature is also determined to avoid low values which have negative effects on the water and mineral nutrition of plants.

SERRISTE also determines the low and high bounds for the water vapor pressure deficit (VPD) and the accompanying set-points. The maximum VPD is a function of the vigor of the plants and of an possible climate change. Indeed, a high VPD (due to a bright day) after a period of low transpiration rates (dull days) leads to physiological disorders because the plants cannot meet the climatic demand. Such situations of sudden climate change are observed in the south of France along the Mediterranean coast. The minimum value of the VPD must fit several goals. First, it must be high enough to prevent disease development especially if this goal is reinforced by a statement of the grower. Second, it must ensure a minimum transpiration rate to ensure proper mineral nutrition (van Meurs & Stanghellini, 1992). The ventilation set-point used for dehumidification is based on the "normal" *heating* set-point to which a correction is applied. It also must be below the "normal" ventilation set-point.

3. A constraint-based resolution framework

The knowledge involved in SERRISTE is described by multivariable relationships and by domains of possible values for each variable. Any variable X (especially the average temperatures and VPD), is associated to a fuzzy set $\mathcal{F}_X$: $X \in \mathcal{F}_X$. For example, the daylight average temperature set for young plants of the Recento variety is defined as (2 20 22 4) which means that the desirable temperature T belongs to the set [20 22] but that T may be taken in the set (18 26). The core of the set corresponds to values that are desirable while the support also includes values that the crop can tolerate although they are not optimal if considered in isolation. The relationships are expressed as constraints: $\Sigma_i\, a_i\, X_i \in \mathcal{F}_r$ where a_i are numerical values (possibly adjusted for the current situation), X_i are variables and $\mathcal{F}_r$ is a fuzzy set. Thus, the day/night thermal amplitude,

ΔTdn, must satisfy: $\Delta Tdn \in (0\ \Delta Tdn_n\ \Delta Tdn_x\ 0)$ where ΔTdn_n and ΔTdn_x are the lower and upper bounds, respectively. It can be noted that in this case the fuzzy set is equivalent to a "standard" set because the support is equal to the core of the set. The values of the bound are functions of the current situation. The night and day average temperatures are also linked by another constraint which states that their weighted mean must belong to the set defined for the 24-hour average temperature.

Stated in the above form the decision problem becomes essentially a constraint satisfaction problem in which one has to find an assignment of values to each variable such that no constraint is violated. The first step in solving the problem is to filter the domains, that is, eliminate from them the values that are incompatible with any of the constraints taken separately. The second step builds a complete solution by progressively assigning values to the variables so that none of the concerned constraint is violated (i.e. for each concerned constraint, the corresponding linear combination falls within the support of $\mathcal{F}_r$). For each solution found SERRISTE determines its degree of acceptability by aggregating the degrees of satisfaction of each constraint (the higher the membership in $\mathcal{F}_r$, the higher the satisfaction of the constraint) (Martin-Clouaire & Kováts, 1993).

For a given situation, there may be several acceptable solutions. They are first sorted according to their degree of acceptability, then by criteria depending on the current goals and state of the crop. For example, if there is no risk of disease development and if the plant vigor is good, then the solution that is chosen is the one corresponding to the highest daylight ventilation set-point, the lowest daylight heating setpoint and the cheapest in energy need. If there are risks of disease development, then the solution with the lowest diurnal ventilation set-point and the highest night heating set-point is chosen, *i.e.,* the solution most probably resulting in the driest environment.

SERRISTE has been developed in the object-oriented environment KAPPA-PC that runs under Windows. The user interface has been designed to allow the grower to mention only the changes in the current situation with respect to the previous day. A publicly available weather forecast service with a computer interface is used to obtain the necessary information, by means of a modem call. It has also been possible to establish a link with most climate computers so as to retrieve the information concerning the greenhouse and outside climate of the previous day. The only missing link, on some greenhouse systems, is the automatic transfer of the set-points.

4. Conclusions

SERRISTE has been tested first in INRA greenhouse facilities and later in extension services. The tests consisted of parallel experiments where two identical greenhouse compartments were used, one managed by SERRISTE, following strictly its solutions, and one managed by the local crop manager. In the extension services tests, this expert was oblivious to the recommendations of SERRISTE and moreover had not been a member of the SERRISTE project. It is therefore reasonable to state that his way of growing a crop is independent from that of SERRISTE. However, the expert could see the progress made by the crop in the SERRISTE compartment.

First of all, the results show that the set-points produced by SERRISTE *do* give the climate they were intended to, which is not so trivial a result given the complexity of the physical and biological processes and of their interactions. SERRISTE also has proven its capability to grow a tomato crop and achieve the same yield as local experts while producing bigger fruits (more fitted for the French market) and sparing energy by some 10% (Martin-Clouaire *et al.*, 1997; Tchamitchian *et al.*, 1997). An unexpected side effect of SERRISTE is that the crops managed by SERRISTE have a better behavior during the hot summer periods. In fact, the "SERRISTE" crop apparently bears more foliage than the "expert" crop and thus has a better transpiring capability and a better cooling effect on the greenhouse; the price to pay for this bigger investment in leaf production is that the harvest in SERRISTE is late by a week or so.

The SERRISTE project started in 1991 and involved scientists from three different domains: farming systems, greenhouse climate/crop modeling and artificial intelligence. Getting to a common understanding and presentation (formulation) of the problem at hand and hence to a common language has been a challenging step at the start of the project. Continuing collaborations on other greenhouse production management projects show that this effort has been fruitful. The integration of the pieces of knowledge "owned" by one or another of the participants into the framework and bringing them to terms with the other pieces has also been hard work. It has however been very useful to each of the participants because their own knowledge was examined under new perspectives, the very target goal not being the least. Finally, despite the geographic distance between the three involved laboratories and the efforts needed to maintain a regular pace in the meetings and in the advancement of the project, the first prototype of the system was available for a first test in the 1992-1993 season, one and a half year after the start of the project.

SERRISTE can be considered as a successful project in terms of research because the goal (build a DSS to plan the daily climate in greenhouse tomato production) has been reached, and also because the habit of working together has not yet faded. However, the real challenge is now to succeed in delivering this product to the intended users, the growers, who seem quite eager to use it (Léonardi, 1997). Even more of concern is the design of a framework which will keep SERRISTE alive, that is update the knowledge base to new varieties at least, and maybe to new practices, and therefore enable to obtain the necessary information early enough. The involvement of INRA as a research institute does not encompass such a permanent support, although INRA may still have an advisory role for the continuing evolution of SERRISTE. The active participation of the extension services in this maintenance/updating process would be a very strong asset because they are in the best position to obtain direct knowledge and experience on new varieties and practices. Finally, the different climate computer manufacturers do not all have the same position towards third party software and some are very reluctant to open their systems, which might hinder the installation of SERRISTE where these systems operate.

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Directions in greenhouse operation and control: an intelligent synthesis between optimality, uncertainty and risk as a possible direction in greenhouse operation and control

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Abstract

This paper discusses the various paradigms of greenhouse climate control: hierarchical versus non-hierarchical approaches, and reasoning-based versus model-based optimal approaches. The key issue is the interplay between the grower, the greenhouse's physical environment and the crop. Present results, problems and future prospects are delineated.

1. Introduction

The greenhouse's main purpose is to provide a protected environment for the crop. The greenhouse also acts as a solar collector. Within a greenhouse, light, temperature, CO_2, humidity, nutrients and chemicals can be controlled, at the expense of certain costs. In addition manual operations, such as de-leafing and truss pruning, play an important part (cf. Challa & Schapendonk, 1986; Hashimoto, 1993; Martin-Clouaire *et al.*, 1993; Martin-Clouaire *et al.*, 1996). Moreover, decisions are needed with respect to pest and disease management.
The purpose of this paper is to discuss the present status of scientific methods to alleviate the operational task of the grower, be it with decision support systems, or with fully automated systems, and to identify the needs for the future. The discussion in this paper is confined to climate management for crop cultivation control.

2. Idealised operation

From a systems point of view, the production system can be seen as a system with heating, CO_2 dosage, ventilation, water supply, nutrient supply and labor input for crop handling actions as inputs, and cost and benefits as outputs. Solar radiation, outside weather conditions, the price of products, and infestations coming from outside, occur as disturbance inputs.

In the ideal case, knowing the exact input-output relations ('models') and the exact patterns of the disturbances, the effects of control actions on crop production could be evaluated, and control could be exerted so as to yield maximum profit. There are two principle reasons why this ideal cannot be achieved:

1. Disturbances are not known, even though some can be measured (mostly environmental variables), forecasted to a certain extent (the weather), or are known on average (e.g. the annual weather cycle, the seasonal price cycle). Some others, like infestations, are known only partially or not at all.
2. Models relating inputs to outputs will not be exact. Partly, this is due to lack of knowledge, which may be reduced by progressing research; partly, this is of a fundamental nature. In particular, crop variability and the occurrence of pests and diseases introduce a stochastic element. Consequently, models may have considerable uncertainty, and may need to be partly stochastic.

Feedback is the answer to disturbances. Making the greenhouse immune for outside weather conditions is one of the main purposes of the control system. It should be noted, however, that the solar radiation is a resource and a disturbance at the same time. So, natural variations will remain and can not be fully excluded.
Models of any kind play a crucial role in getting closer to the ideal of optimal greenhouse control. Reliable models will allow feed-forward control, model predictive control, and various types of optimal control. The answers to model uncertainty are adaptive control (using on-line information about the state of the system), robust control (using *a priori* uncertainty limits set by previous observation or experience), stochastic optimal control, or various methods of heuristic, rule-based control.

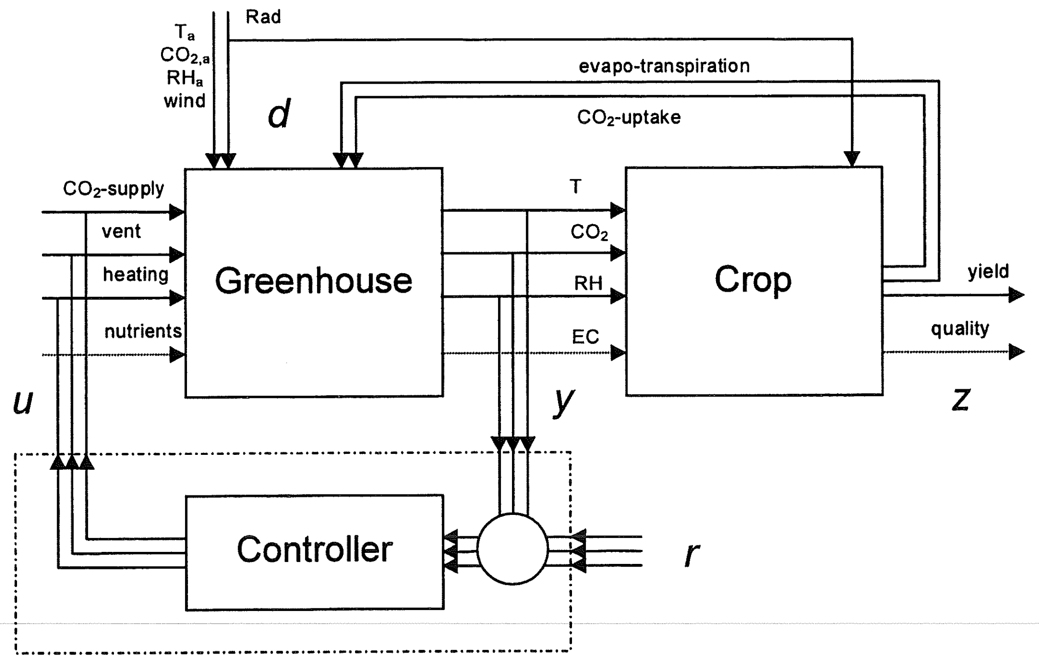

Figure 1. Decomposition of the greenhouse-crop system, and classical controller

3. The greenhouse and the crop

3.1. Greenhouse dynamics

Figure 1 present a picture of the greenhouse plus crop system. The greenhouse dynamics are characterized by relatively short time-scales. Typically, the time constant of the heating system is in the order of 20 minutes, whereas the transfer from heating pipes to greenhouse air is also in the same order. In addition, longer response times are involved due to storage in the soil material. The ventilation responds almost immediately to wind speed variations, but the transfer from ventilation rate to greenhouse climate has a time constant in the order of half an hour or so. From the point of view of the greenhouse, the plant acts as a disturbance, through CO_2 uptake and evapo-transpiration. The transpiration and CO_2 uptake due to photosynthesis may vary almost instantaneously with variations in solar radiation, but the transfer to RH and CO_2 concentration is slower due to the air mass in the greenhouse. The RH behavior can become strongly non-linear if condensation on windows or crop occurs.

3.2. Crop dynamics

The plant produces an internal carbohydrate pool by assimilating carbon dioxide from the air by photosynthesis, under influence of light and CO_2. The response time of photosynthesis is almost instantaneous. From the carbohydrate pool new structural material in the form of leaves, roots and stem, and buds, flowers and fruits when applicable, is formed by growth. Part of the pool is used for growth respiration and for maintenance respiration. Growth and respiration are mainly temperature driven. Its time constant is in the order of several hours to several days.

The total process of plant growth can either be source-limited – at low light and/or CO_2 – or sink-limited – at low temperatures. If we look at daily or weekly averages, we can suspect that – on average – the ratio between source and sink must be kept more or less constant. Consequently, when the photosynthesis has been high, due to high light and/or CO_2, it would generally be necessary to also have a high average temperature in order to achieve balanced or constant ratio growth. In addition, as long as the internal buffer is not completely filled or emptied, the instantaneous temperature value is less important than the temperature integral (Seginer *et al.*, 1994).

It should be noted that it is also possible to influence plant shape and other morphological characteristics with the source-sink concept, although this is less well quantified.

4. Control and operation paradigms

4.1. Hierarchical control

In view of the difference in time scales, plus the availability of measurement devices, practically all greenhouse climate computers on the market are based on the system decomposition shown in Figure 1. The physical system is controlled by a low-level controller, which receives its set-points from elsewhere. The control task breaks down into two: the design of suitable low-level controllers, and the generation of set-points. Automatic controllers nowadays practically always do the first part, but the second task is typically the task of the grower. Climate computers contain a program memory, to store desired control paths or ranges, provided by the grower (Figure 2A). The grower adjusts the desired ranges and patterns on the basis of visual observations on the state of the crop, and other information, like expected weather. He plays the role of supervisor in this hierarchical control set-up.

4.2. Low level control

Most industrial controllers for greenhouse control are based on a collection of heuristic rules and simple PI-loops to operate the controls on the basis of feedback. The performance of these controllers from a pure control-engineering viewpoint is not always satisfactory. The main difficulties lie primarily in the interaction between the variables of the system, and in the fact that the controls have limited and sometimes variable control power (ventilation in wind still conditions), operate with constraints (heating can not be used to cool) and serve more than one purpose (ventilation to cool and de-humidify). Using modern control methods the controller design can be improved considerably (Young *et al.*, 1993; Lees *et al.*, 1996).

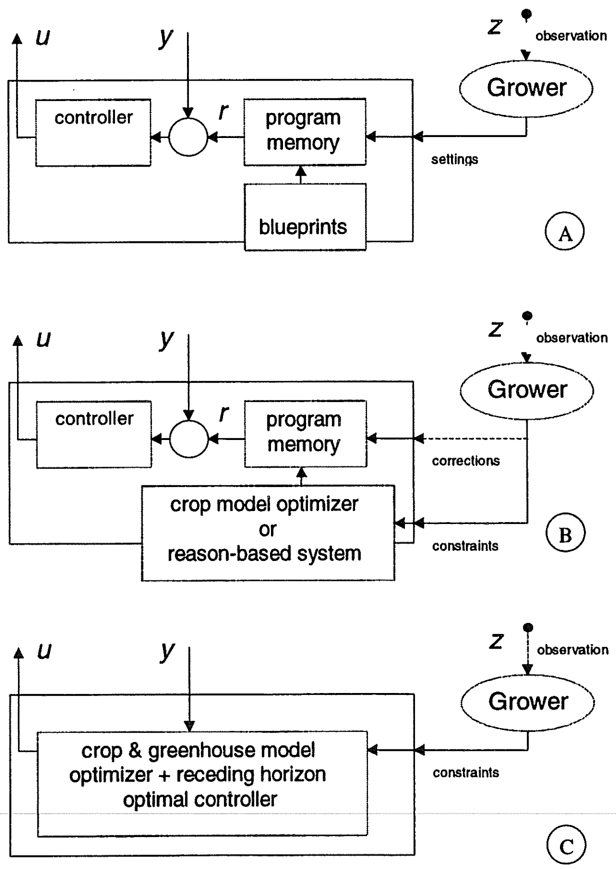

Figure 2. Control and operation paradigms

4.3. Generating set-point trajectories

In Martin-Clouaire *et al.* (1996) a classification is given into two broad classes: the artificial intelligence approach and the optimal control approach. The name "artificial intelligence" is somewhat unfortunate because some of the techniques in the realm of AI, such as neural networks and genetic algorithms, are equally well applicable in the frame of optimal control, as we will see later. Therefore, we rather speak about reason-based approach and model-based approach. The first finds its roots in information science, the second in control science.

Heuristics. The oldest method of getting set-points is by means of blueprints based on experimentation and experience (Figure 2A). The basic seasonal patterns of desired day and night temperatures, and required humidity levels are fixed, and apply to an average season. The grower makes adjustments by making visual observations on his crop. A large number of settings have to be adjusted, with the risk of errors and conflicts. Also, the grower does not receive direct information about the expected consequences of his settings for his crop or for his energy consumption.

Reason-based. The main idea in this approach is to utilize knowledge mainly of qualitative nature to help the grower in finding appropriate set-points (Jones *et al.*,1988; Martin-Clouaire et al, 1993; Hashimoto, 1993). In Martin-Clouaire *et al.* (1996) a distinction is made between the rule-based approach and the constraint-satisfaction approach. Both are based on a combination of scientific and practical know-how of experts. The constraint-satisfaction procedure reported, and implemented in the decision support system SERRISTE, in fact tries to distribute temperature set-points over the day, so as to achieve a certain temperature integral. Selection of non-conflicting strategies resulting from the constraint satisfaction exercise is done on the basis of a context dependent hierarchy of criteria, in particular the minimization of energy costs.

Model-based. In research, much attention has been given to the automatic and optimal generation of set-points, on the basis of crop models (Figure 2B). Examples are the generation of optimal CO_2 set-points (Challa & Schapendonk, 1986); detailed studies of temperature optimization (Seginer & Sher, 1993; Seginer *et al.*, 1994), or both (Hwang, 1993). The goal can be either to maximize crop revenues, or to balance this against energy costs. In all cases the implicit assumption is that required settings r will always be realized immediately by the controller, i.e. the controller needs to be ideal. This assumption implies that dynamics of the greenhouse-controller system can be ignored on the level of crop optimization. The costs of controls can be computed from heat and CO_2 balances in pseudo-equilibrium. The role of the grower is essentially reduced to supervising the generated set-points, and to making corrections on the basis of crop observations.
Models are needed to express how plants respond to their environment. Predominantly, these models have been mechanistic crop models. This is, however, not necessary. Reduced black box models in the form of neural nets derived from the mechanistic models are often more easy to use (Seginer *et al.*, 1994). Also, if sufficient observations can be made on the plant behavior, fuzzy-neural models are another option (Tien, 1997).
The model-based approach also needs methods of dynamic optimization. Various options exists, like dynamic programming and Hamiltonian approach using co-states, in combination with Pontryagin's maximum principle, as well as computationally more efficient shortcuts, such as the so called sequential control search (Seginer & Sher, 1993). In addition, genetic algorithms may be used to search for the optimum trajectories (e.g. Morimoto & Hashimoto, 1996).

Plant feedback. It is important to look at the inputs needed for these approaches. In general, it is the grower who has to decide on the status of his crop. SERRISTE, for example, uses the qualitative notion 'vigor' of the plants. Most model-based optimal control calculations do not use feedback from the plant, and only take into account the external conditions. So, the grower still has to supervise these methods.
The importance of automatic observations on the plant, in what is called the 'speaking plant approach', is stressed in (Hashimoto, 1993). Information about photosynthetic rate, water uptake, CO_2 uptake, turgor pressure, and evapo-transpiration can be obtained, although the associated sensors and measurement techniques have not yet found wide application. Also, image processing has been proposed to detect the state of the crop (Van Henten, 1994). All this information can be used for diagnosis, but also for building observation-based models about the crop behavior.
It should be noted that the insight in plant behavior may also lead to forms of plant process control, rather than set-point control, e.g. the control of evapo-transpiration (Van Meurs & Stanghellini, 1992) by manipulating the root zone EC, and the air humidity. Temperature integral control can be seen as another example: it is an indirect way of controlling the crop growth process. In this context it would make sense to try to achieve a decided temperature integral at minimum cost, as, for instance, in the wind-dependent temperature optimization in Chalabi *et al.* (1996).

4.4. Non-hierarchical optimal control

In the hierarchical approach, the set-points form the intermediate between the goals of the grower and the greenhouse operation system. Its justification is the assumption that the dynamics of the greenhouse play only a minor part in the optimization of overall performance. Irrespective of whether this is true or not, it is quite possible to drop the assumption of ideal control, and to approach the optimal control problem as a non-hierarchical problem, as shown in Figure 2C. In this case, crop and greenhouse models are combined, and the dynamic properties and influences of both on the optimal result is automatically accounted for.
As in the case of optimal set-point generation, the integrated approach is based on optimal control theory, aiming at maximizing the difference between expected crop yield and control costs, according to

$$u^*(t) = \arg\max \int \left[R(z, y(u,d), d) - C(u) - \Pi(y,c)\right] dt$$

where *R* represents the revenues from harvesting the crop (a function of the crop state *z*, and of the greenhouse climate *y*, which in turn depends upon the control input *u* and the external disturbances *d*), *C* stands for the costs which depend upon the controls, and A is a penalty function in order to avoid violations of user-defined constraints *c*. The inclusion of the penalty functions is needed to allow for effects that are not included in the crop models, and to give the grower a handle for risk assessment. A typical example is the inclusion of humidity constraints. If the grower decides to set tight constraints, there is less room for optimization, and the economic returns will be less.
Ideally, the optimization should be done over the whole season. Due to the uncertainties in the weather this is not feasible. Therefore, some form of time-scale decomposition is usually made. In the method proposed in Martin-Clouaire *et al.* (1993), and applied by Tap *et al.* (1996a), the state trajectories of the crop are computed by assuming standard weather, and a

pseudo-static greenhouse, as in the hierarchical approach. The main product of this exercise is, however, not the state trajectory itself, but rather the co-state trajectory of the crop variables. These form a pattern of marginal values for leaves and other plant organs (as applicable), that can be used in a short-term optimization to compute the necessary control action. Feedback is introduced by casting the control computation in a receding horizon optimal control framework (Tap *et al.*, 1996a; Tap *et al.*, 1996b). Basically, the optimization is performed over a relatively short horizon, and repeated after a new measurement comes in, shifting the horizon one step further. In this way, short-term weather forecasts are taken into account, and the controller has an automatic feed-forward component, because model-based predictions are made.

5. Results and discussion

Many of the ideas presented here have not yet been put into practice, and little is known about the final advantages to be achieved. In Tantau (1997) energy consumption simulations are given for various heuristic control strategies. Only minor differences in energy consumption were observed, except when thermal screens were used. The reasoning-based SERRISTE system was put to practice in a comparative experiment. The crops appeared to be more vigorous, and energy savings of about 10% were claimed (Martin-Clouaire *et al.*, 1996). According to Tap *et al.* (1997) the integrated control approach proved feasible, and yielded similar crop quality as the usual control. In simulations for a typical autumn day the total biomass increment was higher, but with a different distribution over fruits and leaves; the loss in production value of 6% was compensated by 50% less energy consumption, leading to a 6% higher net revenue for the grower.
Reviewing these results it is unclear which parts of the overall system contribute most to the savings and improvements. With a rule-based approach, the grower gets advice, and this will help to reduce the differences between growers. If the system's advises are appropriate, a better performance of the whole industry can be expected. In the optimal control approaches it is not clear whether a hierarchical approach is justified or not. By ignoring the greenhouse dynamics, some of the advantages may be lost. It is quite difficult to evaluate the dynamic losses of hierarchical control. To illustrate this point in a little bit more detail, consider the heat loss from a greenhouse. This is given by

$$Q_{loss} = K(t)[T_g(t) - T_a(t)] \quad \text{with } K(t) = U(t)A + \rho c_p(t)\Phi_v(t)$$

Here, the overall heat transfer coefficient K(t) depends on the heat transfer through the glass surface A, with a wind-dependent transfer coefficient $U(t)$, and the ventilation losses, which depend upon the air humidity (incorporated in $c_p(t)$) and the ventilation flux $\Phi_V(t)$, in turn determined by wind speed and window opening. Introducing average values over a certain period for all variables, denoted by an overbar, and a deviation from average denoted by the prefix δ, we can re-calculate the average loss as:

$$\overline{Q}_{loss} = \overline{K}(\overline{T}_g - \overline{T}_a) + \overline{\delta K \cdot \delta T_g} - \overline{\delta K \cdot \delta T_a}$$

From this equation we can learn that the first term of the period averaged energy loss depends upon the given temperature integral of the greenhouse and the averaged outside temperature, and is therefore independent of the control. However, the actual loss can be larger or smaller, depending on the dynamic interplay between the loss coefficient (wind, ventilation, and humidity dynamics) and the outside and actual inside temperatures. The conjecture is that it is mainly the humidity control that largely influences the energy consumption, so that temperature optimizations without considering humidity control are, at least, incomplete, and should be viewed with care.

6. Towards the future

From the above it may be clear that still many questions have to be resolved. For instance, more needs to be done to settle the question about optimality in the hierarchical framework. Hierarchical or not, the optimal control approach is vulnerable because it relies heavily upon good models. However, by introducing robust and/or adaptive methods, some of this drawback may be eliminated. In particular, self-learning models, perhaps using neural nets or gray-box approaches, may strongly enhance the power of optimality methods. Yet, some phenomena will remain difficult to model, and consequently, growers will need knowledge-based support. This is particularly true in assessing cultivation risks. Here, it would be very desirable to provide the grower with an evaluation tool to assess energy effects and expected yield effects of planned settings.
The reason-based approach is directed primarily to achieve satisfactory decision support, whereas the model-based approach primarily strives for optimality. Both are scientifically challenging. From a practical point of view, investments in instrumentation and control need to have a fair payback time; in other words, what is scientifically feasible may not be feasible in practice. Probably, in the future, the best results are obtained when merging both paradigms.

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BETHA: a model-based Decision Support System for ethanol wheat production

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1. Introduction

Since 1992, a new trend has been observed in France: the production of crops for biofuel on set-aside lands. In particular, ethanol wheat surfaces in the North of France have progressively increased up to 12000 ha in 1996. By promoting biofuel production, farmers have sought an alternative use for set-aside land to ensure a portion of their income.
Even if the produced quantities are not high today, there is a hope that biofuels will soon contribute to diversifying the agricultural and energetic outlets. Nevertheless, biofuels have been widely critized: first, they are considered too costly. Ethanol production is only competitive because the French government has exempted it from the national tax for fuel products. Moreover, the bioethanol detractors consider that agricultural practices are too intensive and promote both water pollution (leaching of nitrate and pesticides) and air pollution (N_2O exhausts).
We aim to determine how wheat crop management should be modified in order to increase the gross margin (to improve farmers' income), reduce the cost per ton (to improve competitiveness), decrease the nitrogen left in the soil at the harvest time and pesticide use (to protect the environment) and obtain a positive energy balance, as high as possible once the previous objectives have been taken into account.
To achieve that, we developed BETHA, a system that relies on a set of simple agronomical models to design new crop management plans and on a multiple criteria approach to select them according to their capacity to achieve the goals for ethanol production. In Chapter 1, the framework of BETHA is presented. Chapter 2 and 3, respectively, describe the agronomical and multicriteria analysis models. The evaluation methods of the agronomical model are discussed in chapter 4.

2. A tool for the design of new management plans: framework of BETHA

We refer to strategic crop management, *i.e.,* we aim to anticipate the technical means proper to realise a set of goals over a production cycle (the agricultural system studied is the crop field). A wheat crop management plan bears upon seeding period and density, cultivar, fungicide control and nitrogen fertilisation. For each of these operations, several modalities are defined: as they can be turned into real decision rules according to the crop context, we call them "open options". A crop management plan thus takes form of a combination of open options (e.g., early seeding period (1-10/10), high seeding density, cultivar: Ritmo, reduced fungicide protection (one treatment), nitrogen fertilisation rate: 60 kg/ha less than the advised rate, assessed with the balance-sheet method (Remy and Viaux, 1982)).

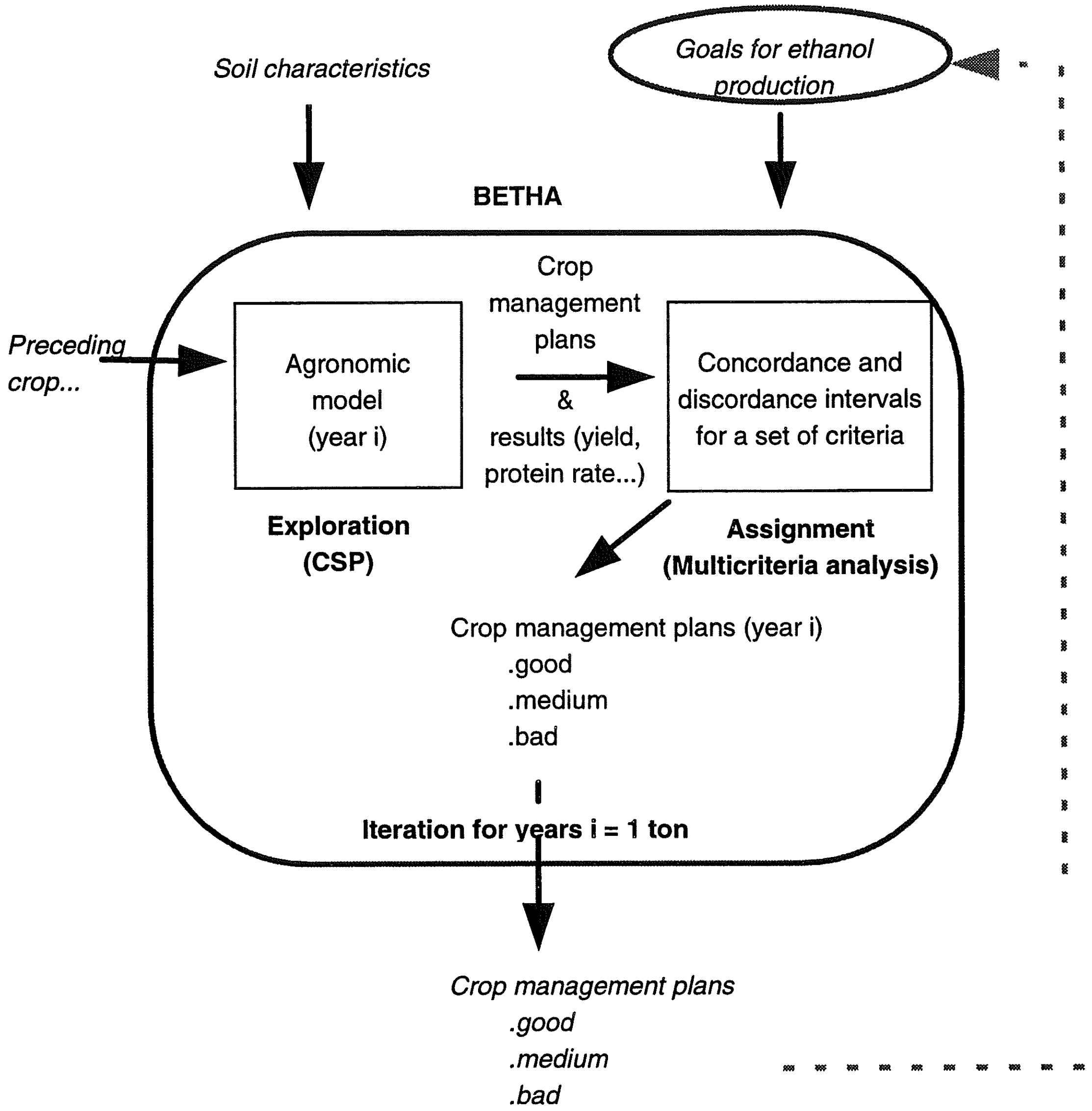

Figure 1. The BETHA components

BETHA then calculates for each crop management plan the values of the criteria and lastly selects the crop management plans considering their capacity to achieve the goals. We used a specific multicriteria method (Vanderpooten, 1994) based on the concordance and discordance principles (Roy and Bouyssou, 1993), which assigns a given plan to a predefined category (good, medium, bad plans). More specifically, for each crop management plan generated, the hypothesis "the crop management is assigned to the "good" category" is submitted to a concordance condition (a majority of criteria is favourable to the affectation) and to a non-

discordance condition (the remaining minority can use a right of veto) in order to decide in favour of the assignment or not.
This process is repeated for a set of climatic years (considered as equiprobable events). We summed up the climatic years in variables involved in the agronomical model. A crop management plan is eventually considered as "good" if the frequency of assignment to the good plans category overpasses 0.8 and if the frequency of assignment to the bad plans category is lower than 0.2. The user can modify both thresholds given its risk attitude.
Once obtained the solutions, the user can slightly modify the goals for ethanol production and evaluate the robustness of the solutions to these changes (Figure 1).

3. The agronomical model

The agronomical model expresses empirical relationships between open options, cultural variables and environmental variables. The attainable yield depends on the type of soil, a year effect (concerning water deficit), the cultivar, the seeding period and the crop density. It allows the assessment of the actual yield, once considered the yield losses caused by diseases or nitrogen deficiencies. The agronomical model also provides values of protein rate and the quantity of nitrogen left in the soil at harvest time.

We chose static and non-deterministic models for several reasons. We wanted the models to consider the effects of techniques on yield and to be based on several references currently used in agriculture to design crop techniques (disease resistance marks of cultivars, nitrogen left in the soil by the end of the winter). Moreover, the models contained variables assessed in several trial nets, which implied few costs of parameter estimation and model evaluation. Last, as they had few parameters, their evaluation from local trial nets was much easier (Cox, 1996; Fischer, 1985).
As CSP algorithms do not work on a time step basis (in other words, CSP variable that resolve with time are not state variables), they appeared possibly appropriate for the processing of our kind of static models. The CSP orientation made us give up all dynamic aspects in our model in favour of summary models using, e.g, variables characterizing the climatic scenarios.
We made use of three types of trial nets to carry out model calibration and evaluation: the first one has been used to assess the effect of increasing nitrogen fertilization quantities on nitrogen absorbed by the crop, yield, protein rate and nitrogen left in the soil at harvest time. The second one allows estimation of the effect of no fungicide control on yield compared to total control. The third one was used to calculate the effect of several types of fungicide control on yield. Concerning the two last trial nets, additional pieces of information are field and crop techniques characteristics (localisation, type of soil, cultivar, seeding date, nitrogen fertilisation rate).

4. The multicriteria analysis model

Before processing the multicriteria analysis model, we have to express the concordance and discordance intervals ($C_{i,j}$ and $D_{i,j}$, respectively) for each criterion x_j and for each category K_i. (e.g., a crop management plan is assigned to the "good plans" category if the protein rate value is between 10.5% and 12% ($C_{i,j}$) and it is not assigned to it if it overpasses 14% or is lower than 8% ($D_{i,j}$)). Let a be a crop management plan and $x_j(a)$ the value of the criterion x_j

for *a*. The value $\mu C_{i,j}(x_j(a))$ measures to what degree $x_j(a)$ belongs to the concordance interval, *i.e.,* to what extent the criterion x_j is favourable to the assignment of *a* to the K_i.category. The value $\mu D_{i,j}(x_j(a))$ measures to what extent the criterion x_j is against the assignment of *a* to the K_i.category. In Figure 2 for example, for the crop management plan *a*, $\mu C_{i,j}(x_j(a)) = 0.45$ and $\mu D_{i,j}(x_j(a)) = 0$.
The concordance and discordance intervals are fuzzy. That allows a good representation of the goals, which appeared often imprecise to the actors of the ethanol production area (farmers, wheat transformers...) we interviewed.

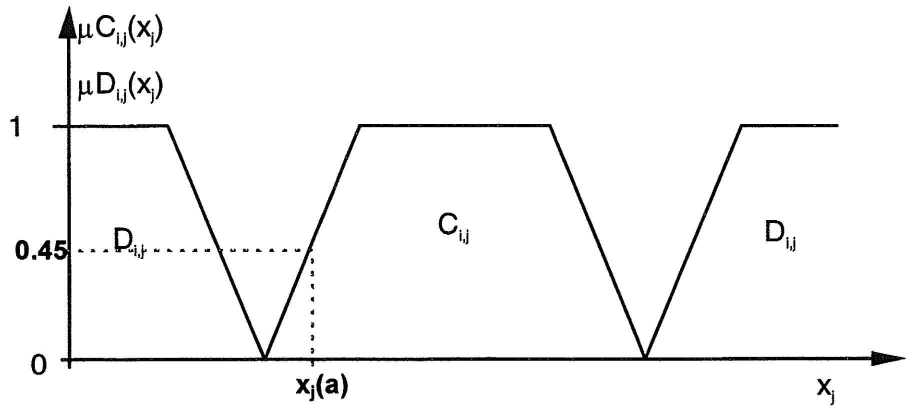

Figure 2. Concordance and discordance intervals

The models of the multicriteria analysis allow aggregation of the partial concordance and discordance measures ($\mu C_{i,j}(x_j(a))$ and $\mu D_{i,j}(x_j(a))$) over the whole set of criteria into global concordance and discordance measures. The assignment to a category K_i. depends on the combination of both values. Last, the models can also consider different weights for the criteria (they are involved in the assessment of the global concordance measure).

5. Evaluation methods of the agronomical model

Not only the agronomical models should explain the most part of variations in trial data but we also want them to have a good predictive value because we aim to use BETHA for decision aid purposes in new contexts. We evaluated the predictive value of each relationship using the trial nets available in our study region, the Chalky Champagne (France). Let us now consider a particular relationship *R* that evaluates the variable *Y*. Its parameters were first estimated on trial nets from other regions. We compared this model with an "average model" -say *Z*- (Colson *et al.*, 1995) that predicts the value of the variable *Y* for the year i from data of all the experienced years but i. *Z* is supposed to have a worse predictive value than *R*. The criteria used to compare the predictive values of both models *R* and *Z* is the Mean Squared Error of Prediction (Wallach and Goffinet, 1989). The results appeared to be acceptable, except for the model relating yield losses caused by diseases to technical and environmental variables. Nevertheless, the one-by-one evaluation of the models doesn't guarantee the good predictive value of the global model (Gaunt *et al.*, 1997). In order to evaluate the whole agronomical model, specific trial nets were carried out in collaboration with farmers and extension services, in which we tested the crop management plans proposed by BETHA. The experimented results appeared to be consistent with the solutions given by BETHA (Loyce and Meynard, 1997). Compared to a crop management plan commonly adopted by farmers, the crop management plans advised by BETHA (*i.e.* low input management plans, with reduced seeding density, less fertiliser rate and fungicide control) increased the competitiveness of ethanol production and the farmers' income. They did not improve the energy balance because of their lower yield but did limit nitrate and pesticide pollution risks.

6. Concluding remarks

BETHA enables us to explore new crop management plans with respect to a given set of goals for ethanol production. As the knowledge included in the tool is separated from the general procedures (the CSP technique and the multicriteria analysis), it could easily be used for wheat outlets different from ethanol. Nevertheless, the CSP framework is more appropriate and computationally efficient than traditional procedural software only if the number of decision variables is high (CSP algorithms better manage combinatorial explosion) and if it is necessary to take in account gradual preferences and fuzzy constraints on crop management plans.

BETHA doesn't aim at ultimate decision making: the user must analyse the range of solutions corresponding to several sets of goals (with different values of weights for example) and several risk attitudes. BETHA can help in providing the user with new ideas about crop management planning or in assessing the effect of some change in the context of a given production.

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Section II

FARM SCALE

Intensive Dutch farming systems: the search for new feasible configurations to meet environmental goals

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1. Introduction

In The Netherlands, as in other parts of Europe, farmers have been very successful in increasing yields per unit area during the last decades. The production techniques utilised, however, have resulted in negative side effects: emissions of pesticides and plant nutrients, (in)organic waste, high energy consumption. It has become evident that these symptoms cannot be addressed one-by-one on ad-hoc basis. Public concern is reflected in a suite of national and international policy statements that call for more sustainable agricultural farming systems.

Sustainable systems meet a combination of socio-economic, ecological and agro-technical objectives of agricultural production (WRR, 1995). The importance attributed to each of these objectives varies among interest groups. Because the objectives are usually conflicting, at least to some extent, the development of sustainable farming systems is characterised by negotiation about acceptable compromises between objectives by various stakeholders. Actors include farmers, agro-industries, consumers and the public sector including environmental pressure groups. Agricultural research contributes to this process by developing technology packages; and by offering methodologies to visualise the consequences of alternative options in a clear and quantified manner.

During the last decade, a promising empirical methodology for developing sustainable farming systems has been elaborated, coined 'prototyping' (Vereijken, 1994; Vereijken, 1997). Prototyping involves application-oriented design and testing of farming systems in collaboration with commercial farmers or at experimental farms. The approach consists of diagnostic, designing, testing and improvement, and dissemination phases, and is now being adopted in all major sectors of Dutch agriculture, including (organic) arable farming, open field horticulture, dairy farming, and flower bulb production.

Shortcomings of empirical prototyping are that, obviously, only few selected prototypes can be tested experimentally; and that the approach builds on 'expert knowledge' which is, at best, summarised in the form of simple rules which unduly narrow the range of available options. Moreover, commercial farms are no suitable test ground for evaluating 'risky' new ideas. Thus, we obtain only a partial picture of what 'fitting' agricultural systems could look like, now and in the future, and we lack a sufficient basis for quantifying the trade-offs between objectives (e.g., 'how large are income losses associated with reduction of per ha nitrate emissions, for different agroecological environments?').

Model-based explorations can remedy such limitations. Models combine detailed information on system components, and can thus explain the behaviour of whole farm systems based on insight in the behaviour of their components. They represent a tool to design systems that meet objectives of the various actors involved, and to quantify the trade-offs between these objectives. A further difference between prototyping and model-based exploration is that the latter approach is less rooted in current production practice, and thus allows to survey a broader spectrum of new (hypothetical) production technologies, with their implications.
This report highlights three case studies addressing the conflict between farmers' income and the environment. The role of models in these studies is evaluated. The sectors discussed are dairy farming, flower bulb production, and arable farming. Multiple goal linear programming was used in all cases as an integrating framework. Our contribution is based on excerpts from original works by Van de Ven and Van Keulen (1996) and Van de Ven (1996) for the dairy case; by Rossing *et al.* (1997a, b) for the flower bulb case; and by Habekotté and Schans (1996) and Schans (1996) for the arable farming case. Parts of Rossing at al. (1997b) were used for the introduction and methodology sections of this paper.

2. Methodology

The method represents a farm as a linear combination of so-called 'activities'. An activity is a coherent set of operations (often a 'production technology') with corresponding inputs and outputs, resulting in e.g. the delivery of a marketable product, the restoration of soil fertility, or the production of feedstuffs for on-farm use. An activity is characterised by a set of coefficients that express the activity's contribution to the realisation of user-defined goals.
The biophysical and economic rules that determine the transformation of inputs to outputs of a given activity are generally non-linear: the pesticides input required for the production of 5 t/ha of wheat grain is not equal to 50% of the amount required for 10 t/ha. The labour requirement in a stable housing 1000 animals is not 10 times larger than the requirement of a stable for 100 animals. The definition of activities must therefore, ideally, be such that all non-linearities are embedded in the values of input-output coefficients. So, rearing pigs in stables for 100 animals is a different activity from rearing pigs in stables for 1000 heads. Wheat production at 5 t/ha is a different activity from production at 10 t/ha. It now becomes clear that activities are discrete 'packages of production technologies', and that the resolution by which this discretisation is performed determines to a large extent the potential outcome of the subsequent optimisation study.
Activities are the largest aggregates or 'building blocks' from which a farm design is constructed. This last step, the design of the farm system as an assembly of activities, is made with the help of multiple goal linear programming (MGLP; see, e.g., de Wit *et al.*, 1988). The procedure consists of a number of optimisation rounds, in each of which all the goals are optimised one by one, while the constraints on the other goals are increasingly tightened. Usually only a selected set of potential activities is 'submitted' to the linear optimisation phase, to limit computation time.
In terms of software, three basic components constitute the 'toolkit' for each of the cases presented in this paper:

(i) an information system that contains data describing the attributes (properties, prices) of soils, crops and crop products, pests, animals and animal products, feeds, manures, fertilisers, pesticides, machinery, fuel, labour, etc.
(ii) algorithms to translate this data information into coefficients that represent the input and output coefficients for each discrete activity; these algorithms are referred to as 'technical

coefficient generators' (TCGs) and may include dynamic simulation models, static models, or simply perform summation over components of an activity (e.g. total labour input for an activity equals the sum of labour inputs of all constituent operations).

(iii) the linear farm optimisation model

3. Three cases of intensive farming

3.1. Case I. Dairy farming

Dairy farming contributes significantly to environmental pollution in The Netherlands, mainly because of imbalanced nutrient cycles. A study by Aarts and Middelkoop (1994) showed that in 1991/1992, well after the implementation of the EU quota system, only 17% (or 80 kg per ha per year) of the yearly farm nitrogen input leaves the farm in agricultural products, mostly in milk (64 kg). Inorganic fertilisers and concentrates account for 80% of the total N input of 487 kg per ha per year. The N surplus is accumulated in soil, denitrified to elemental N, leached as nitrate, or lost by ammonia volatilisation. N surplus values of 140 kg per ha were cited for ecological dairy farms, and 250 kg per ha was shown to be possible in a project referred to as MDM (Management for Sustainable Dairy Farming, cited by Ketelaars and Oenema, 1997). One of the farms developed with the explicit purpose of identifying means to reduce N surplus is the De Marke experimental farm.

De Marke represents dairy farming systems situated on drought-sensitive sandy soils in the eastern part of The Netherlands. The design of this farm was analysed with the help of the above modelling approach. The objectives quantified during the establishment of the real farm were adopted in this modelling study:

- nitrate leaching < 34 kg N per ha per year, corresponding to < 50 ppm nitrate in subsoil percolation water,
- ammonia volatilisation < 30 kg N per ha per year, corresponding to 70% reduction relative to the 1980 standard,
- phosphorus (P) surplus < 0.5 kg P per ha per year, corresponding to 'equilibrium fertilisation',
- milk production around 12 t per ha per year, representing the production on an average dairy farm on sand,
- total N surplus < 128 kg N per ha per year, an estimated acceptable surplus for De Marke based on permitted N loss terms calculated for local conditions.

Under these conditions, farm income was maximised with the help of MGLP. The first two constraints are the norms originally set for the year 2000. Just as in the real de Marke farm, these constraints were maintained as hard boundary conditions in the model runs. The other goals are rather subjective (not forced as such by government regulations), and the effects of relaxing these goals were assessed in the study.

The activities included land use activities, feeding activities, activities related to N flows in manures, animal activities, and purchase and sale activities (fertilisers, concentrates, contract labour). To characterise the various activities, the following TCGs were used:

(i) a model for grass production activities, which was used to generate coefficients for 320 'grassland activities' (= 3 cattle type x 4 grassland utilisation methods x 8 N application levels x 3 roughage-to-concentrates ratios for diets x 3 milk production levels; impossible combinations deleted *ex-post*),

(ii) a model to describe grass cutting and conservation for winter feeding, to generate 32 activities (= 4 product types x 8 N application levels),
(iii) models for maize and fodder beet production activities, to generate 384 options for producing each of these crops (= 3 yield targets x 4 fertiliser-to-slurry ratios x 3 slurry application methods x 4 slurry allocation patterns x 2 catch crops after maize x 2 maize-derived feedstuffs; impossible combinations deleted *ex-post*).

The optimisation was subject to the following additional conditions: land area used equal to area available; nutrient inputs to crops at least equal to crop demand; all produced slurry utilised on-farm, energy supply to animals equal to energy requirement; protein supply at least equal to requirement; and total dry matter intake by animals no more than the physiological limit.
The system with maximum income, but still meeting the indicated nitrate and ammonia emission constraints, turned out to be one that has 85% of the land in grass (63% for fresh consumption, 22% for silage), with daytime grazing only, and with N input of 170 kg per ha, slurry being injected. The remaining 15% of the area is under maize, receives 150 kg N per ha, applied in rows, slurry is injected, no catch crop is grown, and maize is used as whole-plant maize silage. The number of animals in this system is 2.05 cows, 0.6 calves, and 0.5 yearlings per ha. Milk production is 8000 kg per cow per year, totalling 16350 kg per ha per year. Cows receive 2670 kg concentrates per head per year. The total N surplus is 140 kg per ha per year, for P the surplus is 8 kg. The labour income is 73% of the theoretical maximum (73% of Dfl 4380 per ha per year) that could be attained without constraints on N emission.
Relative to this optimised system, the voluntary adoption of the 12-t-milk-per-ha-limit maintained by De Marke experiment farm implies a 20% reduction of labour income, the benefit of which is only a 7% cut in N surplus. The study produced, obviously, many intermediate results that cannot be listed here. To mention only one: minimising ammonia volatilisation results in the same cropping pattern as maximising milk production: 15-20% of the land area in maize, the remainder in grass, with cows stabled continuously. But milk production is 12 t/ha in the first case with 250 kg N applied per ha per year, whereas 17.7 t milk is produced in the second case, with 350 kg N input per ha.

3.2. Case II. Flower bulb production

Current systems of flower bulb production in the Netherlands use large amounts of nutrients and pesticides per unit area. Surpluses were estimated at 231 kg N, 106 kg P_2O_5, and 171 kg K_2O per ha per year (Weel *et al.*, 1995). The level of pesticides input has been estimated at 120 kg of active ingredient (a.i.) per ha per year (Rossing *et al.*, 1997a). High prices of bulb products and land, relatively low input prices and a defensive attitude among growers towards environmental issues are among the causes for these high input levels.
An explorative study was carried out by Rossing *et al.* (1997a) to support the designing - by an association of growers and environmentalists - of environmentally more acceptable production systems. The study synthesised fragmented agronomic information and employed MGLP to explore the options for flower bulb production systems with a time horizon of 10 to 15 years. The study focused on farms located on coarse sandy soils in the western part of The Netherlands.
The goals in this case were (i) maximum gross farm margin, (ii) minimum pesticide input (as kg a.i. averaged over the cropped area), and (iii) minimum N surplus, defined as input minus output leaving the farm in the form of crop produce. Important constraints were farm size, the

possibility to rent additional land free of soil-borne pests and diseases, and the range of crops that could be grown.

A wide range of possible production packages ('crop activities') were defined for tulip, narcissus, hyacinth and lily; one break crop, winter wheat, was introduced because of its favourable effect on soil structure and soil health. Each crop activity was characterised by soil type (sand/clay), soil health (3 levels), cropping frequency (7 levels), crop protection regime (5 levels) and nutrient regime (3 levels). Thus, a total of 3 x 7 x 5 x 3 = 315 hypothetical production packages for each crop-soil combination could be submitted to the optimisation phase; obviously, many practically infeasible combinations were eliminated beforehand.

In addition to crop activities, inter-crop activities were defined, such as soil fumigation, inundation, and prevention of wind erosion with straw. The definition and technological specification of crop and inter-crop activities was not only based on current practices but also on technologies still in an experimental stage of development, and on technologies 'borrowed' from other crops. This enabled a broadening of the vista on new farming options.

The TCGs used to generate coefficients characterising the crop and inter-crop activities were based on empirical information, expert knowledge, and production ecological theory (Rabbinge, 1993; de Koning *et al.*, 1995; van Ittersum and Rabbinge, 1997). In its final form it consisted mainly of equations to express crop-nutrient responses, and a 'shell' to transform tabulated technology specifications with corresponding yield reduction factors into the proper format for use in MGLP. The effects of crop sequence on yield were also accounted for by the TCG.

The farm systems composed from crop and inter-crop activities by multiple goal linear programming were essentially rotations, meeting the three earlier stated objectives with differing degrees of realisation. By maximising farm gross margin at increasingly tighter constraints on the two environmental objectives, the trade-off between market and environment was explored. Point A in Figure 1 represents a reference farm configuration that just meets the (anticipated) governmental targets with respect to pesticide input and nitrogen surplus for the year 2000, and has its gross margin maximised within these constraints. The constraints are nutrient surpluses of 25 kg P2O5, 50 kg K2O, and 140 kg N per ha per year, averaged over the farm area; a total pesticide input of 48 kg a.i. per ha (which is -60% relative to the 1989 mean for the sector), and soil fumigation not more frequent than once per 5 years. Farm gross margin is calculated as financial returns minus allocated costs of casual (unskilled) labour, pesticides, fertilisers, contract-machine use, but not accounting for investments (farm infrastructure). Gross margin is here expressed as an index, set to 100 for maximum gross margin (Dfl 205,000) on farms that just meet the environmental constraints. The index value is zero when gross margin equals zero.

Two development paths were assessed, representing gradually reduced pesticide use and N-surplus, respectively (Figure 1). The development path for pesticide reduction showed that a substantial reduction in pesticide input may be achieved, in the first step, with farm gross margin rather stable (index = 97 at point B). This is by substituting soil fumigation by inundation, and by adopting new low-dosage fungicides in tulip. No changes in cropping sequence or area of rented land occur. Further reduction in pesticide input (B to C) is most economically accomplished by abolishing the use of mineral oil for virus control in lily. The associated yield loss in lily causes a decreased farm gross margin in point C (index = 77). Again, no changes in cropping pattern occur. The third step, zero pesticide input, causes major changes. The rotation changes from tulip-lily-wheat to narcissus-wheat and farm gross margin becomes negative (index = -4 in D). The area of rented land free of soil-borne pests and diseases remains approximately 11 ha in all steps. Tulip is grown on this rented land, with a modest pesticide input of 12 kg a.i. per ha.

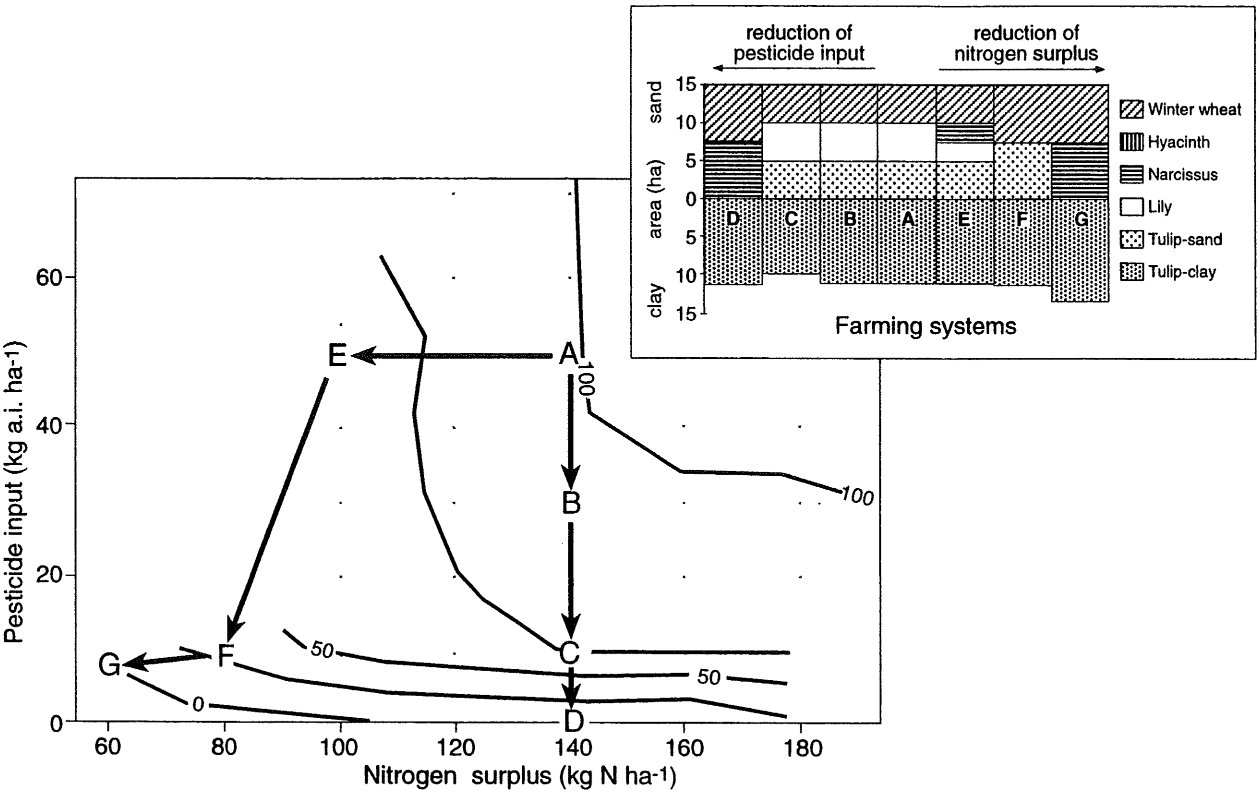

Figure 1. Iso-lines of calculated maximum farm gross margin (index) for different levels of pesticide input (kg active ingredient per ha) and nutrient surplus (kg N per ha) for a 15 ha farm with three full-time workers, situated on a sandy soil, with a possibility to rent 'fresh' (= healthy) land outside the farm proper. Letters in the graph indicate the development paths for pesticide input (A-B-C-D) and nitrogen surplus (A-E-F-G). The small x-es represent calculated points, the iso-lines are interpolated. A farm gross margin index value of 100 represents the farm gross margin of the most profitable system that satisfies the governmental environmental requirements for the year 2000. Inset: Many details are available of the farming systems on the developmental paths. Here, composition of the crop rotation and rented area of healthy clay soil is shown

The development path for N-surplus reduction shows, in contrast, that such reduction is only possible at the expense of a considerable loss of income, given the technologies as defined. A decrease in N-surplus of 30% beyond the levels anticipated for 2000 is associated with a 40% decrease in farm gross margin (Point E, Figure 1). In the cropping sequence lily is replaced by narcissus, which has a much lower gross margin but higher N-efficiency. Experiences on two experimental farms and current trends in the sector support the conclusion that reducing pesticide use affects farm income less than N-surplus reduction. Remedy may be sought in developing new technologies, aiming at more precise application of nutrients in time and space, or in re-evaluating such strategic choices as growing the bulk of nutrient-inefficient flower bulb crops on sensitive alluvial sands.

3.3. Case III. Arable farming

Whereas arable cropping in The Netherlands is relatively clean compared to the sectors discussed above, it generally uses nutrient and pesticide inputs high enough to cause undesirable side effects: eutrophication of surface water, and increased purification costs in the production of drinking water (RIVM, 1996; VEWIN, 1996). The average annual surplus of 173 kg N per ha arable land may be far less than its equivalent on grassland, it is still much higher than values found in most other West European countries. The use of pesticides reduced drastically since the Multi-Year Crop Protection Plan (MJP-G) became effective in 1991, but reductions were largely confined to soil fumigants (3 kg a.i. per ha in 1995), leaving the total inputs of fungicides, herbicides and insecticides virtually unchanged: 5.6, 5.0, and 0.7 kg per ha in 1995, respectively (Lotz *et al.*, 1997).

Integrated farming strategies were explored at several experiment farms. Integrated farming aims not only at maximum labour income, but tries to fulfil other objectives, too: moderate inputs and emissions of agrochemicals, and some level of consideration for nature and landscape values. Emphasis then moves from yield maximisation to cost reduction and improved quality of produce. Where possible, biocides are replaced by knowledge-intensive (but sometimes also labour- or capital-intensive) non-chemical methods, and nutrient management strategies aim at high efficiency.

A project was launched after the experimental stage, to introduce integrated arable farming methods with commercial arable farmers ('innovation farms'). Explorative modelling accompanied this phase. The MGLP model MGOPT-CROP which provided also the basis for the earlier discussed flower bulb case, was developed for this purpose by Schans (1996). The study focused on two regions: the central marine clay district (CZK) and the north-eastern district (NON).

The numerical characterisation of crop activities ('technology packages' approach), and the TCG used, were as described for Case II, with a few minor changes. Crops covered by the TCG and by the corresponding database are those grown at the innovation farms: ware, seed and starch potato, sugar beet, five small grains, maize, grass seed, onion, carrot, pea, bean, faba bean, rye grass, and a number of flower bulb crops. Only a selection of these was considered in the model study: ware and starch potato, sugar beet, winter wheat, maize, onion, and grass seed. Fallow was also treated as an 'activity'. Inter-crop activities such as organic manuring, catch crops and green manures were subject to a set of constraints not listed here (Habekotté and Schans, 1996).

Goal variables in the model study were: gross margin as defined for Case II, N loss per ha, and input of pesticides (active ingredients) per ha. N loss was estimated as mineral N input (in chemical and organic manures) plus net amount of N released by mineralisation (per whole year) minus N removed in crop produce, minus N transferred to the next season through green manures and crop residues.

Optimisations resulted in patterns comparable to those shown in Figure 1 for Case II, with shallow gradients around the point of maximum gross margin, both in the direction of decreasing N loss and decreasing pesticide input. Gross margin drops abruptly for N loss levels decreasing from 100 to 60 kg N per ha in the CZK district. A reduction in N surplus can be attained in both regions by (i) better matching of N supply with crop N demand, (ii) a replacement of organic by chemical fertilisers, (iii) suboptimal N supply, and (iv) changing the cropping pattern. The latter two options inevitably lead to a reduction in gross margin.

A reduction in biocide input is well possible without major losses of gross margin, especially in the NON region, by eliminating soil fumigation. Dramatic income losses with further biocide reductions occur when inputs drop below 5 kg a.i. per ha. This is associated with changes in cropping pattern. (All 'innovation farms' were below this threshold: 3.3 kg a.i. per ha.) The adoption of integrated crop protection packages is hampered in the NON region because of problems associated with mechanical weeding (surface frost; crop abrasion by windblown sand).

4. Discussion: modelling and practice

Both 'stakeholder' groups (producers and environmentalists) were directly involved in the flower bulbs case. The approach of separating objectives and bio-physical options was appreciated by both growers and environmentalists and resulted in bridging the communication gap between these two parties. The existing polarisation appeared to be caused by divergent views on objectives, rather than by disagreement on bio-technical relations. While the *a priori* outlook of growers focused on tactical decision making, the study increased awareness of the importance of strategic choices over tactical choices (introduction of winter wheat as a break crop; the renting of healthy land) to mitigate the decrease in farm gross margin under tightening environmental constraints. Participating farmers actively promoted, as a result of the study, new research on ecology of soil-borne pests at their experiment station. The lack of knowledge in this field had become apparent via the explorations. Despite uncertainty in a number of the agronomic relations, the results were deemed sufficiently robust for testing and improvement on commercial farms. A major project with 'innovation farms' was formulated and is anticipated to start in 1998. All these responses made the potential role of modelling rather convincing.
The dairy study had a different character. Commercial dairy farmers were not yet involved (a project with 'innovation farms' started only recently) and it is therefore too early to assess the role models can have in adjusting dairy farm designs. For the De Marke experiment farm, results indicate that the current farm configuration is not optimal, although it satisfies all targets: income can still be further maximised within the constraints. Such findings should normally provide a starting point for sound scientific debate, leading to either rejection or acceptance of the conclusion. This, however, did not happen. A general distrust in model outcomes on the part of the experimentalists may have been one reason. The omission of uncertainty in grassland production was mentioned as a shortcoming of the model. On the other hand, it seems that real, though experimental, farm systems have a certain 'inertia' that discourages real communication between experimentalists and modellers.
The arable farming case showed that the real innovation farms performed better, in some aspects, than the 'modelled optima'. Real cropping patterns were sometimes different, but more often crop responses at given production technologies (N input) differed from the model assumptions. Real yields were higher than modelled for seed potato, sugar beet (CZK, NON) and onion (CZK), and in starch potato (NON). These deviations are crucial, as exact yield levels of high-value crops largely determine the feasibility of a given farm configuration. Such flaws restrict the acceptance of modelling as a support for prototyping. Further, available computing power (*CPU* time) did not allow to take into account the whole array of crops grown on the project farms. The choices made here for crops to represent 'crop groups' could not ensure sufficient robustness of model outcome: crops *are* different.
Yet, the often raised issue whether farmers must shift cropping pattern or opt for suboptimal nutrient inputs was largely resolved by the model: first lower inputs per crop; only as a last resort increase the share of cereal crops.
Case III highlighted that, in order to fully realise the claims made for modelling in the introduction, it is important that 'prototypers' are constantly fed with model-based

evaluations. This is only possible if the bulk of models and databases is already in existence and fully operational by the time an innovation project starts in the field. Then, model adjustments can be made 'on-the-go', and instant evaluation of proposed options becomes reality.

5. Conclusions

The claims made for modelling in the introduction remain only partially fulfilled. The usefulness of optimising models to 'roughly' assess feasible directions for development is generally acknowledged. Models can serve as rather objective instruments in the debate among polarised groups. Their potential role in the fine-tuning of farm designs in interaction with experimental 'prototypers', on the other hand, has not yet been confirmed by the cases presented.
Where scientific aspects are concerned, a limitation of the models used is the accuracy of crop response calculations. Likewise, this applies to models describing responses of animals to diet composition. This can be resolved by making better use of empirical data. Then - and especially when these data are derived from the very 'experiment farms' or 'innovation farms' themselves - a new function for these models emerges: to keep an 'evaluated overview' over the whole ensemble of farm activities.
In terms of research logistics, synchrony between modelling and field efforts must be ensured if model outcomes are to play a role of any significance in prototyping. Prerequisites for this synchrony are well-documented and flexible data systems accessible to whole research groups, and models (technical coefficient generators) simple enough to allow frequent re-use and updating. They should be built from well-documented modules by recognised experts, and should aim at a fair balance between theory and empiricism. These modules, whether dynamic or static descriptions, must be fit to serve as building blocks not only for TCGs to generate inputs for optimisation models, but also for simulation models used in the evaluation of *a priori* defined farm configurations.

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Risk assessment as an ingredient in decision support for farm management

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1. Introduction

In most cases decisions are made by the farm manager based on his current knowledge of the system. To quantify risks however is more difficult. A more quantitative approach using simulation models can support the farm manager in the decision making process and provide insight in the risks involved (Bouma, 1997).

Three levels of decision making can be distinguished:
i. strategical,
ii. tactical,
iii. operational.

Strategical decisions (i) are taken for the long term indicating the character of the farm: organic farming, conventional etc.. Tactical decisions (ii) are related to a shorter time frame and involves choices on e.g. rotation. Operational decisions (iii) include decisions made on field level such as when to plough, plant or fertilise.
This paper focuses on the operational fertiliser management and the effects on crop growth and nitrate leaching. It by no means is a complete decision support system. The methodology presented is an illustration on how simulation models in combination with geostatistics can provide vital information that can be used in a decision making process. In this approach the farm is regarded as a collection of farm fields. Two cases are presented to illustrate the methodology.
Both spatial and temporal scales are included in the analysis.

2. Materials and methods

The following elements may be distinguished when defining soil research for farm management decision support systems.

1. Establish a soil database, which contains relevant soil characteristics.
2. Monitor crop growth and physical and chemical soil conditions for at least one but preferably several growing seasons for calibration and validation of simulation models for crop growth and solute fluxes.
3. Scenario analyses using multi-annual simulation runs using the validated model. Spatial interpolation to map units areas and creation of risk and response maps (geostatistics).
(after Verhagen *et al.,* 1995)

2.1. Soil database

The studies ware made for a field at the Van Bemmelenhoeve farm in the Wieringermeer, the Netherlands. Soils were classified as fine-loamy, calcareous, mesic Typic Udifluvents (soil Survey Staff, 1975). Soil variability is high: relatively large textural differences are observed over short distances. A soil survey on one farm field was done on a regular grid including short distance observations (Figure 1). Hydraulic conductivity and moisture retention were measured in different soil layers which were distinguished on the basis of differences in texture and organic matter. Systematic testing of differences resulted in the distinction of four signiicantly different functional layers which were used in the simulations. Because of the static nature of the soil body this database, once it is established, can be used for longer periods without the need for updating.

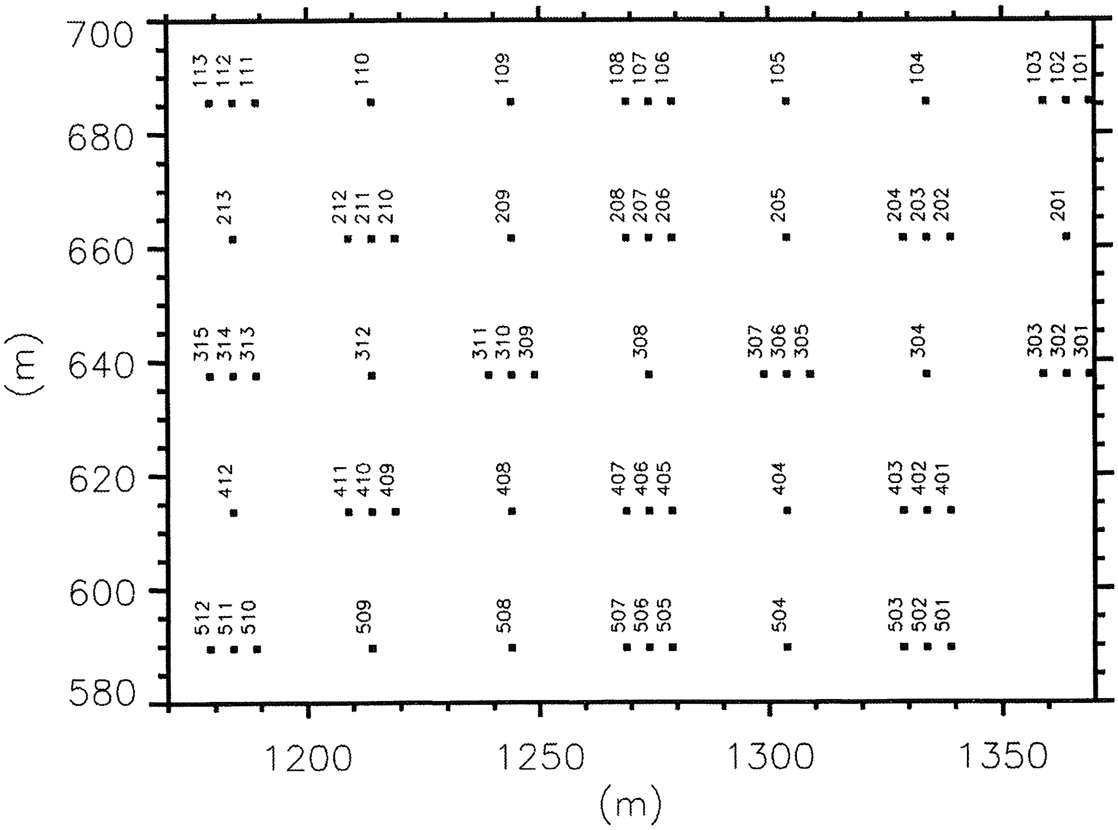

Figure 1. Layout of the soil survey for the experimental farm field. Numbers refer to soil augerings

2.2. Simulation model

When exploring systems behaviour and system dynamics a simulation model is an attractive tool.

A dynamic simulation model can be used to quantify both crop growth and nitrate leaching and to explore various management options and weather scenarios.

A process-based deterministic simulation model is crucial when extending the use of the model beyond the validation period. Simulation of the soil-crop ecosystem was realised by using the

dynamic simulation model WAVE (Water and Agrochemicals in Soil and Vadose Environment, Vanclooster *et al.,* 1994). Wave integrates four existing and well tested submodels for water flow, nitrogen transformations, heat and solute transport and crop growth.
The model was tested with field data and was considered to be validated (Verhagen *et al.,* 1995).

2.3. Scenario analyses

An attractive feature simulations models is that they can be used to explore system behaviour under past and future boundary conditions. In this paper two cases will be discussed:
The first case deals with the simulation of differences in water-limited production levels over a number of years to extract uniform production areas.
The second case study aims at finding the post-harvest N level which will not lead to excessive leaching of nitrate.
Both cases include multi-annual simulation runs based on historical weather data allowing a probabilistic approach.

2.4. Geostatistics

Spatial interpolation between point simulations was performed with ordinary kriging. Kriging is a 'collection of generalised linear regression techniques for minimising an estimation variance defined from a prior model for a covariance' (Olea, 1991). Ordinary kriging is a local estimation technique which provides the best linear unbiased estimator of an unknown characteristic only requiring the covariance or variogram (Journel and Huijbregts, 1978). The (semi)variogram is the function relating both the semi-variance and the lag. The lag is a vector embracing both distance and direction (Webster and Oliver, 1990).
Kriging and semi-variogram analyses were done using GSLIB (Geostatistical Software Library; Deutch and Journel, 1992) and WLSFIT (Weigted Least Squares FIT; Heuvelink, 1993).

3. Results

Case 1. Defining areas with uniform behaviour with respect to water-limited production in different years
For seven consecutive years the water-limited production levels were calculated for each of the 65 point observations within the field (Figure 1). The interpolated results of the simulations are shown in Figure 2 (year 1988 is excluded because no pattern could be distinguished). The yield varies dramatically among the years but in all but one case stable soil related production patterns are observed. The sandy central part of the field in most years produces less than the more loamy areas. Only in 1991, a year with a relatively wet spring, the inverse is observed because the loamy soils are too wet.

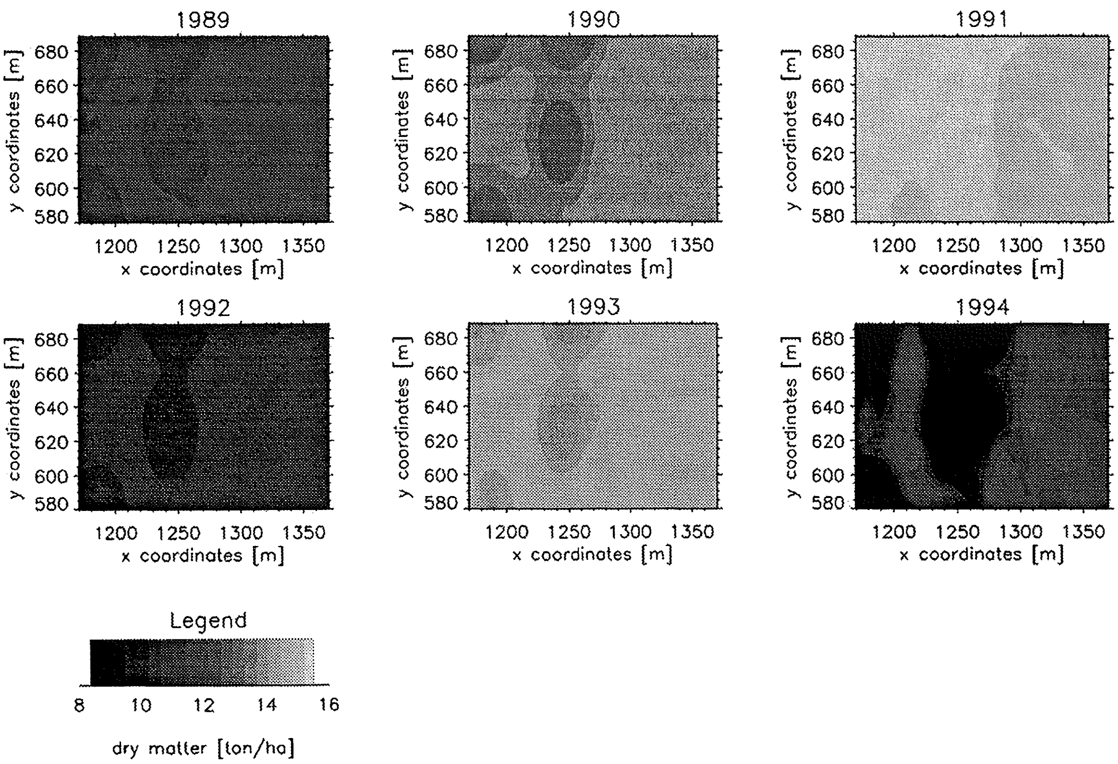

Figure 2. Simulated water-limited production levels of potatoes for the years: 1989–1994

When regarding the field as one uniform unit production related inputs, e.g. fertiliser, are most likely not well balanced. Only in one out of seven years it seems to be justified. In most cases the sandy area produces below average and the excess of fertiliser is lost.

Based on a pattern comparison technique and a predefined threshold value Van Ufffelen *et al.* (1997) extracted a generalised pattern which is characteristic for the field (Figure 3). The choice of the threshold value is based on a percentage of the potential production but could be different for each individual farmer, i.e., it remains the farmer's choice. It is clear, however, that regarding the field as one uniform management unit introduces a certain risk.

Case 2. Defining the critical post-harvest N

Soil mineral nitrogen after harvest is the major source for nitrogen pollution of the groundwater (Van der Ploeg *et al.*, 1995). Farm management should therefore aim at an N profile in autumn which has a low risk of exceeding a pre-set leaching threshold during the wet season. Verhagen and Bouma (1997) have explored this problem by running the WAVE model for twenty wet seasons (15 September - 15 April), considering different N contents on September 15, ranging between 15 and 120 kg N ha^{-1} m^{-1}. The threshold value to evaluate the risk is defined by the amount of nitrate allowed to leach during the wet season. In this study the nationally defined maximum nitrate load of 35 kg is used as threshold.
The simulation results are presented in Figure 4.

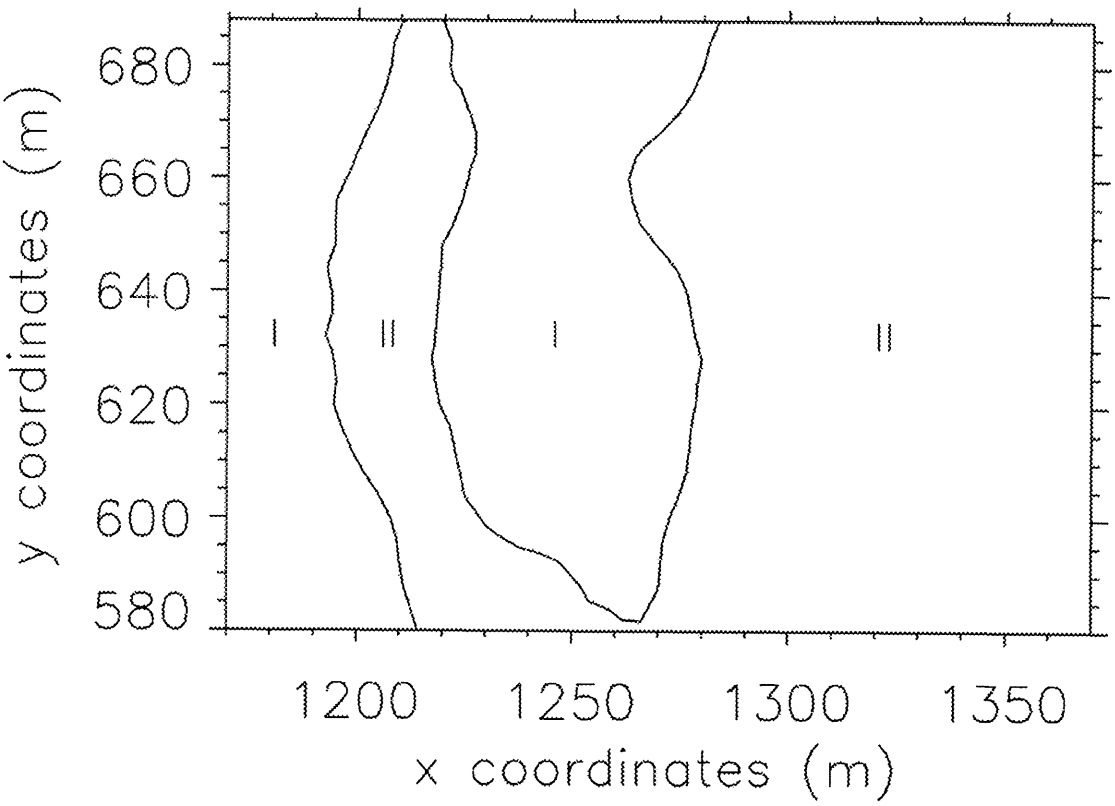

Figure 3. Generalised pattern for the farm field. Area I indicates the low productive area and area II indicates the high productive clayey area

Figure 4 presents the risk level as a function of the initial soil N profile. At the 0% risk level nitrate leaching will never exceed the threshold value when the soil contains the indicated quantities of N. With increasing risk levels the N contents also increases. For each individual profile the allowed quantity of N can be defined for each threshold value and associated risk level.

The spatial patterns of the required N profiles can be created by ordinary kriging. The produced map (Figure 5) can be used to evaluate and focus fertiliser management. Reacting to local differences the fertiliser rate and frequency during the growing season can be set to achieve a set target at the end of the growing season.

4. Conclusions

Using multi-annual simulation studies the dynamic behaviour of the soil-crop system can be quantified. The derived temporal and spatial patterns for production and leaching potential can be used to guide and/or evaluate farm management on field level. Spatial and temporal patterns derived from multi annual simulation provide important input in decision making processes. Choices based on threshold values defined based on financial or socioeconomic criteria can be assessed considering risk levels in both space and time.

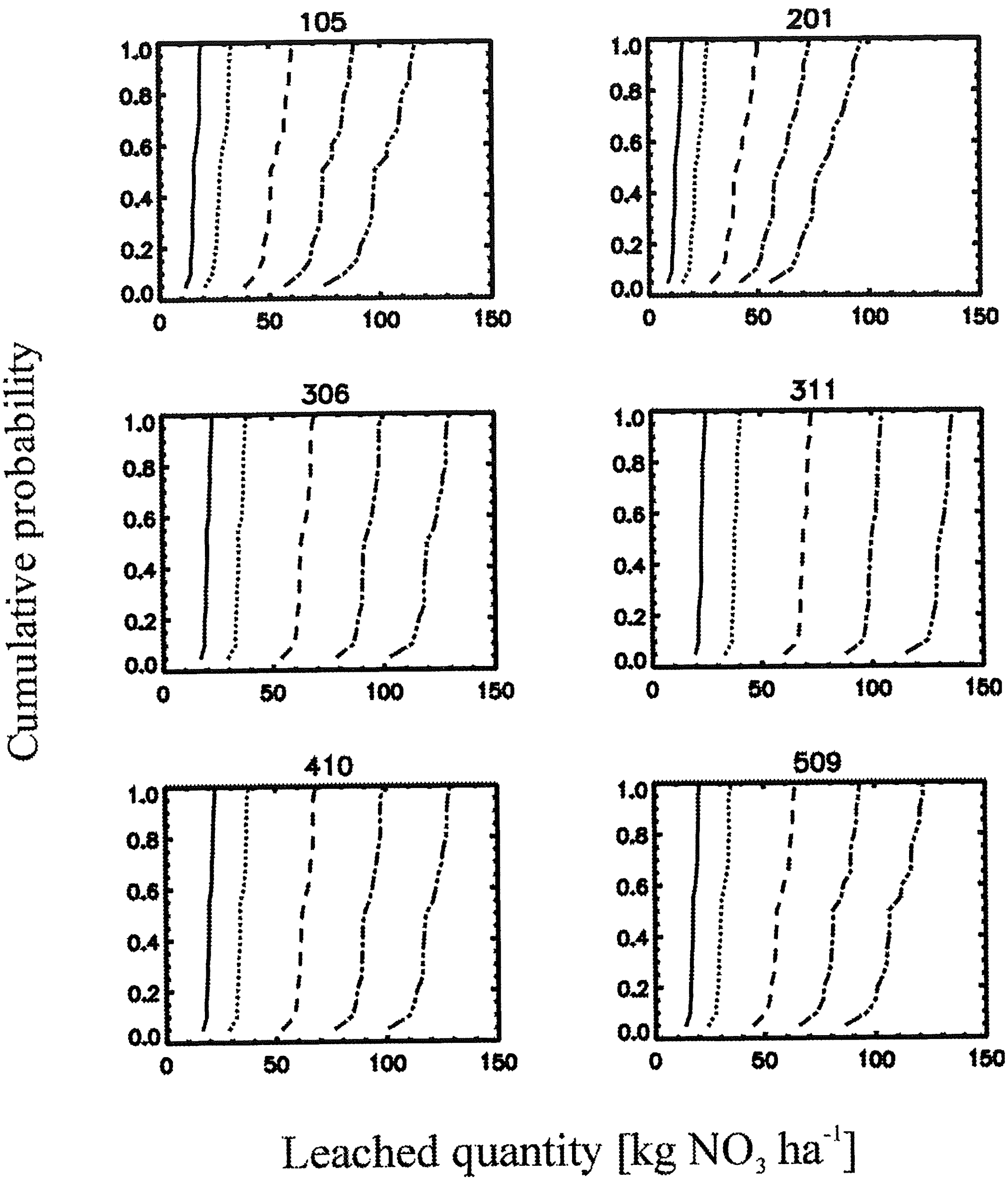

Figure 4. Leaching probabilities (based on 20 years) based on an initial N profile for six representative profiles (numbers refer to Figure 1). Initial N profiles on 15 September: solid 15 kg N ha^{-1} m^{-1}, dotted 30 kg N ha^{-1} m^{-1}, dashed 60 kg N ha^{-1} m^{-1}, dash dot dash 90 kg N ha^{-1} m^{-1}, and dot dot dot dash dot dot dot 120 kg N ha^{-1} m^{-1}

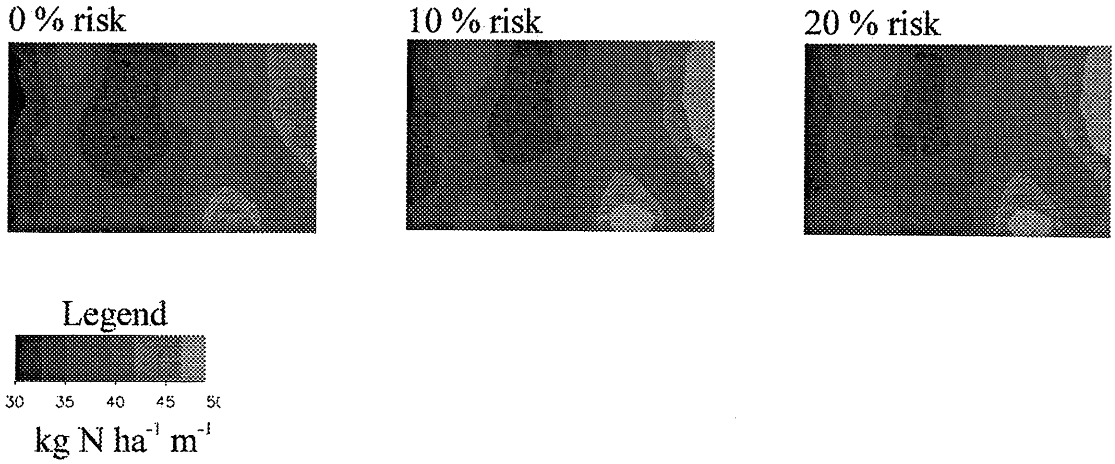

Figure 5. Target maps of the N profile (kg ha^{-1} m^{-1}) on September 15 for the 35 kg threshold value and three risk levels of exceeding the threshold value

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Decision aid and management of irrigated agricultural crop systems

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1. Introduction

The improvement of irrigated crop system management has become a priority mainly for economic and environmental context evolution reasons and because of the increasing interest in collective management of water resources on quantitative and qualitative aspects. Context evolutions lead farmers to reconsider the interest and the role of irrigation on their farm, and the way they manage their irrigation system.
For agricultural crop systems, the irrigation cost (mainly fixed cost) is high in relation to the gross product. Decisions taken before the irrigation season — cropping plan, crop irrigation strategy — are crucial for the irrigation management at the field level during the season. For the most part, this depends on the management of irrigation means.
It is essential to consider risks connected with climate variability and with uncertainties on the economic and regulatory contexts or on the water resource availability. Because of the diversity of contexts, irrigated systems and strategies developed by farmers, there is no single answer. On the other hand, the organisation of the irrigation site connected to the equipment and labour management is a significant question. The analysis of irrigation management has to be done at the whole farm level.
Since about ten years in France, many workers have developed an approach at the farm level on three axes: to deal with irrigated system diversity, interest, role and use of irrigation in farms (Reau & Capillon, 1993; Bourgeois, 1996); to design references and decision support systems (DSS) to help farmers in decision making (Deumier *et al.*, 1995); to design diagnosis methods to select relevant irrigation advises (Fort, 1996; Deumier *et al.*, 1996).
In this perspective, we present two decision support systems developed by INRA and ITCF. The first one (Lora) concerns the choice of the irrigated cropping plan on the irrigable area of the farm. The second one (Irma) is a simulation tool of the irrigation site organisation.

2. Lora, a DSS for the choice of the irrigated cropping plan

This first tool concerns the choice of the irrigated cropping plan on the irrigable area (Jacquin *et al.*, 1993; Leroy & Jacquin, 1994).
Having taken into account soil water capacity, climate and technico-economic context of the farm (potential yields, product prices, subsidies, input costs particularly of water), Lora seeks a cropping plan for irrigated and non-irrigated crops which maximises the margin on the irrigable area, and makes better use of the irrigation set-up in terms of volume and irrigation capacity. The climate and its variability are assessed from data obtained from a nearby meteorological station. The user selects a series of years from those available. Each one is

treated as a possible climate scenario. For each crop, Lora considers different irrigation management options (well irrigated, restrictive irrigation, no irrigation) on the basis of standard rules. It uses agronomic models to design the crop irrigation schedules and to calculate their consequences for yields and margins.
The user can also check his cropping plan. The model evaluates it over all the climate scenarios. Each solution can be analysed in terms of cropping plan, use of water resource and irrigation capacities, and economic results on the series of climate scenario. Thus, the user can assess the value and risk of each solution. It is then possible to modify the hypotheses retained in the data set (economic data, water cost, water resource, etc.) and to check their consequences against the results.
Lora can be used to anticipate changes due to modifications of the economic context or of external constraints in relation with the collective management of water resources (Jacquin *et al.*, 1994; Bouthier *et al.*, 1994).

3. Irma, a simulation tool of the organisation of the irrigation sites

3.1. Objectives

Irma is an irrigation simulation tool (Leroy *et al.*, 1996; Leroy *et al.*, 1997). Its objective is to facilitate the analysis and improvement in organisation of the irrigation sites over the whole-irrigated area of the farm. In technical and economic terms, it evaluates the relationship between the farmer's strategic choices (cropping plan and irrigation strategy per crop) with his tactical decisions during the season whilst keeping in view the conflicting demands on available. In terms of its use, the aim of Irma is to lead the farmer to reflect on his action rationale and on the way in which he organises his work, in his particular context of resources and constraints and in the face of variable factors such as climate in particular. The simulation tool allows us to assess the coherence of this action rationale in the light of the farmer's objectives and strategy, and to seek improvements in it.

3.2. Principles

Irma is based on a representation of the farmer's decision model. This model translates his strategic choices. It takes the form of a set of decision rules for the irrigation scheduling of the different crops and for managing resources throughout a season. This set of rules governs the organisation of the irrigation sites taking in account crops irrigated, fields, available volume and flow of water, structure of the irrigation network, equipment and work time required for its use.
Following a series of interviews with farmers and observation of irrigation seasons we were led to structure these decision rules in the following way:

- rules for irrigation management by crop to decide on start dates and irrigation amounts;
- rules for managing priorities between irrigated crops;
- rules for managing the farmer's working time and the use of water resource, flow and equipment.

This decision model is set against different climate scenarios. For each of them, we simulate the progress of the season by applying the rules to decide on irrigation. It generates irrigation schedules for the totality of irrigated fields in respect with both the constraints of resources and the working conditions of equipment.
Agronomic models allow us to assess the consequences of the irrigation schedules on the satisfaction of crop water requirement and the effect on yields. Economic hypotheses concerning crop price, cost of water and other inputs allow us to calculate gross margins for each crop and for the cropping plan on each climate scenario (Figure 1).
The results obtained for the various climate scenarios can then be analysed from different points of view: organisation of irrigation schedules, use of water resource and equipment, time given over to irrigation, yields and margins achieved, etc. Then, it is possible to envisage the consequences of modifications to the decision making rules and the underlying strategy, the economic data, the irrigated cropping plan, the water resource, the irrigation equipment and the availability of labour.

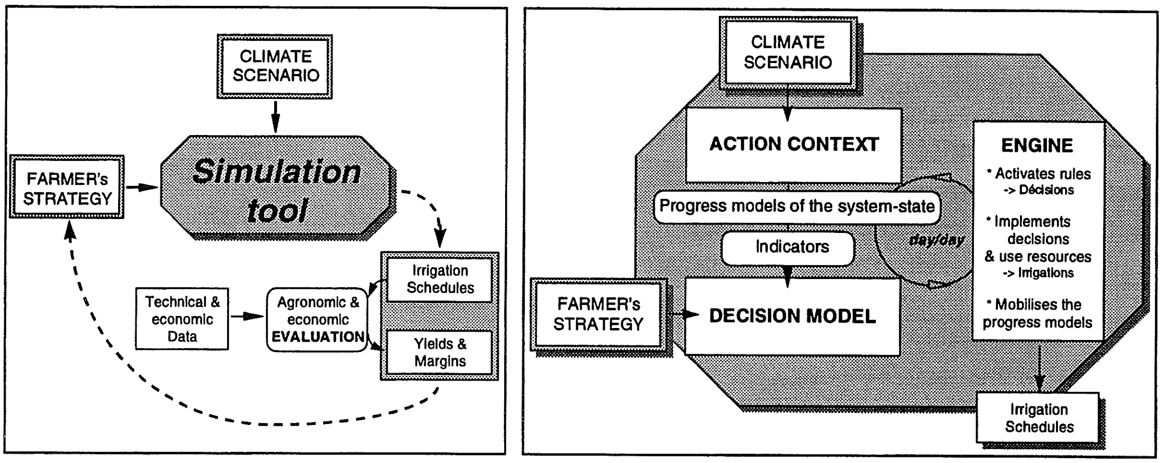

Figure 1. Principles and structure of Irma

3.3. Structure

Irma is structured in five parts (Figure 1):

- A description of the action context i.e. the characteristics of the irrigable area, the available resources (water, flow, labour), the irrigation equipment, the cropping plan and the climatic and economic contexts.
- A representation of the farmer's decision model in appropriate terms. It takes the form of decision rules for the management of crop irrigation, of priorities between crops and of water-resource, irrigation means and labour throughout the season. They mobilise indicators gathered from information on calendar, weather, crop-state, soil water content, resource and progress of work. These indicators must be coherent with those used by the farmer.
- Progress models of the system-state and particularly agronomic models, which calculate the evolution of the crop and of the soil water content as influenced by climate and implemented irrigations. These models supply the data necessary for the indicators mobilised in rules.

- An engine that simulates the application of the decision model to a range of climate scenarios. For each scenario, it generates irrigation decisions. It simulates their implementation while respecting the constraints and conditions of use of the different resources. It mobilises the progress models of the action-context. It then generates irrigation schedules for each field and produces a general organisation for the work sites.
- An agronomic and economic evaluator, which, via models, evaluates the consequences of these schedules on the satisfaction of the water-requirements of the crops and on the yield. Incorporation of data concerning the technico-economic allows us to calculate margins.

3.4. The action-context

It describes characteristics of the irrigable area, irrigation site and equipment, cropping plan, climate, soil and technico-economic contexts of the farm (Figure 2):

- The water resource: available volume, flow, water cost.
- The irrigable area split into irrigation zones taking in account the distribution of the total flow to the fields. Each zone represents a spatial entity defined by an available flow.
- The irrigation machines (type, working flow, area that can be covered) and the work time required to move irrigation equipment to a new position and to set it in motion.
- The soil types (and their water reserves).
- The fields: its area, the zone to which it belongs, defines each field. It is split into irrigation positions. The irrigation position is the basic unit for operational irrigation management. Each one is characterised by its dimensions, soil type and crop present with its sowing date.
- The crops are described in both agronomic and technico-economic terms:

A crop is defined by a crop cycle, i.e., a series of phenological stages and their appearance conditions (temperature sum). It allows us: to simulate stages which can be used as indicators for irrigation rules; to calibrate the agronomic parameters used to estimate the crop's water requirement. A production curve is defined to calculate the yield loss in relation with the level of satisfaction of crop water requirement.
For each crop, the technico-économic data are: the selling price, the level of subsidy, and for each soil type, the potential yield (under well-irrigated conditions) and the level of input costs (excluding the cost of irrigation). These data allow us to calculate margins.

- We use daily meteorological data: rainfall, reference evapo-transpiration, minimum, maximum and average temperatures and average wind-speed. These data are obtained from a nearby weather station. Each weather-year available can be used as a climate scenario.

3.5. The decision model

The decision model (Figure 2) consists of a set of decision rules: those that manage irrigation and define irrigation requirement for each crop, those that establish priorities between crops, those that manage resources (water, equipment, labour). These rules are defined and applied at the **irrigation block** level, each consisting of a series of positions managed in a uniform way.
For each block, we define **a rule governing allocation of equipment**: appropriate equipment is allocated to each block in an order of preference. This allows us to allocate or specialise a particular equipment to one or several blocks and to consider alternative solutions.

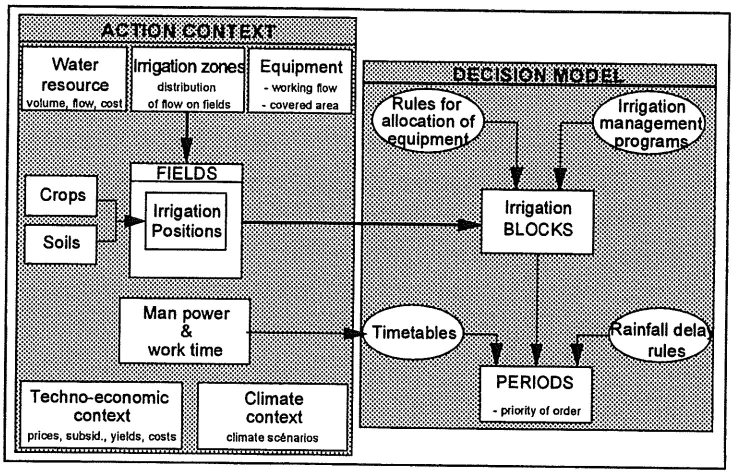

Figure 2. Action context and decision model

Each block is allocated an **irrigation management program**. It is defined by a set of rules to fix the date and volume of irrigations required and by a condition that defines the definitive end of irrigation. The basic form of the rule is "If (start condition) then decision". The "start condition" proposition allows us to determine the date at which an irrigation decision is desirable. It uses different indicators (climate conditions, stage of the crop, soil-water content, length of time since last irrigation, calendar date, water resource level, etc.). The "decision" proposition indicates the amount of irrigation required (Figure 3).

AsSoonAs (Stage >= *10-12_leaves* & Deficit >= 50mm)	Water-depth = 25mm
While (Stage < *Milky_seeds*)	
If (Deficit >= 60mm)	Water-depth = 35mm
While (Stage < *Maturity*)	
If (Deficit >= 80mm)	Water-depth = 25mm
Stop: Stage >= *Maturity*	

Figure 3. Example of irrigation management program

To manage the allocation of water, equipment and labor resources to the blocks, the irrigation season is split into **periods** during which rules of priority are defined. These indicate an order of irrigation for the blocks throughout the period. Each period is also characterised by: a **timetable** to manage labour and defined by a set of permissible time slots in the day for changing position and restarting; a **delay rule following rainfall** to interrupt irrigation momentarily if rain occurs. Several periods can be defined if blocks to irrigate or priority order change, or if timetables are modified to take into account new competition on labour with other farm work.

3.6. How Irma operates

Irma can operate for different climate scenarios. For a given scenario, it makes a daily simulation using the rules previously described respecting the constraints of the resources,

flow, equipment and labour. Daily, if irrigation is possible (no delay due to rainfall), it determines which blocks should be irrigated (irrigation program), and it operates irrigation in the order of priority for the blocks, position by position. At the end of each day, where no more irrigation can be done, it calculates, from agronomic models, the water-balance and crop state of each position. On the irrigation season, it generates irrigation schedules for all the blocks. It evaluates their consequences on the satisfaction of crop water requirement and the effect on yields (production curve) and economic results.
It gives for each scenario: a daily irrigation journal; irrigation scheduling per block connected with crop cycle; organisation of irrigations on all the blocks throughout the season; use of water resource, equipment and labour; yields and margins for the fields and the irrigated cropping plan. Those results can be synthesised over all the climate scenarios and analysed from different points of view.

3.7. Results expected

Three types of results can be expected from the use of Irma:
- on real farms, with the aim of helping farmers in decision making, to diagnose their present irrigation management; to detect critical points and progress margins; to consider the possible evolution to improve the flexibility of the system to deal with variability and uncertainties;
- on farm type, with the aim of anticipating context evolutions, to consider their consequences; to check new strategies and irrigation management rules; to design references;
- to give a way of understanding and making explicit the irrigation management at the farm level and to diagnose the water management on farms taking in account farmer's aims and constraints.

4. Conclusion

These tools are used by research and extension services to deal with irrigation management at farm level. Their predictive value depends on the predictive value of the agronomic models. Some improvements have to be made to better assess the consequences of farmer's practices on production (both in qualitative and quantitative terms) and on the environment. This work is in progress in relation with the INRA Agronomie of Toulouse.

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Decision support for work organization and choice of equipment

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For farmers, the increasing labor productivity is crucial and asks for redefinition of both strategic decisions and management practices. On arable farms, this increase was traditionally made by a systematic rise in the capacity of the machinery. This practice was a simple way to mitigate the risks regarding climatic variability. Associated costs were high. Reconsidering this strategy of assurance is not so trivial because it questions various levels of personal and tacit knowledge such as: theorectical and practical know-how, experience, risk perception, intuition about links between technical performances and economic advantage and other private considerations.
Previous analysis of production management on arable farms (Chatelin and al., 1993; Papy, 1994) have shown that farmer's production management is based upon an integrated vision of different decision levels (from operational to strategic ones). For each crop, the farmer conceives a body of coordinated rules for the successive steps of technical management. Furthermore, whenever conflicts appear between several concurrent activities for allocation of limited resources (labour, equipment), he decides on the basis of priority rules with respect to his aims of work progress in relation to his objectives of production. This vision structures production management by way of programmed patterns of action (more or less implicity) in such a way that the objective 'deadlines' are respected for some key operations. This raises the problem of the relevance of these patterns with a strategic point of view (labour and investment requirements), especially in the new context of production.
To answer the question of labour and equipment requirements on arable farms, we have conceived a simulation tool (OTELO, Attonaty *et al.*, 1993) that focuses on work organization. This instrument is based upon managerial knowledge representation (the decisional model) and simulation processing taking account of the climatic variability. An experiment concerning the use of this tool has been carried out since 1990 in Picardie (north Parisian Bassin) with groups of advisers and farmers. This project motivated us to conceive a set of methods adapted to personal advise and training session for farmers. The aim of such methods is to favour an interactive and cooperative approach between the farmer (the problem owner) and the adviser.
In Picardie, a project started in 1990 aimed to design advice methods suitable with fixed costs, work organization and agro-equipment. This project has taken the form of a collaborative process between extention services, Agro-Transfert[2] and research.
We will present first the main principles of the instrument, then the methods conceived in Picardie, and finally we will use the advice approach.

2 *Agro-Transfert is a section of the "Biopôle végétal" created at the level of the region. Its mission is to provide relay between basic and applied research institutes and extension services.*

1. A tool to check work organizations against a simulation model

The main principle of this tool is to reproduce the decisions of a decision maker faced with climatic events, work progress and work capacity. The aims are is to provide simulation technique as a means to experiment projects in a way that deals with practical problems faced by farmers. It supposes thus to consider the risk on the basis of farmers' vision (in our purpose climatic variability in the form of historical scenarios).
In this perspective, we have designed a representation framework with a structured language suitable to work organization in arable farming systems.
Regarding the language, we implement three types of frames: operations, sequences and periods, according to the hierarchical organization revealed by the study of work organization practices. **Operation** constitutes the operational level at which operations are executed. It contains possible combinations of equipments and manpower and rules to decide traficability, work speed and work quality in regard to climate and state of soil. **Sequences** constitutes rules to manage the succession of operations for cultivation of fields and to adapt the choice of operations to be executed taking account agronomic conditions (see Figure 1). **Periods** constitutes rules to settle the conflicts between concurrent operations and to decide upon labour availability. These rules are expressed with production rules (IF conditions THEN decisions) mobilizing the words provided by the language or created by the user.
The body of rules for the studied case is processed by an 'engine' with structural data (areas, equipments and manpower availabilities) and historical daily weather reports. This engine is programmed to run every days and to provide the detailled report of operations.

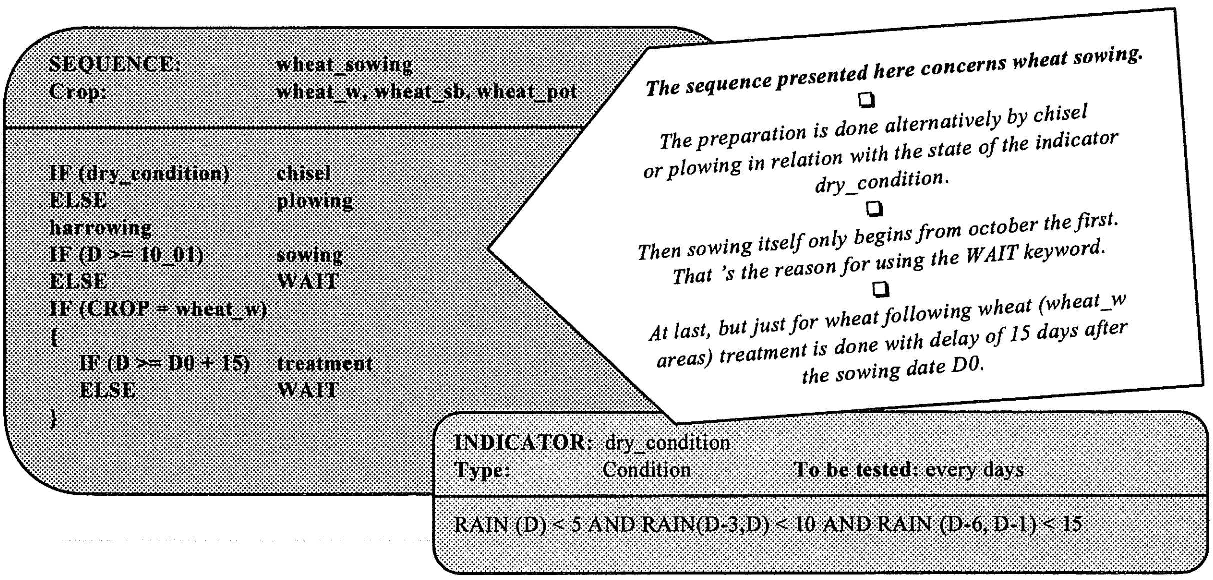

Figure 1. Example of wheat sowing sequence

2. Intervention progress to encourage learning process

The simulation tool has been used as an instrument of intervention in both personal advice and training sessions for farmers. The experimentation has given greater place to joint projects between several farms preparing to share their means of production. This methodological choice has been taken for three reasons: (i) this kind of project is complex and gives good situations to test the robustness of the methods, (ii) such solutions seem to be a major alternative to decrease fixed costs, (iii) more and more farmers consider the future in this sense, but they don't have much experience of problems that can occur in collective coordination. The experiments have been driven by Agro-Transfert and gradually by advisers of extension services. This project has given rise to methodological thought and has led to concrete approaches.
The different experiments (for both personal advice and training sessions) have shown that to benefit from learning process implies to respect a progress during intervention. In particular, it has given prominence to the importance of the analysis of the current situation (if possible). We can now propose a guideline structured around three basic stages:

- **To make explicit the present situation in the form of a model**. Obviously this stage is crucial, because the rules underlying decisions regarding work organization cannot easily be retrieved from direct interviewing. In fact, with a little practice and guidance of a supporting manual, advisers quickly acquire skill on this subject. For farmers, we generally note that the main ideas of their projects take form at this step. Formalizing his own organization appears to be a cognitive trigger action for the farmer to stand back his managing way and to imagine new solutions.
- **To 'validate' this model and to analyse risk.** Such a method requires a 'valid' simulation model. This means that farmers can see sufficient similarities between his farm and the results of his own model. So, farmer's recollections on recent years are confronted with the simulated results obtained with climatic data of the same years. In the course of process, this step is critical to win farmer trust in this experimental approach through simulation processing. This stage leads up to analysing risk. This evaluation is made on the basis of simulations processed for 20-30 historical climatic scenarios. These results allow to discuss on the one hand, the robustness of the model to reach technical aims of farmer, on the other hand, the effect of this variability of results in regard to economic income. The major interest of this step is to confront farmer's risk perception with a homogeneous set of results obtained in the same conditions (cropping plan, means of production, work organization, hypothesis of prices...), except the climate.
- **To design and to compare projects**. In the final stage, the thought process is highly engaged and solutions to be tested are well enough defined. The role of the adviser is thus to help the farmer to translate these projects in a coherent way taking account of the different components. Sometimes we still observe some difficulties for farmers to project himself into the future and to imagine concrete solutions to reaching his objectives. The second role of the adviser is also to guide the farmer to express criteria and to make a balance between different solutions on this basis.

3. Example in a concrete advice situation

The problem faced by Mr. B. is to anticipate the departure of an employee. His farm is characterised by a production system based on a high proportion of cereals, potatoes and sugar beets. It results in a 'bottle neck' in autumn for work organization because sugar beet harvesting, potato harvesting and cereal sowing are competitive. In consequence, this period is crucial because it strongly determines the level of mechanisation and the number of required workers.

3.1. Analysis of the present situation

To test the representation of Mr. B.'s work organization, we have made a comparison between results of simulation and the work calendar for the last two years. In this case, a level of accuracy from zero to three days is performed. Mr. B. has judged this "likeness" sufficient. So, to analyze risk, we have imposed the calendar of key operations over 20 climatic scenarios to compare the simulated end dates of these operations with the objectives of Mr. B. Figure 2 shows that the objective of cereals sowing (November the 1st.) fails five years. To estimate economic risk associated with these delays, a yield decrease of about 0.5 t/ha is adopted after this date. Another important type of criterion concerns the work intensity, expressed, here, by labour hours for each decade.

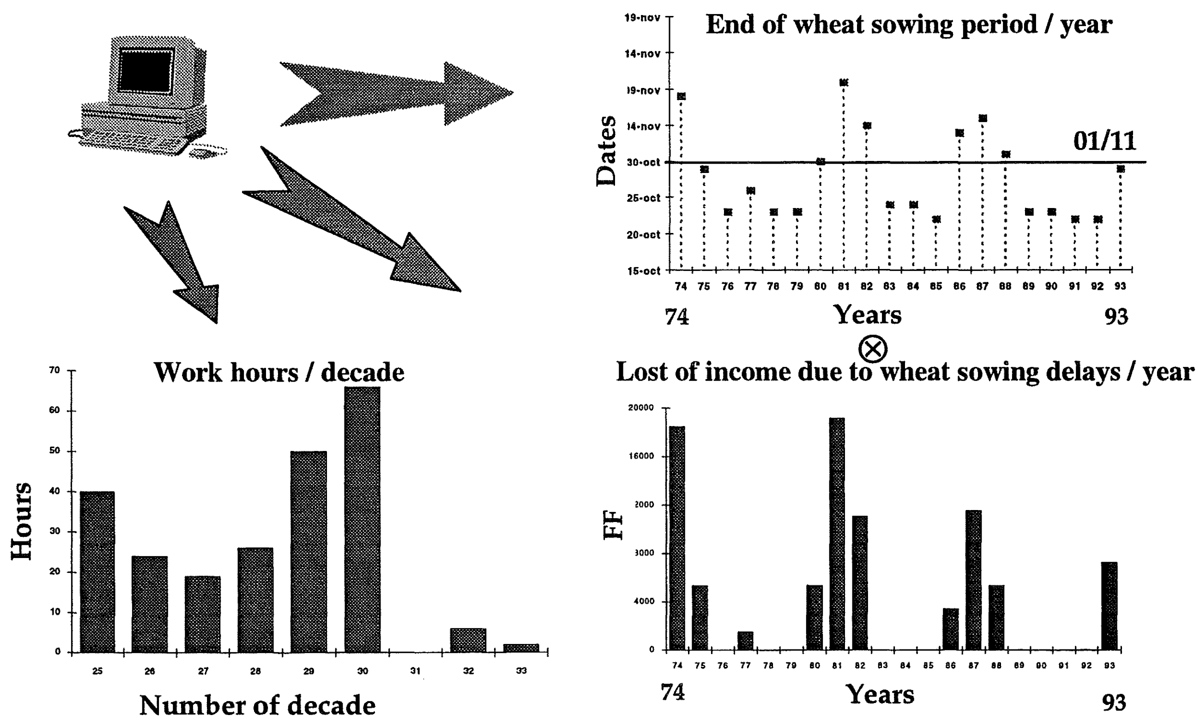

Figure 2. Simulation of present situation

3.2. Building projects and comparaison throught multiple criterions

We have built four projects. Two of them are described in this paper, because others are very closed to actual situation.

The aim of the first project is to study the maintenance of a 'self organization' while decreasing the equipment in spite of the employee departure. For this project, the farmer would have to call a contractor for the sugar beet harvesting. The second project concerns a collaborative organization with another farm of similar acreage. In the two projects an actual cropping plan is maintained with just introduction of set-aside.
In this case, three quantitative criteria have been chosen to analyze each project: economic results compared with present situation, average risks due to late sowing and a criterion of work intensity (spare time of the farmer). The first conclusion is that the economic results of each project maintain a income above the actual revenue of the farm. Furthermore, in the second project, the gain is reached with a lower range of variation and with an increase of spare time for the farmer. The reasons of these gains are mainly the decrease of number of employees, then the decrease of tractors. Of course, we have to be careful with such figures because they imply deep modifications of equipment and management, as well as social consequences.
In addition, strengths and weaknesses have been discussed for each project.

	Quantative criteria			Qualitative criteria	
Projects	Average risks for wheat sowing delays	Free time	Economic results	Positive	Negative
Present situation	10 000 F	62%		Autonomy	
Self organization	1 200 F	65%	+ 850 F/ha	Flexibility	Time availability
Collaborative organization	6 000 F	74%	+ 1123 F/ha	Human relation	Redundancy
				Free time	Flexibility
				Equipment	Succession

Figure 3. Comparison between projects and the present situation

4. Concluding remarks

Through the uses developed in Picardie we can now discuss (in a better way than through the instrument itself) the interests and limits of actor-oriented methods and associated support system applied to intervention at the farm level. Such approaches receive some remarks which can be interpreted in a promising way regarding both the interest for the actors (farmers and advisers) and more restrictive regarding usual constraints of the advice in extension services.
Regarding the farmers, they generally have clear satisfaction with the applied method. For them, the major advantages are to be both concrete and rigorous and to take into account the risk in a way they understand. We generally observe a strong involvement from them. Moreover, they often wish to continue. Yet we have to be careful with the fact that concerned farmers are motived and are often already engaged in the way of change (in fact or in mind). Actually many farmers consider the decrease of fixed costs as a challenge for the future, but they often don't express explicit requests for advice. We have to keep this in mind when initiating some more straightforward methods to make them alive to concrete solutions at this issue.
Regarding the advisers, developing a learning process as a basis for intervention keeps them involved to develop actively a new 'know how' of intervention. They have to combine on the

one hand a comprehensive attitude to help farmers making explicit their management rules and their projects, and on the other hand, a more prescriptive attitude to guide them in researching satisfacing solutions. In short, they have to play a very active role in the process. To summarize, we have attended the emergence of both a methodological thought and new specialized actors in this style of advice. However, because this implies personal investments, the question becomes now: how can their experiences be conveyed to other advisers?

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Farmer's technical decisions representation and decision support

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It is often remarked that farmers do not follow the technical advice produced by the research and extension services, although these technical references mostly proved their experimental value. It is now largely admitted that this fact often reflects an inadequacy between the proposed techniques and the constraints and functioning of farms more than technical insufficiencies or failings of the farmers. Then we think that decision support systems can be relevant not only for the farmers but also for the producers of technical references and crop management systems. It is a way to take into account the constraints functioning on the farm and to increase the pertinence of the production of technical references and crop management systems. Our contribution to the latter consists in building conceptual models of farmers' technical decisions that could be used by research and/or extension services to adapt their references and advice to the management levels and constraints of the farmers. On the basis of these conceptual models, simulation tools have been built: here, we will discuss some points of their use and relations with the proposed representation of farmers' decisions.

1. A conceptual model to represent farmer's technical decisions: framework and a set of adaptative decision rules

Detailed inquiries on a lot of arable farms (Papy *et al,* 1988, Aubry, 1995) have shown that recurrent technical decisions in farms, like managing an annual crop, may be represented by *planning schedules*. These plans are determined by the farmer's objectives, risk perception, experience and learning processes (Nitsch, 1991; Cerf, 1994; Jacobsen, 1994).
For arable farms, we have shown that farmers' production management is based on an integrated vision of two main levels: the crop and farm ones. At the crop level, one major aspect of the decision problem is to manage crop areas often composed of various and heterogeneous fields. At the farm level, the management of limited resources deals with the necessary solving of conflicts between various crops and operations for the allocation of available resources as manpower, equipment, water, and land. In this presentation, only the joint question of crop management and work organization will be considered.
For the level of crop management (Aubry *et al.*, 1997), we opted to represent these planning schedules through *descriptive decision variables* on which the farmer projects his crop management and formalized *decision rules* as the expression of the farmer's modes of action. Each ***technical operation*** can be described through a framework made up of three main components: ***timing, modalities*** and ***batches of fields*** managed in the same way.

- The ***timing of operations*** results from (i) the *chronological order* in which operations have to be carried out for a crop (ii) a *time interval* (beginning and duration) that determines the expected bounds of each operation (iii) the *sessions* that express a possible partition of a time interval. Their number and position characterize them.

- ***Modalities*** include for each operation, the choice of (i) tractors, equipment and workers (ii) the nature and application rate for inputs (seeds, fertilizers and treatments).
- The ***batches*** express groupings of sets of fields, which could be treated in a similar way for an operation. We observed that farmers do not adapt technical operations to each field. In particular for inputs, they apply a limited number of modalities in regard to the number of fields and their variability of state. So for nitrogen or pesticide programs, often no more than 2 or 3 doses were given for a wheat area of 10 to 20 fields. We observed also that the constitution of batches was strongly linked to the design of sessions of operations.

Timing, modalities and batches are determined by the interaction of several types of decision rules. For example, the foreseen timing of each operation depends on its starting and ending rules and on arbitration rules with the other concurrent operations. An illustration is given in Figure 1 for an arable farm cultivating potatoes, sugar beets and wheat in the North of France. During the autumn period, wheat sowing sessions alternate with the harvest sessions for sugar beets and potatoes and with other wheat operations like herbicide supplies.

- The farmer defines the time intervals for the required operations, according to his production objectives, the risks he tries to avoid and/or exogenous constraints (Figure 1-1). For ware potatoes the farmer expresses what he thinks the best harvesting conditions (not too dry to avoid the breaking of the tubers, not too wet to avoid earthy tubers and no risk of compaction of the soil structure). For wheat sowing, he considers October as the necessary period to reach the high yields he hopes for this production. For the starch potatoes and sugar beets, he integrates the constraints defined by the industries that impose to each farmer a certain number of harvest sessions.
- Because of the implements defined for operation, harvesting cannot be performed simultaneously for potatoes and sugar beets, The farmer organizes priorities between crops by sequencing sessions. In addition, he defines three distinct sessions for wheat to respond to different market outlets corresponding to three types of varieties. So, work organization is projected as the alternation between different sessions of each operation (Figure 1-2). We can observe an adaptation of initial time intervals due to the anticipation of eventual conflicts.

2. Using simulation tools to take into account production management

Our research team has built two simulation tools: DECIBLE at a field level and OTELO at farm level. The first one (see presentation by J.M. Meynard) simulates the agronomic consequences of a given action plan expressed through adaptative decision rules for wheat management. The second one (see presentation by J. Mousset) simulates the consequences of work organization rules on the work progress and the calendar dates of each operation. The work organization is described through three types of objects, which partly correspond to those described at the individual crop level. (i) The ***period*** is the time duration during which several operations have to be done for the various crops in the farm. Each period is defined with arbitration rules to define priorities between operations. (ii) The ***sequences*** describe, for a crop or a batch of fields, the chronological order of operations and the choice if alternative is possible. (iii) An ***operation*** determines its implement as possible combination of equipment and workers, intervention conditions and execution speeds.

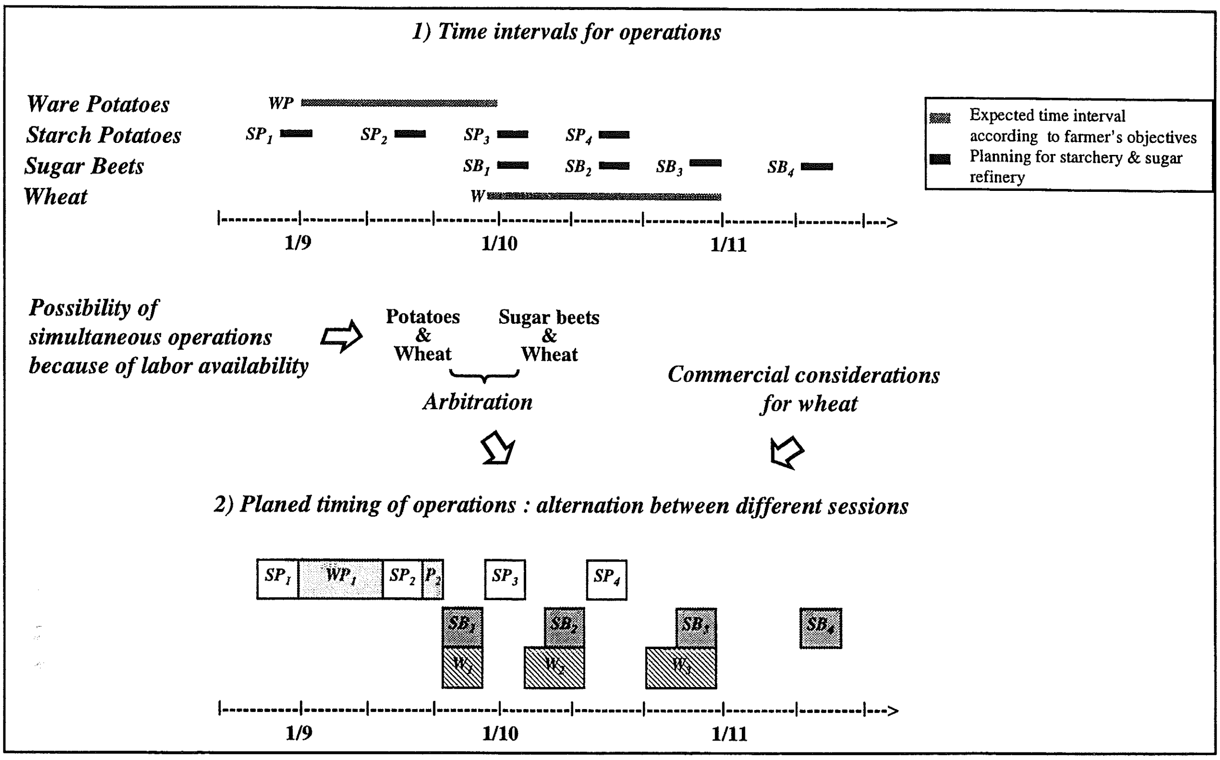

Figure 1. Modeling the timing of operations

2.1. Use of the simulation tools on a farm

The conceptual models propose a representation of the expected planning schedule designed by farmers to manage the crops and/or to organize the work. But real practices are not entirely determined by these forms of planning, because of the influence of sources of variability in the concrete realizations (climate, unforeseen events like breakdowns, etc.). Then, a main purpose of these simulation models is to offer the opportunity to check a considered action plan and to explore its robustness facing the variability (especially of weather) in regard to various criteria. In this perspective, action plans can be translated in a set of decision rules and simulated for a wide range of climatic scenarios.
As an example, we have simulated the consequences of the work organization schematized in Figure 1 for the wheat sowing dates (Figure 2) and the consequences of the variability of these dates for the occurrence of the start of stem elongation (Figure 3). This development stage has been chosen because it is crucial to 'optimize' the nitrogen application on wheat.

Figure 2 presents some differences between the previous representation and the results of simulations of work organization with OTELO. The three expressed sessions of wheat sowing are present but the expected final date of 1/11 for ending the wheat sowing is scarcely respected. Consequently, a part of wheat is sown later and sometimes much later. The areas sown for each session (except the first one) vary a lot from year to year. In fact, by confrontation with these simulation results, the farmer confirmed the frequent occurrence of later sowing sessions, and gave us his rules for choosing sowing modalities in such cases (varieties, densities).

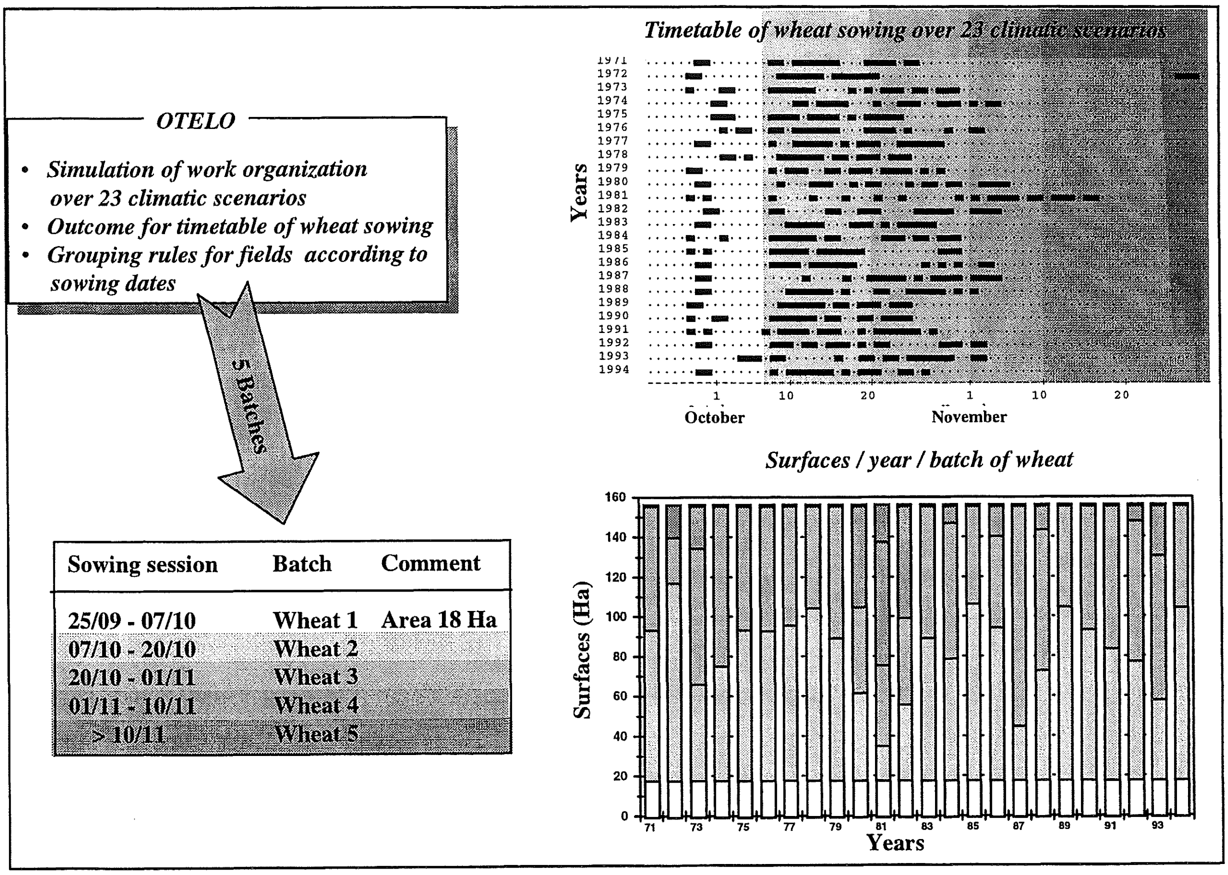

Figure 2. Simulation of work organization and its consequences for wheat sowing

DECIBLE works at individual field level: then we choose to simulate the earliest and latest wheat present in each batch. Each batch was sown with the same variety according to the farmer. We see (Figure 3) the heterogeneity of occurrence dates for this stage between years and fields of a same batch. The date of this stage for the earliest wheat (generally batch 2) varies from 20/02 (1988) to 08/04 (1985). The interval between the earliest and latest wheat ranges significantly between years: from 14 days (1977 & 1983) to 48 days (1986) for the wheat area taken as a whole and from 2 days (1989) to 28 days (1988) for wheat of batch two. This heterogeneity for both the beginning and the duration of the stage makes it difficult to apply nitrogen in spring at a specific optimal date on each field. This remark is all the more important since the global work organization in spring can meet problems of concurrency with other crops having priority, e.g. the seeding of sugar beets and potatoes (see shaded area in Figure 3). This representation of the problem may help him to plan a nitrogen application rule by choosing the one or two fields to observe so as to minimize, at crop area level, the gap between a limited number of dates for the set of fields and the optimal date of each field.

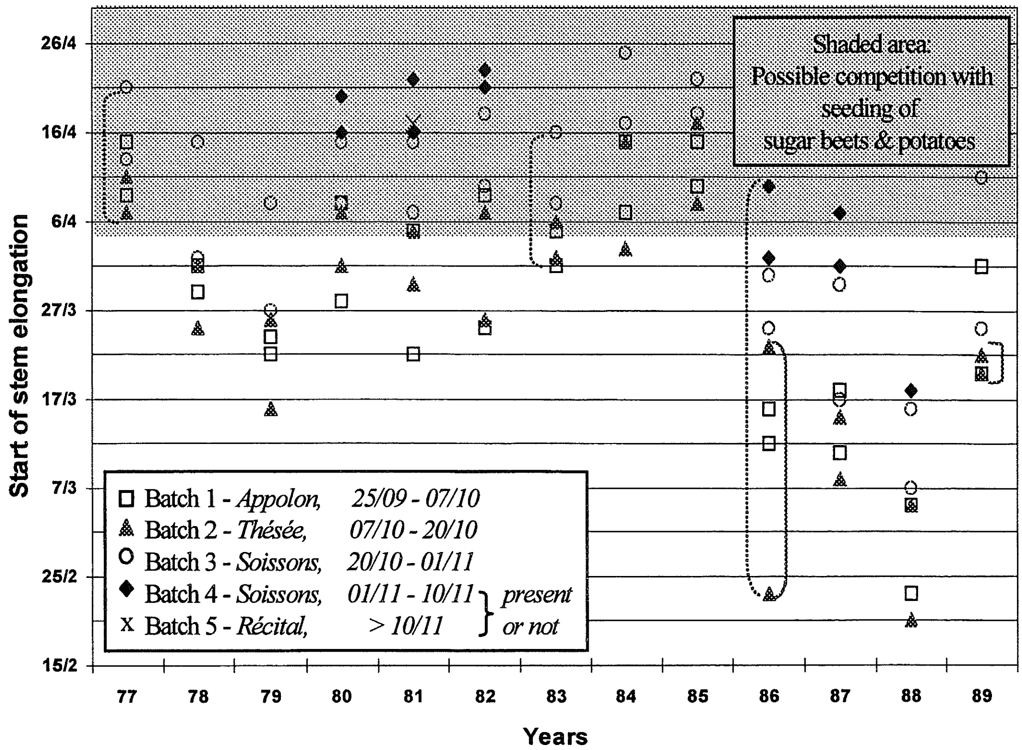

Figure 3. Simulation of start of stem elongation dates with DECIBLE

In this way, the simulation tools offer an operational help to analyze and diagnose the consequences of *a priori* set rules: such a confrontation between conceptual models and simulation results permits to have an interesting and original diagnosis when comparing different plans of actions.

2.2. Taking into account farmers conditions of action in designing simulation tools

As we saw before, because of their constraints and decision rules, farmers may have to face a very large variability of technical situations: the resulting dates and modalities of operations may be very far from the optimal ones from an agronomic point of view. To simulate the consequences of realistic operations on a crop implies to model the effects of combined non-optimal techniques on the crop development, yield formation, disease risks etc. But this knowledge is not often available because a lot of experiments and technical references used for advice or for model-based tools aim to design the optimal action in each context. Then, the critical examination of farmers decision rules leads to questioning the validity range of the current biotechnical models. J.M. Meynard will illustrate the conception of some biotechnical models for wheat in such a perspective.
Another important point is the frequent lack of correspondence between agronomic variables used in crop models and decision indicators used by the farmers. For example, some crop models simulate the aerial biomass of the crop as useful variable to predict final yield, to

diagnose growth limiting factors or to determine nitrogen needs. Farmers cannot easily measure this variable in a field, and *a fortiori* in all the fields of a crop area. At best, farmers can count the number of plants or ears per unit area on some of the fields, and mostly only appreciate a global density of vegetation. Then the question becomes the correspondence between these indicators for action and the pertinent agronomic variables, and it is necessary to work on specific models of "translation".
Last but not least, we showed that pertinent decision levels for farmers are not only the individual fields but also more often batches of fields; we also showed that crop management rules strongly depend on global work organization in the farm. Crop models used as decision support always consider the individual field level and scarcely include constraints of work organization. We are now working on an adaptation of DECIBLE: DECISOLE (work in course); this would allow the simultaneous management of various fields on the basis of a set of rules for a batch.

3. Conclusion

For the work organization, conceptual and simulation models are used in concrete advice situations as basis to discuss equipment, manpower, cropping plan or sharing of production means between several farms (Attonaty *et al.*, 1993; Chatelin *et al.*, 1994). More recently, two technical institutes in France (ITCF and CETIOM) have used the conceptual model of crop management to design more pertinent management systems for wheat and rape seed (Félix *et al.*, 1996).

Conceptual models of farmer's technical decision are a powerful mean to describe crop management decisions on the farms. They are also useful for advisers to understand how constraints of action on farms imply consequences on the crop management and to provide technical management advice that better meets objectives of farmers. In contrast, building simulation tools for decision support poses the problem of theoretical knowledge available to take into account the conditions of decision making process in the farms.

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Section III

REGIONAL SCALE

Explorative land use studies and their role in supporting regional decision making

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Abstract

This contribution focuses on explorative land use studies and their role in supporting decision making processes for the regional level. Explorative land use studies enable a transparent discussion on policy objectives by showing ultimate technical possibilities and consequences of giving different priorities to agro-technical, food security, socio-economic and environmental objectives. A methodology is used in which objective fact-driven technical information is confronted with value-driven objectives under given values of exogenous variables (e.g., regarding population growth and demand for agricultural produce). Land use scenarios are produced showing consequences of different priorities for objectives by using natural resources and technical possibilities in different ways. Interactive Multiple Goal Linear Programming is often used as the integrating tool.

1. Introduction

Main problems with land use in many countries are of socio-economic, ecological, agro-technical and environmental nature. Employment in agriculture and forestry, and their share in the Gross Domestic Product (GDP) are decreasing rapidly in many countries. Agricultural land use is increasingly competing with other types of land use, for instance for nature and urbanisation. Countries may have problems with under- or overproduction of agricultural products. Finally, natural resources are often used in an inefficient way, resulting in negative environmental side effects such as erosion and emissions. Thus, reasons for an active land use policy are manifold. Problem definition and agreement on the need for policy intervention, identification of policy objectives and, subsequently, the means to realize these objectives are the first conditions for any change. In each of the phases of policy making land use studies might play a role, but also, each phase in policy making requires its own type of land use studies.

After problem definition and consensus on the need for intervention, the policy debate often shifts towards identification of the means, the policy measures, before being clear about policy objectives. Reasons for that may be that both the objectives and the consequences of the objectives are unclear. Land use studies that *explore* future land use options can play a role here. They can help in showing ultimate consequences and possibilities of well-defined objectives. This paper presents a general methodology for explorative land use studies for the regional level. Since in many land use policies the ultimate aim is the development of sustainable land use that guarantees sufficient food supply and other societal aims we will first introduce an operationalization of the notion sustainable development.

2. Operationalizing sustainable development

Sustainable development comprises value-driven (what is considered 'good' or 'desirable') and technical (what is 'feasible' or 'attainable') aspects (WRR, 1995). The value-driven aspects in land use include ecological, agro-technical and socio-economic dimensions which can be regarded as objectives and constraints that are given different priority by the various stakeholders. Thus, operationalizing sustainable land use is equivalent to finding compromises that are acceptable for the various interest groups and stakeholders. The weighing of objectives should be done explicitly, based on transparent trade-offs among objectives. Information on these trade-offs should form the basis for strategic decision making. Scientific information can help to structure and organize a sound discussion on consequences of putting different weighing factors to more or less conflicting objectives. This requires a method of analysis that discriminates between information on value-driven preferences to discern the weighing factors, and objective facts-driven scientific information to study the consequences of the preferences. In an iterative and heuristic way this may lead to an operationalisation of the concept sustainable development that can be used in setting priorities to various activities or aims.

3. Methodology for explorative land use studies

Explorative land use studies apply the above described operationalization of sustainable development. In explorative land use studies options are based on i) knowledge of biophysical processes underlying agricultural production possibilities and ii) societal objectives as driven by perceived needs and risks, under iii) given values of exogenous variables that might greatly affect the system under study. Often, but not necessarily, an Interactive Multiple Goal Linear Programming (IMGLP) model is used as a tool to integrate technical information and information on social constraints and objectives, and to generate land use scenarios (De Wit *et al.*, 1988; Van Keulen, 1990). A scenario approach is used to investigate combinations of exogenous conditions, preferences for objectives and technical feasibility. Figure 1 presents a scheme of the methodology.
In contrast to studies using trend extrapolations, basic knowledge on soils, climate, crops and animals and their interactions is used for the design of new land use options. Basically crop performance is determined by growth-defining, growth-limiting and growth-reducing factors. Associated yield and input levels are highly affected by the physical environment in which production takes place (Rabbinge, 1993; Van Ittersum & Rabbinge, 1997). Current agricultural and socio-economic constraints are explicitized and not taken for granted and sometimes deliberately ignored, since they might obscure sight on strategic options.
An approach using the bio-physical potentials for quantification of production technologies is possible for agricultural land use, since agricultural production possibilities are ultimately defined and limited by climate, land properties and crop and animal features. Thus, ultimate agricultural production possibilities are dictated by land use and production technologies that

may result in an at present well-defined maximum. Ultimate food requirements are also rather conservative. In terms of caloric value the share of cereals, root crops and tubers in the human diet falls, while the share of other vegetables, sugar, fruits and, definitely, animal products rises as a consequence of higher incomes, but elasticity of food consumption is ultimately rather low. Requirements for agricultural produce can be deduced from food requirements, but, of course, such estimations do not take into account the use of agricultural products for industrial purposes, which is theoretically unlimited.

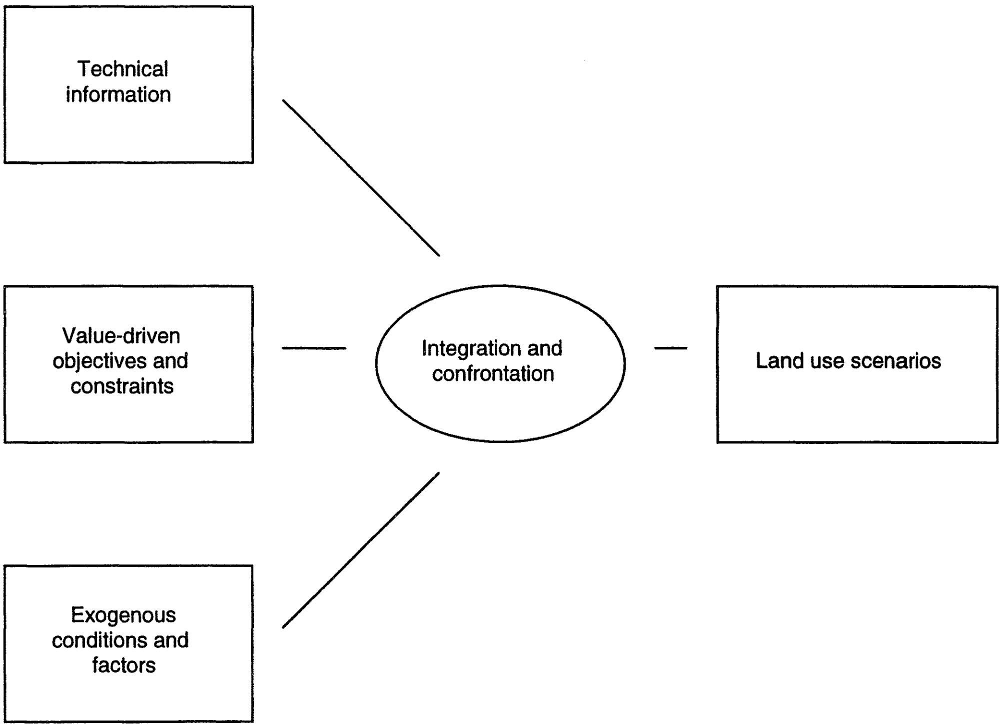

Figure 1. Methodology for explorative land use studies

So far, a number of explorative land use studies have been carried out. At the global level a study was carried out to investigate possibilities for world food production and food security (Penning de Vries *et al.*, 1995), at regional level studies have been carried out for the European Community (WRR, 1992; Rabbinge *et al.*, 1994), the Fifth Region of Mali (Veeneklaas *et al.*, 1991), the Mariut Region in Egypt (Ayyad & Van Keulen, 1987) and, though still in development, for the Atlantic Zone of Costa Rica (cf. Stoorvogel *et al.*, 1995). At farm level explorative studies were conducted for various agricultural sectors in the Netherlands (Van de Ven, 1996; Rossing *et al.*, 1997) and for small household farms in East Java (Van Rheenen, 1995). One, illustrative, example is presented in the next section.

4. An explorative land use study on perspectives for the rural areas of the European Union (Rabbinge *et al.*, 1994)

Immediate motives to carry out a study on perspectives for the rural areas in the European Union (EU) in the early nineties were i) tension between EU and the world market in the GATT negotiations; ii) increasing social pressure for attention to aspects other than agricultural productivity, such as environmental protection, nature and landscape, and iii) the widespread increase in agricultural productivity resulting in increasing surpluses for agricultural products and the associated budgetary consequences for the EU. Target groups of the study were policy makers in the Netherlands and the EU. In addition, the study aimed at stimulating the public debate on the future of rural areas.

The objective of this study was to explore long-term (25 years) consequences of policy objectives for the rural areas of the European Union, given an estimated demand for agricultural produce in the future and regional differences in production circumstances. Technical possibilities that are potentially present in the agricultural sector under different value-driven policy objectives were identified. Agrotechnical, socio-economic and environmental objectives were considered which were finally compiled to eight objectives (Table 1). The objectives were confronted with technical information on land use representing various production possibilities; only constraints that are imposed by the agricultural system itself were considered. Technical information was based on knowledge on biophysical processes underlying crop and animal productivity; application of best technical means at cropping systems level was assumed. Demand for agricultural produce, was derived from assumptions on population stabilisation, imports and exports and prevailing diets. Demand was quantified for both a situation of self-sufficiency and free trade, and for two diet variants: one representing a current average diet in the Union and one comprising relatively more animal products.

Technical coefficients for the land use activities were derived from the results of a mixed qualitative/quantitative land evaluation, using a Geographical Information System in combination with crop growth simulation models (Van Lanen *et al.*, 1992). In the qualitative part of the land evaluation crop requirements of three indicator crops (grassland, cereals and root/tuber crops) were confronted with soil and climate characteristics of approx. 4200 land evaluation units. For those units considered to be suitable for one or more indicator crops, potential crop yields were determined with crop growth simulation models, in which information on crop properties, soils and climate is integrated in a quantitative way (Bouman *et al.*, 1996). Results of the land evaluation and quantification of cropping systems showed that in the north-western part of Europe yield levels were often relatively close to their potential. This implies that further improvement of yields is limited. In other regions of the Union, mainly southern Europe, yield gaps are still enormous and natural resources very much allow improvement of yields. These yield gaps are much less when the condition of limitation due to water availiability is not removed.

In a next step cropping systems have been defined for different production aims (so called production orientations) and crop rotation schemes (De Koning *et al.*, 1995). Three production orientations were considered: yield-oriented agriculture (aiming at high soil productivity), environment-oriented agriculture (aiming at low emissions of pesticides and nutrients per ha) and land use-oriented agriculture (very extensive forms of agriculture with no use of pesticides). The application of the concept of best technical means for quantification of input

and outputs of cropping systems required information from the present production systems and expert judgement on the best way production may take place when the target yield is known.
The information at cropping systems level was confronted in the IMGLP model with wishes regarding performance of the agricultural system, i.e. the eight objectives, and values for the exogenous variable demand for agricultural produce, to produce scenarios on future land use for the EU. The model finds an optimal solution to the problem of fulfilling the demand for agricultural produce while at the same time fulfilling constraints put to the objectives. This can be achieved by choosing different types of cropping systems and locate them in the most appropriate region. Different priorities can be put to these objectives to force an optimal solution in a certain direction.

Table 1. Objectives and scenarios included in the EU study (WRR, 1992; Rabbinge *et al.*, 1994)

Class of objective	Objective
Agricultural	1. maximize soil productivity
Socio-economic	2. minimize costs of agricultural production
	3. maximize total employment in agriculture
	4. minimize regional decrease in agricultural employment
Environmental	5. minimize loss of nutrients per unit of acreage
	6. minimize loss of nutrients per unit of product
	7. minimize input of pesticides per unit of acreage
	8. minimize input of pesticides per unit of product
Scenarios	Descriptors
Free market and Free trade	low costs, free market, minimum of restrictions in the interests of social provisions and environment; imports and exports of food
Regional Development	regional employment in agriculture, regional income from agricultural sector; self-sufficiency for food
Nature and Landscape	conserve natural habitats, creating zones separating them from agricultural areas; imports and exports of food
Environmental protection	prevention of unwanted emission of contaminants from the agricultural sector to the environment, conserve soil, water and air, nature can be integrated with agricultural activities; self-sufficiency for food

The eight objectives enable the construction of numerous scenarios, that are finally summarized in four major political views (Table 1), illustrating consequences of contrasting choices. Their differences give an indication of maximum policy influence. In the Free trade and Free market view, for instance, costs for agricultural production are minimised and no other major restrictions are put to the model. The demand for agriculture produce from within the EU is modified according to expectations regarding new market balances. The model will now select the most cost-efficient types of land use in the most productive regions. In the Environmental Protection view, strict bounds are put to the objectives that represent the loss of fertilisers and pesticides per hectare. Demand for agricultural produce is fitted to self-sufficiency. Ultimately, also in this scenario the costs for agricultural production are minimised, but with the strict bounds as mentioned above.

The model will now select types of land use that have relatively low emissions per hectare and are to some extent still cost-efficient. Table 2 gives examples of one type of results. This table represents the optimum values of the objectives and the selected types of agriculture. Another result of the study is the land use allocation within the EU associated with optimum objective values (WRR, 1992; Rabbinge & Van Latesteijn, 1992).

Table 2. Four land use scenarios for the European Union, in terms of objective values and in terms of type of agriculture

	Scenarios				Today
Objectives	Free market, free trade	Regional development	Nature and landscape	Env. protection	
Agricultural area (10^6 ha)	42	77	26	61	127
Agricultural employment (10^6 MPU)	1.5	2.2	1.8	2.2	6.0
Nitrogen surplus (10^9 kg)	2.1	2.8	2.1	2.1	11
Use of pesticides (10^6 kg a.i.)	60	89	21	33	400
Type of land use (% of agric. area)					
Yield-oriented agriculture	53	35	0	0	na
Environment-oriented agriculture	0.0	1	100*	55	na
Land use-oriented agriculture	47	64	0	45	na

* imposed

Results of the scenarios lead to the following conclusions:

1. Not all combinations of objectives and production systems are possible. Only a limited number of scenarios is feasible.
2. The choice for one dominating objective will inevitably lead to a specific development of the rural areas in Europe. The lack of decision-making at policy level, and efforts to maintain the present land use will lead to high costs, and economically and environmentally suboptimal situations; and societal objectives will not be achieved.
3. Support for regional development through regional authorities will lead to suboptimal solutions at the European level. There is a clear conflict of interests between regionally defined policies and the policies for the EU.
4. A more intensive discussion on objectives and, next, a corresponding set of instruments is necessary.

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Section IV

EXPERIMENTATION AND VALIDATION

An experimental set-up for developing cropping systems

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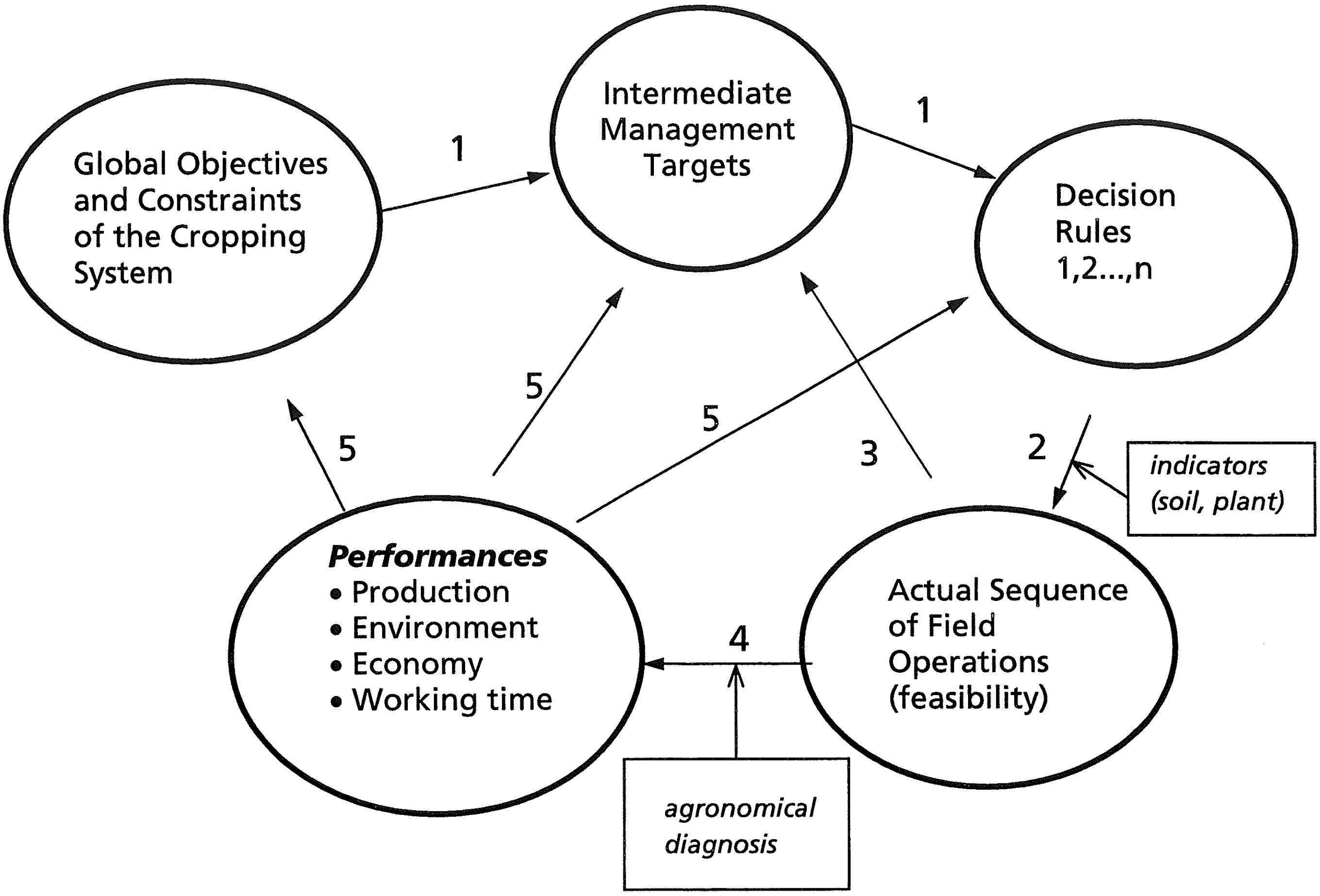
Multi-factorial experimentation does not lead to consistent and comprehensive crop management schemes, presenting a sufficiently broad validity domain (limited number of treatments, statistical significance); on the other hand, it is a convenient method to hierarchize the main production factors and to suggest positive interactions between selected techniques (Reau *et al.*, 1996). Therefore, agronomists were incited to test directly what they called « itinéraires techniques » (Sébillote, 1978), that is logical sequences of cultivation techniques, including the cultivar choice.

Under the favourable price context of the 70's and 80 's, the combinations of techniques aiming at maximum yield were often the most profitable for farmers and were widely recommended in the most productive areas. When the diversity of farmer's objectives and constraints was taken into account, different ways to achieve production or profit were considered too. The challenge of agronomists was thus to imagine specific sets of techniques or crop sequences for each type of production target (yield, quality, gross margin, working time,...) while respecting the constraints from the soil, the climate, the farm organization, or the agricultural policies (Meynard, 1985; Capillon and Fleury, 1986; Debaeke and Hilaire, 1991). But, in these types of experiments, agronomic expertise often prevailed over the full explicitation of each management decision. The need to transfer management methods more easily led to the concept of decision rules, more able to reproduce correctly the farmer's behaviour (Sébillotte and Soler, 1988). A decision rule is composed (1) of a function, which relates the decision to the objectives and constraints, (2) of a solution, which relates the context (described by an indicator) to the action (If...then..., else), and (3) of an evaluation criteria, which is used to check if the function was sustained (Reau *et al.*, 1996). So, it is a set of decision rules which is evaluated on its ability to attain the assigned objectives and not a sequence of technical operations; here, the technical sequence is only the result of the application of management rules.

This approach was applied since 1995 at INRA-Toulouse in a program on « Integrated Cropping Systems» (ICS). In a first step, the global objectives of each cropping system were translated into intermediate (phasic) management targets, then a complete set of decision rules was built to attain these targets (see Figure 1).



1: definition
2: application
3: control (within season)
4: diagnosis (within and after season)
5: revision (after)

Figure 1. An approach to develop integrated cropping systems (ICS)

The main outputs of this work concern: (1) the proposal of new cropping systems, more flexible and integrated, (2) the methodology of building-up and evaluating cropping systems, for research agronomists and advisers, and (3) the implementation of a method to evaluate and self-correct a cropping system, feasible by a farmer. The experimental set-up can contribute to evaluate biophysical models, as well as to test new management schemes, coming from generative modelling methods.
Other experimental designs of this type, but differing by site-specific objectives and constraints, have been initiated more recently in Rennes (Ph. Leterme) and Versailles (J.M. Meynard & B. Mille), through a concerted INRA network.

1. Successive steps in the development of cropping systems

1.1. Definition of initial objectives and constraints

Three systems of objectives-constraints were tested in Toulouse, representing three farm types from the south-west of France; all of them are aiming at profitability under environmental concerns:

A: "High production and clean environment"; when water and labour are non-limiting resources, profitability and pollution limitation are both expected through an accurate determination of crop requirements and an optimum application efficiency (irrigation, fertilization). The possible crops, maximizing gross margin under irrigation, are maize, soybean, pea, and durum wheat.

B: "Technical extensification"; when resources (water, labour) are more limited, input efficiency is expected through a limitation of crop requirements (rationing) in the vegetative phase, together with the selection of crops needing few technical operations and limited watering (sorghum, sunflower). Pea, soybean, durum wheat are still possible crops in this system.

C: "Rustical and simple"; as time for field operations is limited (pluriactivity), and as irrigation is not available, the management strategy is to escape the agroclimatic and biotic stresses by the choice of crop rotation, adapted species and cultivars, sowing date, and by crop rationing (crop density, N fertilization), while accepting a yield decrease but without affecting durably soil fertility (weeds for instance). Wheat, sunflower, sorghum, faba bean and pea are possible crops in this system.

1.2. Proposal of a set of decision rules

After translating the global objectives into a sequence of intermediate management targets (for instance, a period for crop anthesis, a rate of water requirement satisfaction in a given phase, a quantity of N uptake at anthesis, a note of weed covering at harvest), a set of decision rules, sometimes very simple but always explicitly written, is proposed for each system. These rules are necessary to initiate the experimental approach: they should be improved progressively depending on our ability to test their validity and their consistency. The rules can be clustered according to different criteria: 1) the respective contribution of field expertise and modelling in their definition; the soil tillage decision is based on a pragmatical approach, while the irrigation and fertilization decisions are based on validated plant and soil budget methods, 2) their generality: the rule can be only valid in a given pedoclimatic and economic context or can have a wider scope of application, 3) the type of indicators: model outputs (soil water deficit, disease forecast), regional references (cultivar choice), real time assessments (aphids per ear)..., 4) the rule status: specifically studied and evaluated or not; if the decisions rules governing water and nitrogen joint management are fully evaluated, because they are responsible for crop rationing, the rules for P and K fertilization are only slightly evaluated (a soil analysis every four years).

The decision rules were written to be easily used by the decision-maker; only data and methods rapidly available were adopted, such as simple water and nitrogen balance or visual ratings of pests, weeds and diseases during surveying.

1.3. Field application and global evaluation

Cropping systems are applied on realistic fields (farm machinery, soil heterogeneity) in order to test the feasibility of the decision rules *in situ*. The experimental design is composed of 24 plots on a 35 ha area: 12 plots under a fixed 4-year rotation (1. Maize (A) or Sorghum (B,C) - 2. Soybean (A) or Sunflower (B,C) - 3. Pea (A,B) or Faba Bean (C) - 4. Wheat) and 12 plots under a flexible crop sequence. A typical plot (about 1.4 ha) is composed of an analytical area (30-50%) where different levels of a production factor are compared in a classical block design and of a system area which includes control plots and fixed assessment zones (60 m^2).
The three criteria used to appreciate the feasibility are: 1) resource availability (labour, machinery, water) and working conditions (days available for field work), (2) access to the decision indicators (spatial heterogeneity, time for surveying), (3) reach of the global objectives (yield, quality, working time, gross margin...) with the set of decision rules.
The annual statistical comparison of the results is not possible between systems (no replicates) but this is not the objective of the experiment: the challenge is more to evaluate our ability to imagine sequences of operations matching the objectives and constraints of each system than to compare the systems on a given criteria. On the other hand, a comparison of the cumulative effects of the cropping systems is possible, because all the crops are present each year and are arranged as a block design.

1.4. Agronomic evaluation of each system

The agronomic evaluation is based on a diagnostic method applied *a posteriori* and within season, but which does not interfere with the management decisions. The objective is to test the validity of the decision rules with respect to the intermediate management goals and their consistency with respect to the global objectives. This approach is based on three methods:
1) the use of reference curves (for instance, the nitrogen dilution law, the use of optimal yield components, the light use efficiency time-course); the observed data are compared to the optimal values under conditions of a consistent management; 2) the comparison in small plots (10 m^2 plots) of a range of cultivars differing by their earliness or disease tolerance, of a range of crop densities, of fungicide sprayed vs. unsprayed, etc...which are used to validate on the yield basis the most decisive technical choices; no model would actually be so accurate to supplant these comparisons; 3) the use of simulation models to discuss of crop management options and to explore other climatic scenarios and alternative decisions; biophysical models were used to simulate the crop response to various irrigation schedules. The crop diagnostic method was associated with a detailed record of environmental variables: this is the condition to explain the gaps between actual and potential yields and yield components.
The evaluation of each individual decision rule is not possible for experimental reasons. The evaluation of a single rule needs a specific design, where each hypothesis of rule building is tested, as Meynard *et al.* (1996) illustrated clearly for N fertilization of winter wheat using the JUBIL method. So, it is more the technical sequence resulting from the application of a given set of decision rules which is evaluated than each individual rule.

1.5. Revision of decision rules

At the end of the season, the revision of the set of rules consisted of changing completely the rule (sunflower was sown earlier and faba bean was abandoned in C); of modifying the application modalities (economic damage threshold); and of introducing new solutions (a new cultivar).

An illustration of the way decisions are applied, evaluated, and revised is given for two management options (B vs. C) on sunflower (see Table 1).

		Sowing Date	Cultivar	Sowing Density (pl/ha)	Nitrogen (BILN budget) kg/ha	Irrigation (BILH budget) 3 phases	Fungicides	Yield (dt/ha)	Working Time (hours/ha)	Costs 1: inputs 2: machinery (FF/ha)	Gross Margin + subsidy (FF/ha)
B	**Specified**	early, as soon as possible	Short, highly disease-tolerant, mid-late	sown : 66 000	Nupt 171 N rate 110	Irrigation (about 120 mm)	Treated (SPV warning)	33			
	Realized	10 April ***OK***	Santiago	54 000 irregular	110	130 mm (phase 2)	1	34.1	15,4	1: 2534 2: 1388	1259 (+ 3460)
	Evaluation	* birds * slugs * beating	yield < control cultivars	Max Yld for Dmax = 89 000	Nupt 165 ***OK***	ETa/ETref (%) = 94, 76, *95*: ***too much***	+ 3.6 dt/ha ***OK***	increase the yield goal (37)	irrigation sprayings		
	Choice in 1997	8 Avril	Mélody	66 000	120	limitation : 70 mm	1				
C	**Specified**	later than B	High Early	56 000 sown : 60 000 (late)	Nupt 115 N rate 40	No irrigation	Non-treated	25	C < B		
	Realized	15 Mai	Albena (moderately disease-tolerant)	58 000	40	0	Non-treated	33	7,8 ***OK***	1: 684 2: 1068	2978 (+3460)
	Evaluation	***too late*** (emergence, sensitive phase)	= control cultivars ***OK***	Dmin enough (38 000)	Nupt 113 ***OK***	ETa/ETref (%) = 90, 71, 84 ***OK***	3% harmful symptoms ***OK***	> goal (no drought in 1996)			
	Choice in 1997	8 Avril (= B)	Labrador (early sowing)	57 000	65	0	0				

2. Further methodological requirements

Two types of models have been identified above: 1) models to generate cropping systems (for and by the decision-maker), and 2) models for agronomic short- and long-term evaluation of these systems.

In the first case, we identified a need for an automatic method replacing the systematic use of expertise:

1) when converting the global objectives into intermediate management goals (yield components, nutrition index, light use efficiency...) and,
2) when translating these goals in terms of operational decision rules, easy to spread. The first step could take advantage of recent AI tools (see Con'Flex, J.P. Rellier in this issue) for solving typical constraint satisfaction problems. The second step looks more difficult to make self-acting with available tools.

Secondly, there is a need for a method to test the overall consistency of a set of decision rules. This requires the use of simulation models reproducing the interactions between techniques and environmental variables. These models should predict the impacts of biotic stresses on the crop but also the potential risks of disease contamination (or weeds spread) in relation to climatic and crop management conditions. In order to optimize both sunflower sowing date and cultivar choice (earliness, disease tolerance), we need a model simulating the water deficit probabilities as related to crop development but also the risks of contamination by *Phomopsis helianthi*, a harmful pathogen of sunflower, and the resulting yield losses. The specifications of this model should be: decision rules as input data, simulation of main biotic stress (crop- and site-specific), simulation of crop rotation.

3. Contribution to the development and transfer of new cropping systems

It has been well established that simulation, optimization, or constraint satisfaction are key methods to develop innovative sequences of techniques or crops, in a context of socio-economic uncertainty and a wider range of objectives and constraints. Multi-factorial experiments would be enough to quantify complex interactions that are difficult to model *a priori* (for instance, between crop stand and disease development). In many sites, cropping system experiments have only a display function, demonstrating *in situ* the feasibility of office-built systems. But for agronomists, the implementation of such a global set-up is a source for better formalizing the decision-making process. This knowledge, learnt by experience, stimulates the discussions with modellers when developing methods of conception (generalization of an expert approach) or system evaluation (need of a model to decide on optimal sowing date of sunflower).

4. Collaborations

If this approach is intended to be multi-disciplinary, we must admit that attracting specialists on ICS experiments is a real challenge. The decision rules approach is not familiar to analytical

scientists. For testing their research hypotheses, they usually require experiments where a single factor is varied while all other factors remain constant.
The revision of rules brings closely together agronomists from the advisory and extension services, but the transfer of results towards the farmers will not be so direct as for analytical aspects.

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Validation of models at different scales

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1. Introduction

The act of validation of a model might have several interpretations: to give a logical proof that the model is correctly derived from a small number of irrefutable certainties; to give a statistical proof that the model is appropriate for a specific end in view; to perform a series of critical tests on the appropriateness of the model for a specific end in view. Obviously, the substance of validity supported by critical testing depends highly on the number and severity of the tests. Some authors would say that critical testing is less than validating; and subsequently conclude that large-scale models cannot be validated (e.g. Konikow & Bredehoeft, 1992). In this note, I employ a broader definition of the concept of validation, so as to include critical testing: the major method of convincing oneself and others of the reliability of a model for a purpose.

In mathematics, a theorem is valid in the logical sense if it has a proof that proceeds without errors from the assumptions to the conclusion. But the status of the basic laws of physics is not as secure as the status of the axioms of mathematics. Newtonian mechanics, for instance, was for centuries the radiating example of flawless modelling, but later Einstein showed that it is not correct for extremely high velocities. This illustrates that validation in the logical sense is impossible in empirical sciences; but also that an imperfect theory may be valid in the sense of having been proven useful in specific situations. Although one can never prove the universal truth of a model about nature, it is sometimes possible to prove that a model is appropriate for a limited type of application. Most often, however, data shortage will preclude this approach. Instead, the model is criticised from different sides to bring out those points that may be vulnerable. The testing proceeds by exposing those vulnerable points to a critical examination. A model will be used for some purpose as long as it has not been invalidated for it. If it is invalidated, it is modified, often only slightly, and the testing recommences. The above is a specialisation to models of the theory of Popper (1963) about the growth of scientific knowledge by trial and error. In addition, Lakatos (1976) pointed out that, in contrast to what is sometimes believed, even mathematics mainly proceeds by critical testing rather than by strict logic.

When building process-oriented models for agricultural, ecological or environmental phenomena, one attempts to derive conclusions from more or less elementary assumptions, just as in mathematics or physics. But the phenomena studied are complex and variable; in models for such complex phenomena the elementary assumptions can hardly ever be considered as irrefutable first principles: they always contain simplifications. Thus, the only relevant notion of validation of a model for such complex phenomena is to inspect the appropriateness of the model to the limited end in view. If the systems modelled are sufficiently numerous, and sufficiently small in space and time, positive validation is sometimes possible in the form of statistical statements about prediction errors in the population of systems modelled. Otherwise, critical testing is indicated. This procedure has the disadvantage that it has no obvious endpoint, but the great advantage that it suggests model improvements. It should be kept in mind, however, that models for complex phenomena are seldom as stable as the small number of basic physical laws that stayed almost unaltered for centuries and that survived continuous testing. In contrast, many agricultural, ecological or environmental models have been much less thoroughly tested, because they are application-specific and short-lived.

2. Statistical validation

A model can serve various ends, for instance demonstration, education, or the intellectual pleasure to sharply formulate vague assumptions and to study their implications. To assess the effectiveness of a model with respect to such purposes is more like art-criticism than like plain science. But models may also be used to predict. In that case, assessment of the prediction accuracy is a major type of positive validation. One should prove that the prediction error is small in some sense in some population of situations were the model is to be applied.

2.1. Assessment of prediction accuracy: calibrated models

The following hypothetical example embodies the simplest case of assessment of prediction accuracy. Assume that a model, say for sugar beet yield in The Netherlands, has been completely parameterised on some set of calibration data. In order to estimate the model's prediction accuracy a fresh set of validation data is collected, consisting of measurements of final yields in a random sample from the population of Dutch sugar beet fields over a large number of seasons.
We mention various standard analyses that can be performed on the sample, depending on the number of replications of the measurement and the number of predictors that is validated In the case of one predictor and one observation per sampled unit, the analysis might start by checking if there exists any demonstrable relation between prediction and measurement. If so, one can study the distribution of the error made in predicting the measurement. For instance: - find an upper confidence limit for the mean squared error of prediction; - find an upper confidence limit for the probability that the error exceeds some bound; - find a confidence interval for the systematic component of the error. Note that small samples will often lead to oversized confidence intervals, that is to inconclusive results. The model may be said to have been validated for the intended application if the outcome of the analyses are satisfactory. A less satisfactory outcome, however, might be partly due to measurement error. And the purpose is not to predict measurements, but the actual states of the systems. If there is information about measurement error, for instance through duplicate measurements, one can correct for measurement error. When there are several alternative models, samples of the kind mentioned may be used to compare their performance. See also Wallach and Goffinet, 1989.

2.2. Assessment of prediction accuracy: generic models

Suppose that we have a sample of situations as before, but that some parameters of the model still have to be calibrated. Then we have to cope with the 'optimism principle': the

phenomenon that a model often appears to predict better when it is applied to the data used for calibration, than when it is applied to fresh data.
An estimate of prediction accuracy can be obtained by *splitting* the sample into two parts, for instance randomly: one for calibration the other for subsequent validation.
Alternatively, one may apply *leave-one-out cross-validation*: for each situation i, use the whole sample, except i, to calibrate the model, to predict the outcome of i, and to compare prediction and observation. Leave-one-out cross-validation is the simplest form of positive validation of a generic model. Several alternatives, namely k-fold cross-validation and various kinds of bootstraps, are discussed and provisionally compared in Efron and Tibshirani (1993).

2.3. Examples

Examples of conclusive proof of smallness of prediction error in the goal population are scarce. Usually, the data are too poor, either qualitatively or quantitatively.
Graphs of predicted versus measured often pertain to dependent states of systems, for instance the time course of one state variable of one system. Such data require a different analysis based on additional assumptions about the interdependence; solid conclusions still require a sufficient number of independent systems.
In De Koning *et al.* (1993) the statistical validation of regional harvest prediction across Europe is complicated by lack of information about measurement accuracy, and by dependencies between the data.
Metselaar (1998) notes a shortage of validation data for maize growth models (potential production) in the Netherlands.

3. Critical testing

If there is a shortage of data for positive statistical validation, critical testing is indicated. This situation is most common in agricultural and environmental modelling above the field-season scale. The systems modelled are large in the space-time domain, and the study may comprise doom-scenarios that one would rather not see realised.
The problem is what tests to perform, and when to stop testing. Obviously, the most accessible and vulnerable points should be tested with priority. Some obvious points will be mentioned below.
Probably, one might best start with testing if the model is internally consistent in the sense that: - it is correctly derived from the assumptions formulated (the truth of the latter is not questioned); - dimensions and units are compatible; - mass is conserved; - parameters and state variables lie within their natural ranges. If the model consists of re-used submodels that have already undergone some testing, the coupling of submodels deserves special attention.
Very often environmental models comprise submodels devised for different spatio-temporal scales. This may lead to inconsistencies or to unwanted loss of information.
Submodels might be statistically tested at smaller space-time scales than that of the whole model. But, if there is no information about space-time correlations of submodel prediction errors, one does not know to what degree small-scale errors cancel-out at larger scales.
The error ensuing from model simplifications might be studied by comparison with a more complex model which is temporarily assumed correct.

3.1. Uncertainty and sensitivity analysis

Almost invariably with complex models, uncertainty about the value of system parameters and of exogenous variables is a vulnerable point. To test this point one should inspect the way in which the parameters have acquired their values. It will appear that the parameters of the model are imprecise. With some serious effort one might be able to evaluate parameter accuracy. Similarly, one should try to evaluate the imprecision of model inputs such as soil or weather data. Uncertainty analysis translates parameter and input imprecision into uncertainty about the model outcome. At present most uncertainty analyses are based on computer experiments rather than on mathematical analysis. Various software facilities are available for standard uncertainty analyses (e.g. Jansen & Withagen, 1997). The analysis can function as a test whether uncertainty in the inputs considered is not so large as to make the model useless. Moreover the analysis gives information about what input uncertainties cause most uncertainty in a model output: this may be of help in establishing research priorities. Another spin-off of computer-experimental uncertainty analysis is that the model calculations are performed many times over a range of inputs, which holds a test of the model and the software.

3.2. Example

Rossing *et al.* (1994) and Jansen *et al.* (1994) study the uncertainty of a model for the supervised control of pests in winter wheat, and the effects of these uncertainties on decisions. The studies may be viewed as a critical test if the model is suitable for decision support under the current uncertainty about parameters and exogenous inputs.

4. Discussion

Positive validation in the sense of (statistical) assessment of prediction accuracy of a model for a large system is seldom possible because of lack of data. It should be noted that a model with a poor absolute prediction accuracy may still be suitable for decision support. Some research has still to be done on the question how to validate statistically the usefulness of a model for decision support.
The alternative is validation by critical testing. Since this testing has no obvious endpoint, one has to decide when to stop. Accepted minimum standards would be welcome. With respect to models used for prediction or decision support, they would probably include:

- delimitation of domain of application,
- documentation of calibration,
- critical discussion of vulnerable points,
- agreement with client about tests to be performed,
- sensitivity or uncertainty analysis of major model outputs with respect to uncertain inputs,
- documentation of tests performed (including a description of the way in which calibration and validation data were separated).

See also Penning de Vries *et al.* (1995). Institutes producing models for prediction or decision support should carefully manage data for validation and calibration. To facilitate validation, they should limit the numbers of (sub)models and versions and stimulate the (re)use of existing (sub)models.

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Section V

METHODOLOGY

Crop management decision-making based on dynamic programming and constraint satisfaction techniques

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1. Introduction

A crop management plan is defined by agronomists as a logical and ordered sequence of cultivation operations applied to a crop. The choice of a particular action at some stage has consequence for the future because it could affect availability of resources or limit options for subsequent decisions. Some agronomically important events such as the future weather are highly uncertain and so are consequences which might result from a particular action. Thus the proper resolution of the crop management problem requires to have at each stage a conditional policy that can deal with the different possible future states. A policy provides at each remaining decision stage a mapping from the possible states to the appropriate actions.

The main contribution of the present paper concerns the development of a constraint satisfaction framework that is appropriate for searching such a policy. It involves the resolution of a sequence of constraint satisfaction problems (CSPs) in the spirit of dynamic programming which offers a sound mathematical formulation of sequential decision problem solving. Each CSP in the sequence essentially represents the agronomically possible transitions between two consecutive states under the effect of a decision and random events.

2. A dynamic programming approach of the sequential decision problem

Dynamic programming provides a general mathematical tool for computing an optimal policy in a sequential decision problem. Our planning problem is considered as a *q*-stage decision problem in which decision making at each stage is based on feedback from the environment. In other words, we assume that the state of the environment is known before making decision at any stage. Each state depends randomly on the previous one and on the previous decision: this is a so-called Markov decision problem (Puterman, 1994).

We further assume that at each stage *t* the possible pairs {state, decision} reward more or less the decision maker. The reward at stage *t* when the state is $X_t=x$ and the decision is $D_t=d$ is denoted by $r(x, d, x')$ where x' is the value of state X_{t+1} resulting from the application of decision *d* in state $X_t=x$. With the extra hypothesis that the set of all states can be enumerated, a proper way of computing a policy is to reduce the q-stage decision problem into q one-stage problems.

Let $v_t(x)$ be the maximal expected reward obtained during stages $t, t+1,..., q$, if the system is in state $X_t=x$ immediately before the decision at stage t. The function that relates v_t to v_{t+1}, given by formula (1), includes an additive aggregation of the immediate reward of decision d in stage t with the expected reward associated to the subsequent stages.

$$v_t(x) = \max_{d \in D} \Sigma_{x'} \Pr(X_{t+1}=x' \mid X_t=x, D_t=d). (r(x, d, x') + v_{t+1}(x')) \quad (1)$$

where $t=1,...,q$, and x' is the state resulting (with a known probability level) from execution of decision d in state x, and $v_{q+1}(x')$ is the reward from the final state.

In our crop management planning problem, the reward level rather conveys the compatibility of the pair {state, decision} with agronomic rule and biological laws. We assume that this compatibility degree (i.e. satisfaction degree) takes value in [0,1], 0 meaning full dissatisfaction and 1 full satisfaction. Assuming that no compensation effect takes place, the overall satisfaction must be as low as the worst stage satisfaction. Thus, equation (1) turns into equation (2) where the + operator is replaced with the min operator:

$$v_t(x) = \max_{d \in D} \Sigma_{x'} \Pr(X_{t+1}=x' \mid X_t=x, D_t=d). \min(\mathrm{sat}(X_t=x, D_t=d, X_{t+1}=x'), v_{t+1}(x')) \quad (2)$$

Equation (2) says that the rational decision maker chooses the decision d* that maximizes the combination of the satisfaction of the current stage context and the satisfaction associated to subsequent stages. This equation is the basis for the backward induction mechanism used for solving the crop management planning problem. Indeed, we can work our way backward starting from the last stage calculating the expected satisfaction accounting just for this stage, using then this result to account for the last two stages and so on until we have accounted for all stages.

3. Crop management planning with constraint satisfaction techniques

3.1. The basic CSP framework

Formulae (1) and (2) require that all possible states at each stage be enumerated explicitly. This is not always possible in practice due to the size (possibly infinite) of the state space. The constraint satisfaction approach is used to represent the state transition rules and generate only the states that are possible in a given situation. A Constraint Satisfaction Problem (Tsang, 1993) classically consists of:

- a set of variables $V = \{V_1, ..., V_n\}$;
- a domain $F = F_1 \times ... \times F_n$, where F_i is the discrete and finite domain of V_i;
- a set of constraints $C = \{C_1, ..., C_c\}$, each C_j bearing on a subset $\{V_{j1},..,V_{jk}\}$ of V and defining the tuples $(v_{j1},..,v_{jk})$ of compatible values for the variables concerned.

In this framework the set of constraints represents precise knowledge and imperative requirements on the variables. Solutions are complete assignments of V that fully satisfy all constraints in C.

To take into account preferences over assignments, constraints can be represented by fuzzy relations and domains can be fuzzy (Fargier, *et al.*, 1994; Martin-Clouaire and Rellier, 1995). A fuzzy constraint is satisfied to a degree rather than fully or not at all. The satisfaction of all the constraints by a complete instantation $v = (v_1,\dots, v_n)$ is computed as:

$$\text{sat}(V=v) = \min\left(\min_{j=1,n} \mu_{Fj}(v_j), \min_{i,\, i=1,c} S(C_i, v)\right) \quad (3)$$

where $\mu_{Fj}(v_j)$ is the degree to which v_j is member of the fuzzy domain F_j, and $S(C_i, v)$ is the degree of satisfaction of C_i by v.

3.2. Probabilistic CSP

The presence of uncontrollable and uncertain variables, also called parameters, induces incompleteness in the specification of CSP to solve (Fargier *et al.*, 1995) because some constraints hold only for particular values of parameters. To each possible situation corresponds one candidate CSP with both universal constraints (active whatever the situation is) and situation-specific constraints. To the CSP is assigned the probability that the corresponding situation is the real one. Any solution of a candidate CSP is a solution of the real problem with this probability value. For each candidate fuzzy CSP, an assignment can be qualified by a degree of satisfaction together with the probability of the CSP under consideration. Let $(CSP_1,\dots,CSP_k)$ be the set of candidate fuzzy CSPs. We define e(s) the expectation of satisfaction of a solution s as follows:

$$e(s) = \Sigma_{j=1,k}\, P(CSPj) \,.\, \text{sat}(s, CSPj) \quad (4)$$

where $P(CSP_j)$ is the probability that CSP_j corresponds to the real problem, and sat(s, CSP_j) is the degree of satisfaction of CSP_j by the solution s and is given by formula (3).

3.3. *q*-Stage probabilistic CSP

Solving the sequential decision problem with a constraint satisfaction approach amounts to solve a sequence of probabilistic CSPs, each incorporating a particular constraint that conveys the possible states in the next stage together with their corresponding degrees of satisfaction accounting for the subsequent stages.

The resolution process that produces the optimal policy works as follows:

- solve CSP_{q+1} which is a fuzzy and those CSPs for which the variables describe the final state and the constraints are unary and represent the goals or preferences concerning the final state. This constraint directly provides what corresponds to v_{q+1} in formula (2).
- solve CSP_q (including an uncertain parameter L_q) and generate the unary fuzzy constraint of the possible states (so far in the reasoning) at stage q together with the corresponding degree of satisfaction. This unary fuzzy constraint is needed by CSP_{q-1}.
- solve CSP_{q-1} and so on until none is left.

What remains to be explained is how the satisfaction $v_t(x)$ of formula (2) is computed as a result of solving the probabilistic problem CSP_t:

- (i) the resolution of CSP_t generates a set of complete solutions which are instanciations of $\{L_t, X_t, D_t, X_{t+1}\}$. In each candidate CSP, defined by a particular value of the parameter L_t, a particular value of X_t may be compatible with several values of D_t and such a couple *{x, d}* is compatible with a single value *x'* of X_{t+1};
- (ii) the degree to which a partial solution *{x, d}* satisfies the CSP defined by a particular value of L_t is sat(*x, d, x'*) as computed with formula (1) but is bounded by the maximal satisfaction $v_{t+1}(x')$ obtained during stages *t+1,..., q* if the system is in state *x'* after stage *t*;
- (iii) the degree of satisfaction of a given decision *d* at stage *t* if the system is in state *x* is the expected satisfaction e({*x, d*}) computed with formula (4), in which the summation over *j* accounts for different values of X_{t+1} corresponding to different values of L_t. Thus, P(CSP*j*) has to be replaced with the probability (given by the distribution on L_t) of the situation in which $X_{t+1}=x'$ results from $X_t=x$ and $D_t=d$;
- (iv) finally, the best decision at stage *t* in state *x* is the decision *d** with the highest expected satisfaction and $v_t(x)$ is equal to *e({x, d*})*. In particular, the best decision at the first stage is d_1* which maximizes $e(\{x_1, d_1\})$ where x_1 is the observed initial state.

4. Example

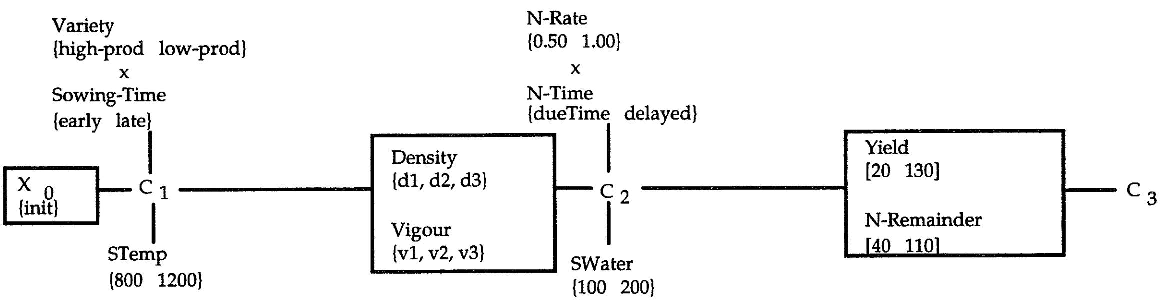

Figure 1. A simple constraint network for wheat crop management planning

Let us consider a partial description of the wheat crop management planning problem. Two stages are distinguished (Figure 1). At the beginning of the first one, we have to decide to sow a high vs. low productivity variety, early vs. later in the fall (D1). At the beginning of the second one, we have to decide to fully vs. partially satisfy the nitrogen needs and to apply fertilizer at due time vs. a bit later (D2). Decisions are informed by observation of the crop. The initial state is unique whereas the state at beginning of stage 2 is one out of 9 pairs of 3 density values and 3 vigour values. The final state (objective) is defined by the yield level and the quantity of nitrogen remaining in the soil. A preference function is defined over the domains of these two variables (Figure 2). One climatic random event occurs at each stage, with influence on, respectively, a sum of degree days (Stemp) and the amount of water available to the crop (SWater). Tables 1 and 2 report the states resulting from execution of decisions given the initial state and the value of the random variable. The optimal policy starts with D1={high-prod early}. Expected satisfaction is 0.85 (Figure 3).

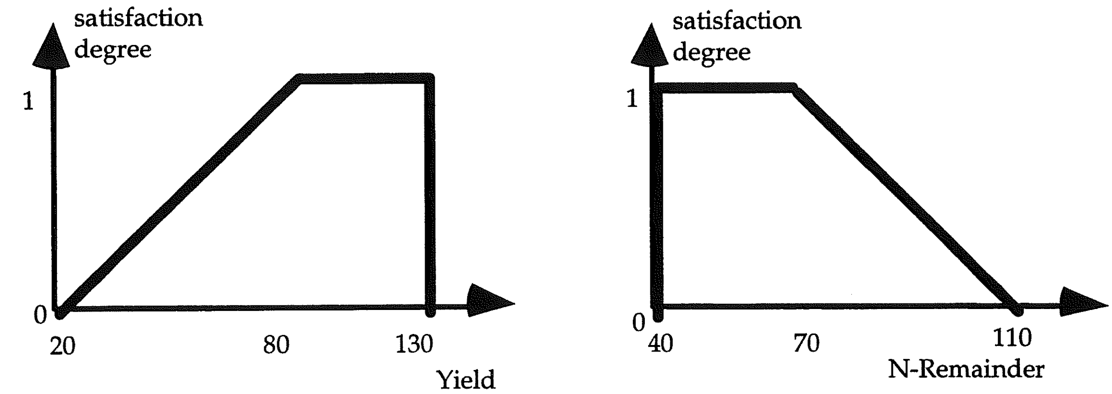

Figure 2. The C3 constraint: fuzzy objectives

Table 1. The C1 constraint for stage 1

STemp	proba	high-prod		low-prod	
		early	late	early	late
800	0.5	Dens.=d2 Vig.=v2	d1 v2	d2 v1	d1 v1
1200	0.5	Dens.=d3 Vig.=v3	d2 v3	d2 v3	d2 v2

Table 2. The C2 constraint for stage 2 (in each couple of figures, the first one is the yield level and the second one is the quantity of nitrogen remaining in the soil)

Density	Vigour	SWater=100 (proba=0.5)				SWater=200 (proba=0.5)			
		N-Rate=0.50		N-Rate=1.00		N-Rate=0.50		N-Rate=1.00	
		due Time	delayed	due Time	delayed	due Time	delayed	due Time	delayed
	v1	45 65	25 65	85 95	55 85	55 75	35 75	95 105	65 95
d1	v2	55 60	35 60	95 90	65 80	65 70	45 70	105 100	75 90
	v3	65 55	45 55	100 85	75 75	75 65	55 65	115 95	85 85
	v1	55 60	35 60	95 90	65 80	65 70	45 70	105 100	75 90
d2	v2	65 55	45 55	105 85	75 75	75 65	55 65	115 95	85 85
	v3	75 50	55 50	115 80	85 70	85 60	65 60	125 90	95 80
	v1	45 55	25 55	85 85	55 75	55 65	35 65	95 95	65 85
d3	v2	55 50	35 50	95 80	65 70	65 60	45 60	105 90	75 80
	v3	65 45	45 45	105 75	75 65	75 55	55 55	115 85	85 75

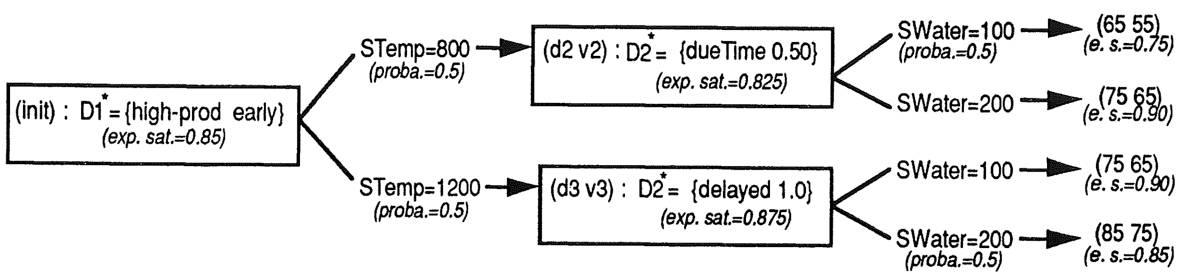

Figure 3. The optimal conditional policy

When we constrain the expected satisfaction of the policy to be greater than 0.8, states {*d1 v1*}, {*d1 v2*}, {*d2 v1*}, {*d3 v1*} and {*d3 v2*} are discarded after the resolution for stage 2, thus lightening the following resolution for stage 1. It could have happened that in some state at some stage no decision could be made, i.e. that only unacceptable goal values could be obtained whatever the decision and the coming events. We have assumed that the degree to which the multiple goal is attained is the minimum value over the satisfaction degrees of the goal components.

5. Conclusion

This paper has briefly presented a constraint satisfaction approach of planning. The present research is motivated by the crop management planning problem but the proposed approach is quite general. Our sequential decision problem has been tackled by solving a sequence of constraint satisfaction problems (CSP) in a way inspired from the backward induction mechanism used in dynamic programming. An important issue is that in practice the states which may be encountered at each decision stage during the cropping season cannot be enumerated explicitly due to the size of the space that could be needed. Therefore, the main benefit that can be expected from the present approach relies on the powerful capabilities of CSP techniques to generate the above-mentioned states.

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Which crop models for decision support in crop management?

Example of the DECIBLE system

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Decision support for crop management has now become one of the main reasons for building or improving crop models (Gaunt *et al.*, 1997; Boote *et al.*, 1996). But while it is generally agreed that the contents of a model must depend on its end use, most of the models that are presently proposed for crop management were primarily designed as summaries of information on crop physiology. Our group has designed a wheat crop model specifically for inclusion in the Déciblé decision support system: all the variables and relationships incorporated at each stage of model building were selected with reference to the general objectives of the decision support system, rather than because they represented the latest in analytical data. It is not clear that all the choices made in model building were ideal, even with respect to these objectives. However, this experience, and other more recent ones (e.g.: Loyce & Rellier in this workshop; Aubry *et al.*, 1997) can be used as references in an attempt to define more accurately what is required of crop models used in decision support.

The objective of the Déciblé decision support system (Aubry *et al.*, 1992, 1997) is to help rationalize the agreement between farming methods and the production objectives for a plot of winter wheat. The initial variables are the characteristics of the plot before soil tillage and sowing (soil type, state following the previous crop) and a set of decision rules (called the action plan) covering the various cropping operations (ploughing, sowing, fertilizing, pest control, etc.). The software can be used to simulate the technical decisions to be taken by a farmer who has adopted the action plan, according to various climatic scenarios, and the consequences of their application for the yield, crop quality, gross margin, quantities of mineral nitrogen at the end of the crop. This helps him choose one of the several available plans that corresponds best to a given set of specifications. Déciblé carries out a sort of small scale experiment on the types of wheat behaviour, so that it can, in a few minutes, provide the equivalent of 15 years of results. The typical user of Déciblé is a development engineer or a group of farmers looking for a new crop growing strategy to cope with a new context (change in the grain-input cost ratio, new varieties, or crop protection or new environment regulations), or a new application, such as wheat for biscuit-making or fuel, etc. The software is written in C, and is presently being evaluated in close cooperation with the users (ITCF: Institut Technique des Céréales et des Fourrages).

Déciblé contains two types of models. One is a decision model that acts as a pilot by simulating the cultivation decisions triggered by the action plan for each climatic scenario - a simulator of crop management. A specific language that borrows heavily from artificial intelligence has been established for this type of decision support tool (Attonaty *et al.*, 1991). The second is a crop model in which the data are the features of the environment (soil, climate) and the crop management generated by the decision model. The changes in the development stages, the yield and protein content, in soil reserves of water and nitrogen, and in the structure of the ploughed layer are thus simulated with interaction among them all.

The specific requirements that use as a decision support impose on crop models can be grouped under three headings: (i) Those concerning the input and output variables, which must depend on the nature of the decision that the operator wishes to improve and the criteria by which the results are evaluated; (ii) Those concerning the area in which the model is valid, which must correspond to the range of growing situations (soil, climate, cropping systems) in which the decision support system is to be used; (iii) Lastly, the robustness of the model for use as a decision support system.

1. Model input and output variables

A crop model used for crop management considers four types of input variables: (i) Variables describing the initial state of the plot, e.g., soil characteristics and properties, nature of preceding crop, quantity and characteristics of the residue left on the plot, etc.; (ii) Climatic variables; (iii) Variables related to the cropping operations on which the decision support is focused, but also to those that may influence the results; (iv) Indicators of the crop condition at a given moment (soil mineral nitrogen at the end of winter, record of pest outbreaks, etc.).

The output variables are of two types: (i) Those on which the selection of the "good solutions" is based (yield, quality, environmental impact, change in plot fertility); (ii) Certain intermediate variables that can be used for tactical decisions, such as the amount of disease, risk of nitrogen deficiency, etc. at a given moment.

Difficulties first arise because the input variables needed by the model are not always available to the potential user of the decision support system. The human and financial cost of gathering a new set of information is often such that it is more reasonable to try to adapt the model to the information available than to obtain the necessary new data. Thus, for example, the soil characteristics such as water content at field capacity or permanent wilting percentage are more generally available than the parameters of the Darcy flow equation, justifying the selection of a model of water supply using a simple water balance in models like Déciblé; the availability of input variables thus influences the form of the sub-models and their performance. It is clear that the simplification imposed by using the water balance prevents certain applications, such as an assessment of the water raised by capillarity under dry conditions; but the simple model is quite adequate for selecting a variety or a sowing date, estimating the yield and loss of input effectiveness due to a dry year or to a shallow soil.

The second difficulty arises because of the discontinuity of analytical knowledge. The relationship between the farming methods, the crop and the environment are complex and it is rare that the available analytical knowledge is sufficient for complete reconstitution: the short-term and long-term effects of cropping systems on certain environmental variables (diseases, parasites, weeds, soil structure, etc.) are difficult to predict, despite the significant advances that have been made in recent years. Also, crop models are better at simulating yield than product quality or the impact of the crop on the environment, although these variables are essential for defining sustainable cropping systems.

The modeling of the effects of fungal disease on wheat yield carried out by Chevalier-Gérard *et al.* (1994) is a good illustration of the difficulties that this discontinuity of analytical data posed for Déciblé. A drop in nitrogen fertilizer, late sowing, lower crop density, or using resistant varieties are all known to reduce the risk of disease. But these technical choices often also lead to a drop in potential yield. A crop management that requires little fungicide, but is effective, can only be applied if it is possible to estimate the consequences of these various choices for the potential yield and yield loss due to disease, while still taking climate into account. The epidemiological models developed to date are not adequate: they generally do not take into account the effects of cropping systems on epidemics; neither do they contain enough information on the effects of the parasite complex on crop production for them to predict damage. The model used in Déciblé overcomes the problem, using a linear fit equation to directly link the relative yield loss to farming practices (nature of the preceding crop, sowing date, amount of available nitrogen), to the resistance of varieties to different diseases, and to the overall climate for the year. In this sub-model, available epidemiological knowledge is poorly used because it is impossible to link it to complementary knowledge of the same accuracy.

2. Evaluation of the model

A crop model is generally evaluated by "comparison of the prediction of the model with experimental observations other than those used to build and calibrate the model" (Whisler *et al.*, 1986). However, the prediction errors do not all have the same consequences for decision making. Some may have severe consequences, leading to a poor choice, while others may have no consequence. Thus, a crop model used as a decision support must also be evaluated for its capacity to identify the most pertinent decisions in a given context. It is therefore evaluated by comparing the techniques chosen by using the model as a decision support, and those that appear to be best in the experimental comparisons. The quality of the model can be evaluated directly from the gains or losses (financial, environmental, etc.) caused by its use (Meynard, 1997).

The model must be evaluated within the range of environments and cropping systems where it will be employed as a decision support system. Several workers have emphasized that an empirical model whose validity is clearly restricted to the fitted range may be much more effective as a decision support tool than a mechanistic model whose area of validity is not clearly defined (Fisher, 1985; Meynard, 1985; Passioura, 1996). Hence, the evaluation constraints must be included early in the model building process.

First, because the structure of a model greatly influences the cost of its evaluation and its adaptation to new production conditions. The higher the cost of gathering the variables needed for evaluating a model, the smaller the number of plots on which it will be possible to evaluate it. This raises the problem of how the diversity of environmental and cropping systems can be sampled. The modeling of yield in Déciblé is based on the relationship between yield components and the states of the environment (Meynard, 1985; Gate, 1995), as the cost of collecting yield components from a plot of land is much lower that that of monitoring biomass, which is required for evaluation of a standard crop model. Similarly the estimation of the response to nitrogen fertilizer is not based on a modelisation of the soil carbon and nitrogen cycles, and the transfers of nitrogen via the roots, but on the breakdown of the response to fertilizer proposed by de Wit, which links the soil nitrogen supply to the amount of nitrogen absorbed by an unfertilized crop, and describes the effect of fertilizer by its apparent recovery fraction. Major data bases for these two variables are now available because of the many experimental studies on fertilization carried out by agricultural advisers. The sub-models used in Déciblé, such as the balance sheet method (Rémy & Hébert, 1977), which estimates the soil N supply and the equation of Wibawa (quoted by Meynard *et al.*, 1997) which estimates the effect of soil structure on the recovery fraction are thus easy to validate and to correct if necessary. This is similar to the ideas of van Duivenbooden *et al.* (1996) who proposed using an analogous model for land use planning.

Second, because the approach which consists of building a model and then comparing it to experimental data (and if necessary fitting it by changing certain parameters), may be dangerous. If certain limiting factors are not initially included in the model they could remain unknown. The fitting of the model to the situations affected by these limiting factors may, in itself, alter the value of the parameters. Another, more pragmatic solution is to base the model on an agronomic diagnosis carried out on a representative sample of farmers' plots (Doré *et al.*, 1997). These identify the factors limiting production or the effectiveness of inputs for each plot (Meynard & David, 1992), and finally the characteristics of the environment and the cropping system that influence the demonstration of these limiting factors. This identifies the most frequent bottlenecks and the functions that must be concentrated on in the investigations and model building for the study zone. For example, Meynard (1985) showed that the main factors limiting the wheat yield in the Paris Basin were the compactness of the topsoil, shoot and root diseases and temporary nitrogen lack due to late fertilizer application. The effect of these factors was taken into account as a priority in Déciblé. In addition to the disease damage sub-model referred to above, we have built a new sub-model for the change in the soil structure caused by soil-tillage, compaction by tractor wheels and climate. The soil structure is described by the qualitative variables proposed by Manichon: clod organisation and the internal porosity of the clods. The fraction of large, non-porous clods has a direct influence, causing a drop in the fertilizer recovery fraction.

3. Model robustness

Models used as decision support systems must be robust (Fisher, 1985; Passioura, 1996). We believe that two aspects are particularly important. First, the model should not lead to catastrophic decisions if it is used outside its domain of validity. An exceptional year, an unsampled cropping system, a change in farming practice, could each lead to the use of a decision support tool outside the domain of validity determined during its evaluation. Second, approximate model input data should also not produce catastrophic decisions. Like the validity, the robustness of a model is assessed with respect to a specific application. The fact that Déciblé includes models of yield based on its components with the parameters of the relationships between components based on regional data bases, is an indication of robustness. There is no risk that the yield component values will be outside the observed range and that an aberrant yield will be obtained. Although the potential weight per seed and the decrease of the weight per seed as a function of the number of seeds are regional and varietal parameters, this is a small constraint given the regional data bases available. This is a way of avoiding inaccuracies that are produced by using certain turnkey crop models.

Some aspects of robustness cannot be predicted when the model is built. Meynard (1985) found that the yield component based models he used to develop wheat cropping system strategies gave poor predictions for crops with heavy take-all infestations, but they were robust enough to identify crop management strategies that were better under these condition than those usually used by farmers in the Paris Basin.

4. Conclusion

Taking into account the specificities of decision support in the Déciblé crop model led us to build a brand-new model. In relation to the high number of existing crop models that had been built for other purposes, it is now possible to use in a hybrid approach, using existing sub-models and building other specific new ones. The three points covered above can be used to construct an analysis grid for existing models so as to select those best adapted to a given objective of crop management. They also provide the model builders with reference information in order to integrate the constraints linked to their use in crop management as early as the conception of the models.

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A simulation-based learning tool for virtual experiments

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1. Towards an exploration support system

In today's agriculture, the redefinition of new options for crop management is crucial. Classical experimental methods can be used but these are very expensive and time-consuming. For that reason, the interest in using simulation tools based on crop models has increased in the last years, and some projects are currently under development to provide users with Decision Support Systems for estimating the economics and environmental effects of particular technical decisions concerning the selection of variety, seed rate, sowing date, fertilization, etc.

For instance, in the context of the winter wheat crop production, such a simulation tool (DECIBLE) has been developed (Meynard *et al.*, 1997). It allows virtual experimentations of new crop management strategies and their implementation in practical situations. An important part of this project consisted of identifying and representing crop production strategies. The formalism that has been retained is based on decision rules to be applied by the farmer during the vegetation period considering e.g. the sowing, nitrogen supplies etc... This kind of simulation tool is based on two main components:

- a crop model for the elaboration of the yield strongly related with the effects of technics and environmental conditions (soil, climate) on various criteria (quantity and quality of the yield, risk of diseases and lodging, wastage of inputs etc.).

- a decision model representing the management strategy using a specific descriptive language suitable for this type of decision problems. This model plays the role of a farm manager by simulating the technical decisions during the crop production period.

The notion of strategy is crucial in the crop production context. At the beginning of the simulation, precise information (date, quantity, etc.) concerning field operations are not available since the farm manager often selects them depending on the progress of the season. Instead of these *a priori* decisions, it is necessary to use a strategy, which is just a formal model of the decision behaviour of the farm manager. Thus the general meaning of a strategy is a mapping from the descriptions of the possible current situations to the set of field operations. In DECIBLE, the syntax of the strategy is based on an IF-THEN rules formalism linking the state indicators of the system (crop growth, climate, soil etc.) and the executable actions. IF-THEN rules are a human-natural and efficient way for describing decision behaviour, but any mathematical function could be employed.

One main aspect of the redefinition of new farm production systems consists in adjusting/modifying the current decision behaviours of the farm managers to adapt them to the new economical context. Nevertheless, the use of simulation models like DECIBLE by crop production plan engineers (researchers and advisers) have made clear that it was not so trivial for them to explore quite different strategies than those actually used in practice. To help users to explore a wide range of solutions, and thus to enable them to select more suitable strategies for newly encountered production contexts, one needs a system which is able to generate automatically some *a priori* interesting strategies, given constraints and criteria to optimize. In this perspective we are implementing Machine Learning techniques in a tool conceived as an Exploration Support System.

2. Automatic generation of strategies as a Markov decision problem

Considering winter wheat crop production, the problem of automatically generating a crop management strategy can be theoretically considered as a Markov decision problem (Puterman, 1994) with the following important characteristics:

- the problem is a finite-horizon one, with particular state-spaces and decision-spaces at each stage;
- state and decision variables can have continuous domains;
- the time (decision date, observation date) must be explicitly taken into account;
- the stochastic evolution of the crop process due to weather uncertainty is an essential feature of the problem;
- we do not have a formal Markovian model of the crop growth process and we have to deal with delayed rewards.

To illustrate this Markovian Decision Problem representation, we consider the DECIBLE simulation model. Winter wheat crop management can be decomposed into a sequence of *N* decision steps concerning successively sowing, fertilizing, etc. At each step is associated a state space Si and a decision space Di. A crop management strategy Π is a set of sub-strategies {Π1, ..., Πn}, and each sub-strategy Πi is defined as a function which maps each state s of Si to a decision d of Di. These spaces Si and DI are characterized by a set of state or decision variables. For DECIBLE, some of these variables and their domains are presented in the following table:

	sowing	1st nitrogen supply	2nd nitrogen supply
state variable	-sowing time: [15/09-15/12]	-tillering -number of plants	-soil furniture: [0,100]kg/ha -start of stem elongation: [01/03-15/05] -biomass: [30,120]g/m^2
decision variables	-seed rate: [100,300]g/m^2 -variety: {soisson, ..}	-time_N1: [15/01-01/03] -dose_N1: {0}+[40,100]kg/ha	date_N2: [01/03-15/05] dose_N2: {0}+[100,200]kg/ha

For a given one year weather time serie, the strategy is executed decision stage after decision stage, from the initial conditions before sowing until the harvest. To select interesting strategies, a numerical criterion is used to grade this strategy execution. In the MDP formalism, this criterion is decomposed into a sum of local rewards at each step, but it can only depend upon the final situation (for instance the yield). Furthermore, this criterion can be the result of numerous calculations (veto, weighted sum, etc.) to aggregate different performances. To take into account that users do not know the weather in advance, we have to consider the expected value of this criterion. Thus as the global criterion depending on Π we try to optimize the following form:

$$V_{\Pi} = E\left(\sum_{i=1}^{N} r_i\right)$$

where the r_i values are the local rewards at each step.

Unfortunately, most of the previous characteristics of the problem are prohibitive to use classical dynamic programming algorithms to generate optimal strategies maximising V_{Π}. The main reason is that the resolution principle of these algorithms is based on an explicit and flat discrete representation of state and decision spaces, with perfect knowledge about the stochastic dynamics of the controlled system. This representation is a probability distribution governing the next state of the system given the current state and the current action. This probability distribution is usually represented as a set of transition matrices. In our case however these matrices are not available, since we do not have an explicit formal model of the crop growth. Instead, our knowledge about the biophysical processes is embodied in the simulation model. A solution would consist in estimating these probabilities by simulating a large number of different sequences of actions with the simulation tool for different weather sequences. This would require a huge memory space and an important computation time for our particular decision problem.

3. Reinforcement learning and crop management

Classical dynamic programming technics are not suitable to generate automatically strategies for the crop production problem. The close but still different approach we have chosen consists in defining an exploration support system that iteratively generates, evaluate and adapts strategies, until it provides a high quality solution.

The system directly manipulates strategies. At each iteration, the more or less local strategy modifications depend upon the strategy evaluation given as an expected value. This expected value cannot be calculated analytically, and we can only estimate it, by simulating the strategy with a large number of different weather sequences. The number of available time series at a given site is usually around a few tens, which is not numerous enough for a correct optimization of the strategy. Consequently we use a stochastic weather generator, that can provide as many different sequences as needed by the evaluation and optimization modules. The weather generator we use is an extension of the one developed by Racsko *et al.* (1991). The system stops when the quality of the current strategy is above a threshold, or when it does not improve anymore. Our expectation is that this approach, which defines interesting strategies in an incremental way according to a general method called Reinforcement Learning, is really adapted to the present exploration context.

Reinforcement learning (Kaelbling *et al.*, 1996) is one of the major approaches to solve Markov decision problems with unknown transition probabilities. It consists in the learning of a mapping from situations to actions (control rules) so as to maximize an expected scalar reward. Q-learning and R-learning, two of the most studied reinforcement learning algorithms, are direct adaptive methods since they do not rely on an explicit model of the Markov process. Q-learning (resp. R-learning) only maintains estimates Qn of utilities Q*(s,a) for each state-action pair (s,a), an optimal action for state s being any action a that maximizes Q*(s,a). In the case of a finite-stage process like in a crop management problem, the estimate Qn of the function Q* is regularly updated after each trial of the crop simulation, according to the selected actions and the observed rewards. The principal advantage of reinforcement algorithms like Q-learning or R-learning relies in the fact they do not necessitate a probabilistic model of the controlled system, since they just need to observe the transitions and the associated rewards in the course of the process evolution.

Within the finite-horizon framework, and for the Q-learning algorithm, learning a strategy Π consists in learning at each decision step the associated sub-strategy Πi defined by the local value function Qi. These functions Qi from Si X Di to IR can be represented in different ways. We can use decision rules, neural nets, CMAC representation, etc. Each of these cases corresponds to a discretization of the continuous spaces Si and Di. To each cell of this discretization a corresponding real valued weight is associated. The value Qi(s,d) of a state s in Si and a decision d in Di can be calculated as a function of the weights wj of the active cells that cover s and a. This function depends upon the chosen representation, and is classically a sum or a max function.
The structure of the discretization can be defined a priori (CMAC) or can be refined during the learning process (decision rules, neural nets). We have presented in Attonaty (1997) an approach combining reinforcement learning and genetic algorithms for the generation of decision rule structures.

Given a cell structure, weight learning has as a purpose to establish the values of these cells which define an optimal value function Q*. We achieve this learning task with reinforcement learning technics. These lead to the definition of algorithms that iteratively update the weight values; if we observe the transition ($s_{current}$, $d_{current}$, s_{new}, $r_{current}$) at step n, then we update the weights of all the active cells relatively to ($s_{current}$, $d_{current}$):

$$w_{n+1} = (1-\alpha_n)w_n + \alpha_n\Psi(r_n, s_{new}, Q_n)$$

where α_n is a small learning rate decaying over time and Ψ a function estimating the error between the current value function and the optimal value function.

In the two following figures, we present an example of function Q2 we have obtained for the second decision step which corresponds to the 1st nitrogen supply. Here a CMAC representation has been used for estimating the function Q2, which consists in an *a priori* regular grid defined on E2 = tillering X plant number and D2 = time_N1 X dose_N1. The criterion we try to optimize is the final yield. The maps of Figures 1 and 2 have been obtained after 100,000 iterations (3 hours of computation time on a pentium PC). Figure 1 represents the optimal expected yield given the current observation of tillering and plant number:

$$E(\text{yield}) = Q2^*(\text{tillering, plant number}) = \max_{t\_N1,d\_N1} Q2(\text{tillering, plant number, t\_N1, d\_N1})$$

Figure 2 illustrates the effects on the expected yield of the decision variables time_N1 and dose_N1 for the particular state in stage N1 defined by tillering = 231 (16/02) and plant number = 230, assuming that an optimal policy will be followed at the second nitrogen supply:

E(yield) = Q2(16/02, 230, t_N1, d_N1)

As we can see, the shape of each surface is already showing the emergence of a trend. More iterations are nevertheless needed to get clear results. Furthermore, the analysis and the interpretation of such figures by agronomists require 3D visualization tools, which we are currently developing.

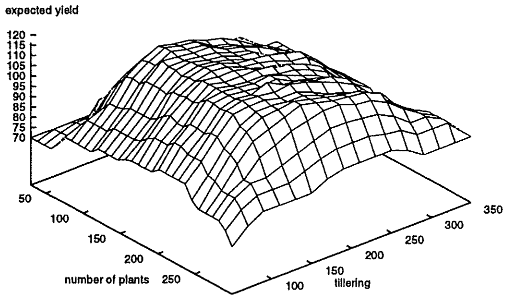

Figure 1. 1st nitrogen supply decision step.
E(yield) = $\max_{t\_N1,d\_N1}$ Q2(state, t_N1, d_N1)

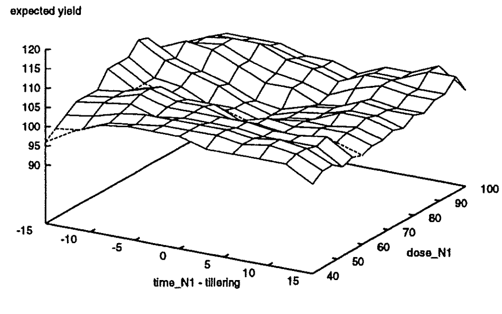

Figure 2. 1st nitrogen supply decision step.
E(yield) = Q2(15/02, 230, decision)

4. Conclusion

The exploration support system we have presented in this paper combines crop simulation and learning techniques to help users to define new crop management strategies. It explores a wide range of possible strategies, and searches for the one for which the evaluation is maximal. This system is still under development, but current results suggest two main topics that require further investigations: (i) how do machine learning principles enable the automatic generation of interesting crop management strategies, given production constraints and complex evaluation criteria? Assuming a positive answer for the winter wheat domain, will it be possible to generalize this tool to different biophysical systems? And if so, which assumptions concerning the biophysical models are needed? (ii) Can these simulation-based learning approaches enhance the facility of using decision support systems by researchers, advisers or even farmers? Can this exploration support system really generate new peculiar strategies and so develop new knowledge? Any answer to this last question will be an important progress for the DSS community.

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Statistical aspects of optimal decisions

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1. Introduction

An important use of models is to calculate optimal decisions. We consider here two statistical aspects of model-based optimal decisions. The first, which we consider only briefly, concerns the statistical modelling of unexplained variability. The majority of this paper concerns the evaluation of calculated optimal decisions. It is important to evaluate the quality of those decisions for several reasons. First of all, the decision maker needs to know how much confidence he should place in the calculated decision. Secondly, one wants to know the room for progress in improving the calculated optimal decision. Finally, one wants information on how the calculated optimal decision could be improved. The problem of model quality in general, and model predictive quality in particular, has been quite thoroughly studied. However, there has been little work on the evaluation of a model when the use of the model is to calculate an optimal decision. We consider the specific problem of calculating optimal nitrogen fertilizer doses. However, most of the results apply quite generally to calculated optimal decisions.

2. The elements of a calculated optimal decision

1. First one must define the population of situations for which we seek an optimal decision, the decision space and the objective function. As an example, we consider the problem of calculating the optimal amount of N fertilizer to apply to a field. The target population could be the farmers' fields in some region. There is a single decision variable here, e.g. the amount of fertilizer to be applied. As a simple objective function we take average gross margin. If the optimal strategy is to apply the same dose *d* of fertilizer to every field, then the average gross margin is $J(d) = pE[Y(d)] - cd$ where *Y(d)* is yield at dose *d*, the expectation is over the target population, *p* is the unit price of the crop, and *c* is fertilizer unit cost. More generally, we will calculate not a single optimal dose but rather an optimum fertilization strategy *S*, which associates different doses $d^S(w_i)$ with different plot characteristics w_i (for example previous crop, soil nitrogen at the end of winter, average past yields, etc.). The average gross margin for the strategy *S* is now

$$J(S) = E[j(S,w_i)] = E[pY(d^S(w_i),w_i) - cd^S(w_i)] \quad (1)$$

where $j(S,w_i)$ is the gross margin for a field with characteristics w_i.

2. We require a response model, that describes how the variables of interest respond to the decision variables. For our example, suppose that gross margin depends only on yield, so

that yield is the only response variable of interest. A possible simple model for yield as a function of fertilizer dose is $E[Y(d)] = f(d;\Theta) = \theta_0 + \theta_1 d + \theta_2 d^2$. If the model includes field characteristics, then we note the expectation of yield $f(d, w_i; \Theta)$.

3. A set of training data must be available, to be used to obtain an estimator $\hat{\Theta}$ of the parameter vector of the response model.
4. Given the above elements, one can calculate the estimated optimal strategy by maximizing the objective function, using $\hat{\Theta}$. When the optimal strategy reduces to a single optimal dose for all fields, this simply involves maximizing a function of the dose. When the optimal strategy associates different doses with different field characteristics, one simply maximizes the objective function separately for each value of w_i.
5. Finally, one wants to analyze the estimated optimal strategy. How good is it, and how could we improve it? This of course requires the definition of a criterion of goodness. Since by assumption the goal is to maximize the chosen objective function, it seems reasonable to use the value of the objective function as the criterion of goodness of an estimated optimal strategy. The problem then is to estimate the value of $J(S)$ for each strategy of interest *S*, and to identify and quantify the factors that determine this value.

3. Modeling the response to the decision variables

The model that describes how the system responds to the decision variables is obviously of fundamental importance. The model for the expectation of the response will often be based on agronomic considerations. The statistical part of the model describes the random variation around the expectation. Here we consider briefly the choice of the statistical model.
The typical structure of data for optimal decision problems is that each unit (for example, each field) receives a number of different levels of the decision variable (for example, several different N doses). The observations can then not be assumed to be independent. An appealing method of modeling the dependence is by means of the use of random parameter models, which involve two stages of modelling. In the first stage, the response for field *i*, dose *j* is modeled as

$$Y_{ij} = f(d_{ij}, \Theta_i) + \varepsilon_{ij}. \qquad (2)$$

The ε_{ij} represent measurement error, and can reasonably be assumed independent. In the second stage the distribution of Θ_i values in the population is modeled. In the simplest case

$$\Theta_i = \beta + \eta_i \qquad (3)$$

where β is the expectation of the parameter vector over the population, and the variance-covariance matrix of η_i represents the between-field variability of the parameters. If the parameter vector is modeled as a function of field characteristics, then

$$\Theta_i = g(w_i) + \tau_i \qquad (4)$$

For the response of yield to N fertilization, random parameter models often are consistent with the data (Wallach, 1995a). That is, the response curves for different fields can often be described by the same parametric function, but with different parameter values. Furthermore, this modelization has a number of appealing statistical features. It provides a quite flexible, but nonetheless parsimonious model of the dependence of data for the same field. It allows

one to separate within field and between field variances. Finally, algorithms are now available for estimation of the parameters for non-linear random parameter models.
The importance of a reasonable statistical model should be emphasized. First of all, the estimated parameter values will depend upon the statistical model, and a more accurate model may be important in order to obtain unbiased, or more efficient parameter estimators. Secondly, we will wish to investigate the effects of different uncertainties on the calculated optimal strategies. It is the statistical model that defines these uncertainties.
An example of the importance of the statistical model concerns the use of field specific data (Wallach, 1995b). In general, optimal nitrogen doses are calculated for a field chosen at random from the target population, independently of the training data. Suppose, however, that we want to calculate the optimal dose for a field for which there is past data. The way to take account of such data depends on the statistical model. It is quite straightforward when a random parameter response model is used. In this case the distribution of the parameter vector is altered, because we now need the distribution conditional on the past data. This leads to an empirical Bayes calculation of the updated parameter distribution, which is then used to calculate the optimal dose.

4. Evaluating models that are to be used for calculating an optimal strategy

We argued above that the logical criterion for evaluating an estimated optimal strategy *S* is the value of the objective function *J(S)*. This then is also the logical criterion for evaluating the model that leads to the estimated optimal strategy *S*. This criterion is specific to the optimization problem, and is quite different than the criteria which are generally used for model evaluation, such as R^2 or the mean squared error of prediction. Those criteria are general in the sense that they depend upon the behaviour of the model over the full range of values of the explanatory variables. The objective function criterion, on the other hand, depends on model behaviour at the calculated optimal value of the decision variable. Note that *J(S)* is always a scalar, which makes it quite easy to interpret.
The value of *J(S)* depends on the true response function, which is unknown. The problem then is to estimate this criterion. The following discussion is based on Antoniadou and Wallach (1997), where different estimators of the criterion are proposed and compared.
Suppose that a model is based upon some initial fertilization studies. Then an optimal fertilizer dose strategy *S* is calculated based upon this model, and subsequently these doses are tested on a random sample of *N* fields. Then a natural estimator of *J(S)* is the average gross margin for these fields. However, this type of situation rarely occurs. First of all, one would not normally want to wait for the testing data to become available before assessing the quality of an optimal strategy. Rather, one would want to use the initial data both for developing an estimated optimum strategy and for assessing the quality of that strategy. Furthermore, one can rarely make a definitive choice of possible models, and of a sensible objective function. Both of these tend to evolve over time. In general, then, one may wish to estimate *J(S)*, without having yield measurements that correspond exactly to the calculated optimal doses $d^S(w_i)$.
An estimator that does not require measurements at the estimated optimal doses is obtained by assuming that the model is correct. This model-based estimator is

$$\hat{J}_{mb}(S) = 1/N\sum_{i=1}^{n}[f(d^S(w_i), w_i;\hat{\Theta}) - rd^S(w_i)] \qquad (5)$$

There are two main reasons that this simple estimator is unlikely to be satisfactory. First of all, we are using the hypothesized model to interpolate between observed doses. If the model were correct this would be a logical method for interpolating, but in general we are not confident of this assumption. And of course if we wish to evaluate different models in order to choose the best, then clearly we do not want to assume that a particular model is correct. The second difficulty is that the model-based estimator uses the same data to estimate the optimal dose function, and to evaluate the quality of that dose function. This is typically the kind of situation which leads to bias in the estimate of model quality.

A natural approach to eliminating the dependence of the estimator on the model is to use a non-parametric estimator. Suppose first that the estimated optimal strategy proposes the same dose for all fields. Let Y_{ij} and d_{ij} represent respectively the observed yield and the applied dose for the j^{th} dose in the i^{th} field. We plot the observed gross margin values, that is the values of $pY_{ij}(d_{ij}) - cd_{ij}$, versus dose. Let *g*(*d*) be a non-parametric curve fitted to this data. (In practice, we used local quadratic regression to obtain the curve). The curve is a non-parametric estimation of $E[pY(d) - cd]$. The non-parametric estimator of our criterion is then simply $g(d_{opt})$ where d_{opt} is the common calculated optimum dose. In the case where the calculated optimal dose can be different for each field, we can make the calculated optimal doses coincide by translating the data for each field by an amount equal to the calculated optimal dose.

This non-parametric estimator does not correct for the second problem with the model-based estimator, namely the bias induced by using the same data to estimate the position of the maximum of the objective function, and to estimate the value of the objective function. We can eliminate this problem by combining the above non-parametric estimator with a cross validation-type estimator of the maximum dose for each combination of site and year.

An extensive simulation study was carried out to compare the quality of these three different estimators. First, the estimators were compared on the basis of mean squared error, which is the sum of a bias squared term and a variance term. The major differences between the model-based and the non-parametric estimators are due to differences in the bias term. The bias contribution is always small for the non-parametric estimators, but can be large for the model-based. Thus the non-parametric estimators are clearly preferable to the model-based estimator. Within a wide range of circumstances there is little to choose between the two non-parametric estimators. However, the bias contribution might become large for models where the ratio of the number of parameters to the number of data points approaches one. In such cases, it would probably be wise to use the non-parametric cross-validation estimator. On the other hand, when there are very few data points and the within field variance is large, it would seem advisable to use the simple non-parametric estimator.

A second method of comparison is to use each estimator to choose the best model in each simulation, and to compare the average values of J(S) for the chosen models. In any case, using the non-parametric cross-validation estimator to choose the best model leads to a significantly larger average value of the objective function than does the model-based estimator.

5. Sources of error that affect the calculated optimal strategy

In the preceding section we were concerned with an overall evaluation of a model. In the present section, we wish to consider particular sources of error, and show how they affect *J(S)*. For these more detailed studies, we will use model-based estimators, which assume that the model is correct. A logical way of combining the approaches in the previous paragraph and in this paragraph would be to first make a choice of model, and then investigate sources of error.

5.1. Errors in the parameters

In general the response is modeled with some parametric function, and the parameters are estimated by fitting the model to a set of data. There will be some error in the estimated parameter values, and this will lead to a reduction in *J(S)* for the estimated strategy based on the model. The error in the estimated parameters can be reduced by augmenting the data set. Whether or not this is worthwhile can be determined by comparing on the one hand the cost of the extra data, on the other hand the increase in *J(S)* (which is also expressed in monetary terms) that this would procure.
The study in Wallach and Loisel (1994) explores this effect in detail. They consider the simple case where the calculated optimal dose is the same for all fields, but the results are extended to the more general case in Wallach (1995a). Specifically, we consider the expected loss due to parameter estimation, defined as

$$R=E[L(\hat{d}_{opt})]=E[J(d_{opt})-J(\hat{d}_{opt})] \tag{6}$$

where d_{opt} is the optimal dose calculated using the true parameter values, and d_{opt} the optimal dose based on the estimated parameter values. Using a second order Taylor series expansion of yield at the optimal dose as a function of the parameters leads to the expression

$$R=-1/2\mathrm{tr}(\hat{\Psi}\hat{\Sigma}_{\hat{\Theta}}) \tag{7}$$

where $\hat{\Sigma}_{\hat{\Theta}}$ is the estimator of the variance covariance matrix of the parameter estimators,

$$\Psi = \left[\frac{\partial d_{opt}}{\partial \Theta'}\Big|_{\Theta}\right]' \cdot \frac{\partial^2 J(d)}{\partial d^2} \cdot \left[\frac{\partial d_{opt}}{\partial \Theta'}\Big|_{\Theta}\right] \tag{8}$$

and $\hat{\Psi}$ is the approximation obtained by using estimated parameter values in the above equation. The prime denotes the transpose of the vector. The above formula is in fact quite easily evaluated, and gives the reduction in the objective function due to using estimated parameter values, compared to using the true parameter values. The formula is based on a linearization approximation, but a simulation study showed that this approximation is quite good, at least for the case studied.

5.2. Residual error of the model

The model is not a perfect predictor, and this also degrades the quality of the calculated optimal strategy. The residual error of the model can be reduced by introducing additional explanatory variables. However, this implies that to apply the optimal strategy to a field, one must measure these variables. Whether or not this is worthwhile can be determined by comparing the costs of the extra measurements, with the associated increase in $J(S)$. A secondary effect of introducing additional explanatory variables is that this is normally accompanied by additional parameters, and the errors in estimation of those parameters will tend to reduce $J(S)$, as explained in the previous section. This effect of additional explanatory variables must be taken into account as well.
In Wallach (1995a), the case where a random parameter model is appropriate is considered. In the absence of explanatory variables, the parameters have a distribution as indicated in eq. 3. Since the model does not then include field characteristics, the calculated optimal dose is the same for all fields. It is calculated to maximize the expectation, over Θ_i, of the objective function. If we have a model to explain partially the variability in Θ_i, as in eq. 4, the optimization calculation leads to an estimated optimal strategy and a corresponding value of the objective function $J(S)$. To compare this value with the case without field characteristics, we can use the model-based estimator or one of the non-parametric estimators described above. We can also evaluate $J(S)$ for the case where all the between-field variability in Θ_i can be explained. This value is of interest, because it indicates the maximum value of the objective function that can be attained by basing the optimal strategy on additional explanatory variables. This calculation does not require that we actually have a model to explain all the between-field variability. It is based on Monte-Carlo sampling from the distribution of Θ_i. For each sampled value of the parameter vector, the optimal dose is calculated. This is in accordance with the assumption that for each field the parameter vector can be predicted without error, and so the appropriate optimal dose can be used. We then calculate the corresponding value of the objective function for each field. The average over fields of these individual objective function values is the $J(S)$ value we seek.

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Spatial and temporal statistical procedures to support decision making for smart farming

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1. Introduction

Data collected in space and time are increasingly relevant for agricultural phenomena. The reason is a growing awareness of the dynamic environment: sustainibility requires a continuing balance between input and output of agricultural systems. In smart farming decisions have to be made on the basis of space-time data: to interfere in the development of a plant disease, to optimize the distribution of leached pesticides in a homogeneous medium and to adequately monitoring of the groundwater.
In this paper I will give some thoughts on space-time statistical procedures for decision support. Procedures will be presented to characterize variability in space and time and to design optimal sampling strategies. In this paper we propose a simulated annealing based procedure to optimally distribute possible sampling locations, using a quantitative optimality criterion. The paper will be illustrated with a study on a fungal soil-borne disease in cotton.

2. Case study

The case study we apply in this paper concerns the pathogen *Phymatotrichum omnivorum*, that causes root rot in cotton in the south-western United States and northern Mexico (Kenerley and Jeger, 1992). The pathogen attaches to the roots and infects the plant. As a consequence the infected plants will die within a few weeks, with the length of this period depending upon soil conditions. The data that we analyzed (Jeger *et al.*, 1987) concern a field of 32 rows of 80 m, monitored in April 1984. Inter-row spacing was 0.9 m. The first appearance of the rot was in early June. Measurements were made on 12 June, 19 June, 26 June, 3 July, 10 July, 17 July, 31 July and 7 August. The position of each diseased plant within a row was marked with a wire flag and the distance from a standard reference line marked at right angles to the rows was measured with a hand held tape. Where an uninterrupted sequence of diseased plants was present only the plants at the extreme positions were flagged and measured. The sequences describe the development of root rot in space and time, and provide a rather complete covering of the area at 8 successive sampling days.

3. Variability in space and time

The incidence as described in the case study can be analyzed as a variable taking values in space and time. Other examples are the changing ground water level, the concentration of nitrate or fertilizer in the soil or yield developing during the growing season. Variables in space (*S*) and in time (*T*), are associated with their positions $s \in S$ and $t \in T$. They are usually subject to random (stochastic) influences, such as local soil conditions, differences in seed varieties, and unpredictable weather conditions. Hence they can be modeled as a random field *Z(s,t)* (Journel and Huijbregts 1978). We will commonly assume that this field is observed at observation times $t_j \in T$, $j=1,...,k$ and at spatial observation locations $s_{ij} \in S$, $i=1,...,n_j$ at t_j.
In order to make any inference at all, we need to make some assumptions concerning the first and the second moment of the random field. The strongest assumption would be that the field is secondary stationary, that is with a mean and a covariance function which are independent upon a translation vector. Here we will make the somewhat weaker assumption that the random field obeys the intrinsic hypothesis:

1. $E[Z(s+h_S,t+h_T)-Z(s,t)] = 0$
2. $Var[Z(s+h_S,t+h_T)-Z(s,t)]$ depends solely on $h = (h_S,h_T)'$ where h_S is the distance in space and h_T is the distance in time.

Therefore, stationarity is assumed only for the mean and for the variance of pair differences, and not for the space-time variable itself. For the cotton root rot data the constant expectation in time may be achieved by considering the residuals with respect to an adequate (linear or quadratic) time trend. Moreover, it has been argued (Journel, 1992) that as long as one is interested in the domain of the observations inclusion of non-stationarity parameters does not make much difference in predicted or simulated values, and often leads to cumbersome calculations.
Under the intrinsic hypothesis, the variogram $\gamma(h) = \gamma_{S,T}(h_S,h_T)$ in *S* and *T* is defined as

$$\gamma_{S,T}(h_S,h_T) = \tfrac{1}{2} E\left[\{Z(s+h_S,t+h_T) - Z(s,t)\}^2\right] \qquad [1]$$

The value ½ is included to allow a simple relation with the covariance function $C_{S,T}(h_S,h_T)$: $\gamma_{S,T}(h_S,h_T) = C(0) - C_{S,T}(h_S,h_T)$. To estimate the variogram we compute the sample variogram as a function of *h* by:

$$\gamma_{S,T}(h_S,h_T) = \frac{1}{2 \cdot N(h)} \sum_{i,j=1}^{N(h)} \{z(s_{ij}+h_S,t_j+h_T) - z(s_{ij},t_j)\}^2 \qquad [2]$$

where $z(s_{ij},t_j)$ and $z(s_{ij}+h_S,t_j+h_T)$ is a pair of observations with a spatial distance at t_j approximately equal to h_S, the total number of such pairs being equal to $N(h_T)$. Pairs of observations are therefore grouped into distance classes: the pairs with approximately the same distance contribute to estimation of the variogram for that specific direction.
The estimator [2] is based upon isotropy, i.e. the correspondence between one unit in time to one unit in space. Isotropy, however, is seldom (if ever) encountered in the space-time domain, because no natural measure exists to combine spatial with temporal units. Therefore a distance *r* defined as $r = \sqrt{h_S^2 + \varphi \cdot h_T^2}$ is commonly applied, which includes the space-time anisotropy parameter φ.
In practical studies, modifications of the general model may be required. These modification can be imposed by data availability, or by the inherent properties of the field to be studied.

1. Random fields $Z(s,t_j)$ with a time-specific expectation over all spatial locations. At each of these times, the spatial variability is modeled by the variogram. This approach was successfully applied to optimize sampling for groundwater management (Stein, in press).
2. Random fields which are replicates of spatial fields in time, i.e. fields with different expectations, but with the variogram proportional to a single model. A single (spatial) variogram can be estimated using observations collected at each of the instances. For each distance each pair of points contributes to the estimate of the variogram, irrespective of the time of measurements (Sterk and Stein, 1997).
3. Random fields for which the instances in time are replicates in space to model dependence in time. The variogram can be estimated using observations collected at each location. For each distance h_T each pair of points contributes to the estimate of the variogram, irrespective of the location of measurement. Such a model, although it essentially includes dependence *in time*, does not take into account spatial dependence that may exist between observations.

We will follow the general space-time model for the root-rot data.

4. Optimal sampling in space and in time

The question is often relevant how many observations to take at which positions in space and at which moments in time to meet a quantitative objective function. We wish to maximize an objective function $\varphi(S)$ depending upon a sampling scheme S. The objective function we wish to pursue in this example is an optimal spread of points such that the numbers in each distance class is equal (Warrick and Myers, 1987). Initially, the observations are spread randomly over the area, yielding a design S_0. Next, a new scheme S_1 is obtained by moving an observation over a random vector r. The scheme S_1 is excepted with probability 1 if $\varphi(S_1) \leq \varphi(S_0)$ and with probability $P = e^{\frac{1}{c}(\varphi(S_1)-\varphi(S_0))}$ if $\varphi(S_1) > \varphi(S_0)$, where c is a parameter that decreases in time. Therefore, an improvement is always accepted, and a deterioration with a time-dependent probability as well. Such procedures are known as simulated annealing (Aarts and Konst, 1989). The spatial equivalent as applied to the design of sampling schemes is given in (Van Groenigen and Stein, subm.).

5. Results

For the root-rot data consider that 100 observations are to be made during the season, that no fixed monitoring locations are required and that variability between weeks is relevant. We may decide for 10 lag distance classes in space, e.g. multiples of 5m in the 32 by 80 m area, and for 8 distance classes in time, leading to 4950 pairs of points distributed over 80 space-time distance classes.

Figure 1 presents the near-optimal monitoring density. The optimal distribution pairs of points (62 pairs) is not fully reached, with numbers of pairs ranging from 48 to 66 (Table 1). Notice that a clustering occurs, because sufficient pairs of observations must be available for small distances as well as for larger distances. Clustering also occurs in time, with increased sampling in weeks 0 and 7. The procedure can be generalized by imposing additional constraints, such as assigning a specific month in which no sampling is required, or a minimum (and a maximum) number of samplings for each week, use of a number of fixed locations, etc. Each additional constraint would yield a solution which is further removed from the optimum, but may be more realistic to apply in practical circumstances.

Table 1. The number of point pairs obtained with spatial simulated annealing for each combination of spatial lag and temporal lag. The optimal scheme would have 62 pairs in seven out of eight classes, and 61 pairs of points in the other distance classes

Temporal lag	Spatial lag (m)									
(weeks)	0 - 5	5 - 10	10 - 15	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45	45 - 50
0	63	64	65	66	63	63	62	61	62	61
1	64	64	66	66	66	65	65	66	64	64
2	61	61	61	61	59	58	60	59	60	61
3	57	57	56	56	56	55	56	56	57	58
4	53	53	52	53	53	53	52	52	52	53
5	51	52	51	51	50	50	48	50	53	53
6	53	52	51	49	49	53	53	53	53	53
7	56	56	59	59	58	57	56	59	59	60

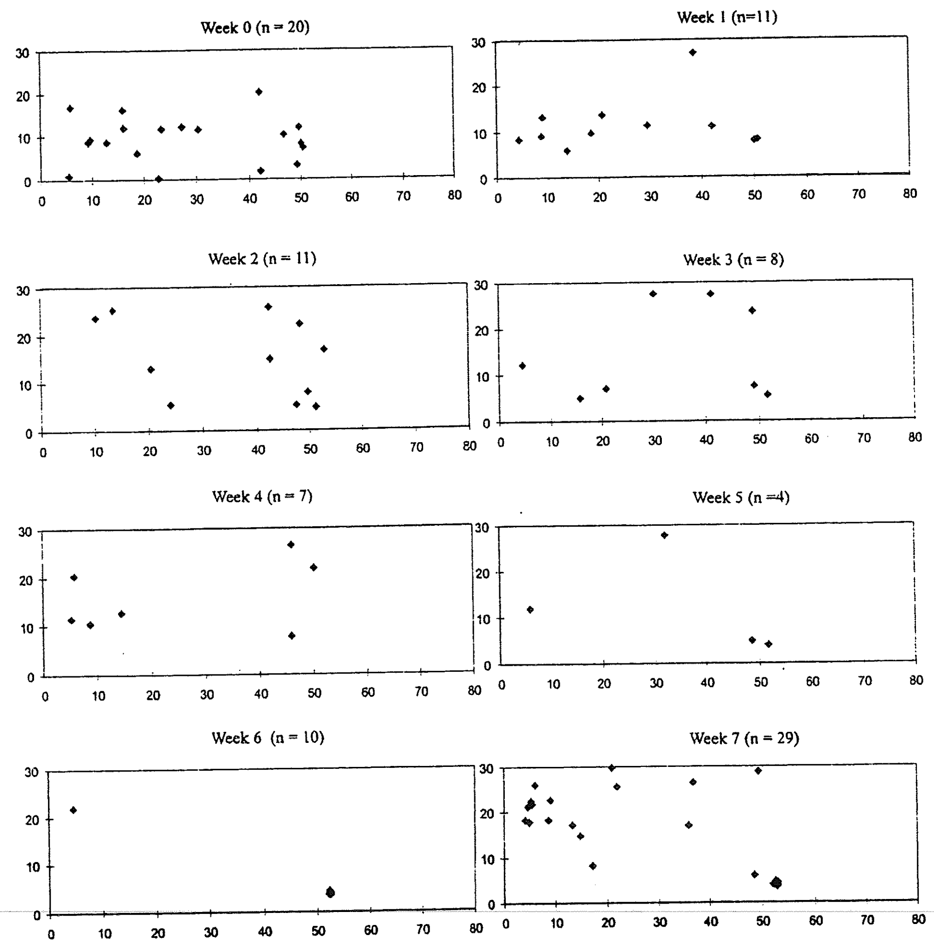

Figure 1. The optimal sampling scheme for distributing 100 observations over 8 sampling days in a 80 m by 32 row area. Optimality is defined as equal numbers of pairs of points for each distance class

6. Concluding remarks

In this study we presented an approach to optimize sampling in the space-time domain. The space-time dependence was described using variograms. The procedures thus developed can be extended towards non-stationarity as well. Only the calculations will be more cumbersome, and the results may be more difficult to interpret.
To set up a monitoring system in space and time we optimally selected the sampling locations. The criterion focused on optimal estimation of the space-time variogram. The optimization procedure, however, is flexible enough to optimize other quantitative criteria and to include additional constraints. One criterion that we studied recently was even distribution of the data over an area. Another criterion was minimization of the kriging variance. The latter is more complex than the other two, because some information about the dependence function must then be available. The procedure is therefore promising to solve optimization of a monitoring network for a large range of practical problems.

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