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Simulating management strategies: the rotational grazing example

M.J. Cros [a], M. Duru [b], F. Garcia [a], R. Martin-Clouaire [a,*]

[a] *Unité de Biométrie et Intelligence Artificielle, INRA, Biometrics and Artificial, BP 27, Auzeville, 31326 Castanet Tolosan cedex, France*
[b] *Station d'Agronomie INRA, BP 27, Auzeville, 31326 Castanet Tolosan cedex, France*

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Abstract

This paper argues in favour of a simulation approach relying on an explicit and rigorous modelling of the management strategy that underlies the farmer's decision-making behaviour. A strategy is defined as a roadmap of intended technical tasks over a management period. It is tied to an overall objective and specifies what to do depending on the situations encountered. An essential feature is its flexibility, enabling it to cope with stochastic fluctuations of the environment. In order to evaluate the worth of a strategy, the advocated approach relies on a simulation tool with which the effects of applying the strategy are evaluated under different hypothetical weather conditions. The example of a rotational grazing dairy production system is used to illustrate the modelling and simulation of a management strategy covering a production season. SEPATOU, the simulator built for this application domain, is designed to be used by extension services and farming system scientists. It provides a framework for virtual experimentation that can help to enhance decision-making capabilities of primary producers and find new or more profitable management strategies.

Keywords: Decision support system; Management strategy; Climatic variation; Simulation; Rotational grazing

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[*] Corresponding author. Tel.: +33-5-61-28-52-86; fax: +33-5-61-28-53-35.
E-mail addresses: cros@toulouse.inra.fr (M.J. Cros), mduru@toulouse.inra.fr (M. Duru), fgarcia@toulouse.inra.fr (F. Garcia), rmc@toulouse.inra.fr (R. Martin-Clouaire).

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1. Introduction

Internationalisation of markets, shifts in consumer demands and requirements, rapid evolution of technologies and a greater concern for environmentally friendly production are among the recently emerging factors that make competitiveness much harder to achieve and maintain in the agricultural production industry. Unlike the relatively stable context of the past decades, farmers must now strive for a dynamic competitive advantage that requires a well mastered understanding of their production processes so as to control them under various constraints and toward specific objectives, both of which may change from one year to the next. Consequently, increasing importance has been placed on the ability of making the wisest decisions possible concerning configuration choices and day-to-day technical management. It is striking to see how profitability varies from one farm to another just because of the differences in the management skills of the farmers. The most successful farmers usually operate on the basis of their expectations of what situations could occur and what the appropriate reactions could be in order to ensure that their production system stays on the right track. In other words, monitoring the profitability of an agricultural production system requires a management strategy based upon a conditional plan of actions specifying the intended courses of operations attached to the possible futures.

As part of a decision-support project, the present paper argues in favour of a modelling and simulation approach of the management strategies developed to monitor agricultural production systems. The systems addressed can be either a single farm enterprise (e.g., a crop on a set of fields managed in the same way), or a combination of highly interdependent or interlocking farm enterprises (e.g., a livestock enterprise that produces milk from different feeds and a forage enterprise that supplies the grazing grass to the dairy cow herd). The managerial task considered in this paper deals with the making and implementation of decisions concerning timing, amount and mode of use of various resources (land, labour, machinery, inputs) in the production of commodities such as milk, cereals, fruits, etc. More specifically, only production management aspects are considered. Marketing and financial aspects (organisation and control of capital: when to invest, where to find capital, when to replace machinery) are beyond the scope of this study.

The following section describes the management problems and management strategies in agricultural production systems. Section 3 emphasizes the usefulness of management strategy simulation for analysing and improving the performance of agricultural production systems. Section 4 illustrates these concepts for the specific case of a grazing system management for dairy production. The SEPATOU simulator that is built according to the computational exploration philosophy advocated in this paper is briefly presented.

2. Management problems and management strategies

2.1. Management problems in agriculture

Management problems are dynamic in nature due to changes from one year to another (in available resources, in economic context and legislation) and due to unpredictable fluctuations within a production cycle (climate and sometimes prices of the produce sold or of the inputs). Thus, management cannot be reduced to day-to-day running of a pre-established rigid set of actions and must be seen as a temporally structured cognitive process. To some extent, farm enterprise management is similar to production management in the manufacturing industry. Essentially, the complexity of the problem stems from the large number of uncertain data to deal with and the numerous decision-making steps and alternatives to consider. A classical approach to cope with such a complexity in industrial production management is to break down the problem into different elementary functions such as planning, scheduling and control of the production process (Schneeweis, 1995). In farm management, analogous breakdowns of the decisional and technical activities have long been ignored, mainly because of the predominance of the concept of the farmer as the unique decision maker and actor on his/her farm. However, due to the nature of the processes that must be controlled and the level of uncertainty about the future, there are important differences between farm management and industrial production management. As opposed to industrial processes, the response of crop yield and livestock output to inputs is highly subject to uncontrollable variations as a result of weather and disease for instance. In agriculture, the biophysical systems play the role of machines in industrial manufacturing except that they are not really optimised with regard to production objectives. Moreover, the socio-economic environment is generally more multiform and less controllable by farmers. To sum up, farming systems seem to be more hazardous, more complex and less standardised than industrial production systems.

Despite these inherent difficulties, farming system researchers (Sebillotte and Soler, 1988) developed a conceptual model of the management decision-making process for agricultural production systems in the 1980s. The framework has been studied within the setting of different production systems (e.g., sugar beet, wheat) and softwares based on this conceptual model have been implemented (see Gibon et al. (1989); Attonaty et al. (1991); Rellier (1992); Olesen et al. (1997)), giving the concept of management strategy a more concrete content (Aubry et al., 1997). Current efforts along these lines aim at further developing and formalising the notion of strategy for more difficult management problems such as handling the various operations in greenhouse production (Martin-Clouaire and Rellier, 2000; Rellier et al., 1998). Another example is rotational grazing that is briefly presented in the next subsection. This example is further developed in Section 4 to illustrate, in particular, a management strategy designed to deal with this problem.

2.2. An example: the rotational grazing management problem

In France, many dairy cow production systems rely strongly on a grassland feeding resource that is exploited through rotational grazing (moving animals from pasture to pasture) and supplemented by conserved feed (maize silage and hay) and concentrate in winter when the herbage mass is insufficient. The rotational grazing management problem concerns almost 90% of the dairy producers because of the scattered field pattern of many French farms (Pflimlin, 1995), and because this management practice is appealing as a result of the flexibility in choosing the interval length between two grazing events (Parsons et al., 2000).

The late winter to early summer period is a particularly crucial phase in which the diet must switch progressively from purely maize-concentrate feeding to predominantly or entirely herbage-based feeding. The general objective of the farmer is to keep the milk production at a desired level throughout the production period by proper utilisation of the herbage resource despite the uncontrollable fluctuations of some important factors such as weather. The factors which the dairy farmers can control include the stocking rate, the daily cow diet, the nitrogen fertilisation of the pastures and, most importantly, the movement of the herd to a chosen pasture. The main difficulty in this management problem stems from the fact that the herbage production process interacts strongly with its concomitant use through grazing (Parsons, 2000). For rotational grazing to be successful, the herbage supply must match the demand as closely as possible, at least over the spring period. The underlying control problem is a complex one because it involves a multivariable optimisation with both direct immediate effects (e.g., cow intake) and indirect delayed effects (availability and quality of the pasture for subsequent grazing). An appropriate quantity/quality trade-off of the available herbage should be maintained throughout the period under consideration in keeping with the intended profile and constraints of the use of conserved feed and concentrate. The herbage growth rate can be controlled to some extent by appropriate nitrogen fertilisation. Too much herbage can be as big a problem as too little. It has been shown that in order to have herbage of good quality, grazing should be intense and regular (Hoogendoorn et al., 1992; Duru et al., 2000). For rotational grazing to be successful, the turnout time (Coléno and Duru, 1999) and the timing of rotations must be carefully chosen to match the state of the pasture (Kristensen, 1988). At some point, poor quality or an excess of herbage can be corrected by harvesting some pastures as hay or silage.

The manager (i.e., the farmer) must find a coherent combination of choices so that an almost optimal production of milk is ensured over the whole production period for a sufficiently representative range of climatic conditions. Several satisfactory combinations might exist. The determination of the best ones depends on the characteristics of the production system such as land resources per cow, milk quota per ha, labour constraints or economic targets. In any case, this requires anticipation (i.e., planning) of the set of fields definitely allocated to grazing, the set of fields set aside to cope with weather fluctuations and grazed only if necessary, the supplemental feeding (harvested feed and concentrates) profile over time, the fertilisation policy, the cutting policy and the field rotation policy. These planning decisions underlie the day-to-day determination of the technical operations that should be done although these operations have to be compatible with and tailored to the actual situation.

The period considered in the management task covers nine months from the beginning of February until the end of October. The starting date corresponds to the physiological change of the sward from the vegetative to the reproductive stage (Peacock, 1975), the time at which the first fertilisation operation may have to be performed. The ending date corresponds to the calving period. It is also the time when the herbage production diminishes strongly, making it necessary to turn to a winter diet based on harvested feed, and maize silage, in particular. Practically speaking, if no major feeding problem occurs before August, then the rest of the period is easy to deal with except in the case of severe drought. The feeding management problem is never exactly the same from one year to another because the stock of maize silage at the start of the period varies due to weather conditions in the previous year and the size and characteristics of the herd may change too (Coléno et al., 2002). Since the main difficulty with this problem lies in the management of the grassland feeding resource, we will simply refer to rotational grazing management from now on.

From an economic point of view, the problem is crucial because grazed grass is less expensive than maize silage and presents a more attractive image of dairy produce to consumers (Pflimlin, 1995). The current heavy use of maize silage can be explained by economic influences such as grants for maize silage. Another reason stems from the management difficulties associated with grazing. It is particularly hard to determine appropriate rates for nitrogen fertiliser, amounts of hay or silage, the area to be allocated per cow and rotation policy, in advance. In order to obtain target milk output per cow, energy intake per cow needs to be high and regular, whereas the available amount and quality of grass are very sensitive to weather and sward management, particularly grazing pressure and rotation length. Thus, emphasis on minimising risks has led to the decline in the use of grazing for feeding cows (Coleno, 1999). This conservative attitude can be partially explained by the farmers' lack of knowledge with respect to the mastering of the complex interaction between grass growth processes and livestock grazing and milk production.

2.3. Management strategy: a conceptual decision model

A key assumption of this study is that farmers, consciously or not and effectively or not, decide and act on the basis of management strategies that define the proactive and reactive aspects of their management behaviour. A strategy can be seen as a set of planned tasks that incorporates capabilities to adapt to perturbations with respect to the average course of future events (Sebillotte and Soler, 1988). The context-dependent adaptations are means to cope with the stochastic nature of the environment. Another way to characterise this conceptual decision model is to consider the temporal and hierarchical organisations of the management task. Even if the different cognitive and physical processes of an agricultural production system are managed by a single person (the farmer), it is worth considering a hierarchical breakdown of the management problem in order to better understand it and provide support for more effective and robust decisions. The hierarchical breakdown pertains to the distinction between various planning tasks having different time horizons. One of these levels corresponds to action determination made at implementation time as a function of the current situation.

The management process can be illustrated as a function of the following aspects:

- one or several production objectives (e.g., maximising milk production, minimising herbage waste and consumed maize silage);
- a set of intermediate goals (e.g., maintaining an appropriate quantity/quality trade-off of the available herbage) which the farmer tries to achieve;
- some planned junctures (e.g., the end of the first rotation cycle) between the farmer and the production system, where she/he makes some observations and diagnostics;
- a set of rules that enables the farmer to decide how to adapt his/her management trajectory to particular events (e.g., significant climatic deviations) monitored at juncture times or any other time (like an alarm);
- a set of rules that specifies what to do on a daily (or shorter) basis, depending on the current state and available resources, in order to accomplish the planned trajectory.

The management task can also be broken down according to the different undertakings involved, each being itself structured into simpler subtasks that are relatively independent from the point of view of the resources they need. Of course, the different plans for these subtasks must be coordinated.

As far as the hierarchical representation of the decision-making processes is concerned, three main functions can be identified: planning, observing/monitoring and acting. The planning function determines a temporal organisation of relatively abstract subtasks on the basis of an anticipated course of future events (intermediate goals and devised courses of actions). It also provides an initial plan and may occasionally (at the juncture points) perform some adaptations when adverse trends (bad weather) or opportunities occur. The acting function expands the active subtasks specified in the plan by applying situation-dependent procedures (decision rules) that generate executable (also called primitive) actions to be performed on the controlled biophysical system. The acting function is invoked much more frequently than the planning function. Finally, the observing/monitoring function is responsible for gathering relevant data about the biophysical system and external environment, in order to provide information for the planning and acting functions.

A plan cannot be specified directly in terms of primitive actions and physical variables because such a plan would be too complicated to express and adapt due to the multitude of possible situations that might occur, given the uncertainty about the future. Thus, the definition of a management procedure necessarily requires (essentially for planning and observing/monitoring functions) the use of abstract concepts that do not always correspond directly to tangible facts and decisions and that are often the result of an important cognitive activity reflecting the empirical knowledge of the farmer or the community of farmers as accumulated over a period of time.

Within this conceptual model of the management decision-making process, a particular farm manager's strategy can be defined by specifying:

- how to plan, adapt and coordinate long-term (with respect to the production horizon) management trajectories for the different tasks involved in the production process;
- how to generate the immediately executable actions on a daily basis, expanding the planned trajectory of each active task as a function of the current situation;
- the important events that have to be monitored;
- the interpretations of the data that are needed in order to feed the decision process.

Since efficiency and risk control are directly dependent on the management strategy, it is necessary to study management strategies to improve the production results. A preliminary step is to express them formally. The benefits of explicit representation of strategies are undoubtedly important. First, the concept of strategy is often seen from a very restricted point of view as a rigid sequence (or even a set) of decisions that are themselves reduced to the assignment of values to a set of decision variables, whereas the truth is much more complex, as different case studies have shown (Aubry et al., 1997; Martin-Clouaire and Rellier, 2000). Another reason to investigate strategies is to draw up the complete picture of what constitutes the decision-making behaviour of a farmer for the production system under consideration. It clarifies weak points of the decision-making process and forces the decision maker to face issues that are sometimes unconscious in his/her own mind. Therefore, it facilitates critical analysis and improvement as well.

3. Simulation of management strategies

3.1. Simulation versus optimisation

Two modelling options for the management strategies are possible depending on the kind of decision support one intends to provide. The first one, which is widespread today, amounts to taking a family of relatively simple strategies, classically under the decision vector form (with all the implied limitations as pointed out above), and developing an optimisation approach to search for the "best" decisions according to a well-defined numerical criterion (see Botes et al. (1996); Parson (1998)). The second approach, which is the aim of this paper, consists of modelling the strategies and biophysical processes as thoroughly as possible, and to simulating their interactions using a computer. This approach can be used to support a trial-and-error learning process (Fig. 1) by rapidly exploring alternative management strategies at almost no cost. The simulation gives basic figures for the evolution of the biophysical system which makes it possible for the user to analyse the merits and shortcomings of the strategy applied (Attonaty et al., 1996).

The main reason why we think that this second approach is preferable is that there is usually no universal optimal solution to a particular management problem because the efficiency of a solution depends on the specific constraints and subjective judgement of the farmer. Furthermore, the whole management problem of agricultural production systems is generally too complex to be addressed with optimisation tech-

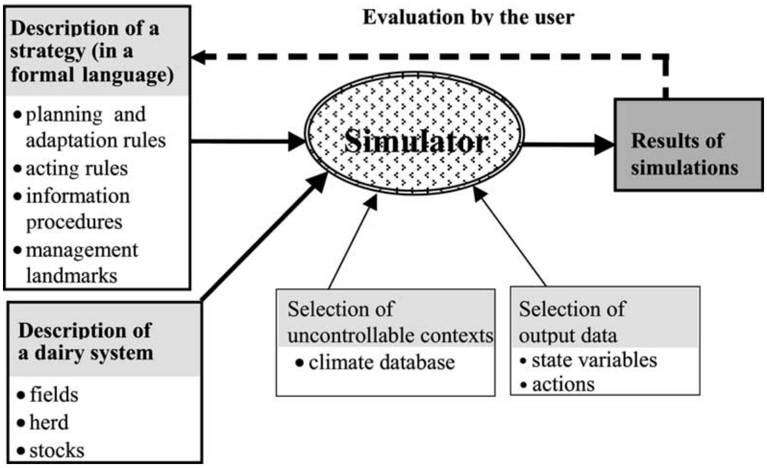


Fig. 1. Simulation as a tool in a trial-and-error learning process.

niques. Hence, in order to stay within the realm of classical management science based on mathematical operation research techniques (e.g., linear programming or dynamic programming) it is necessary to over-simplify the strategy representation and, thus, to look for solutions that generally do not correspond to feasible practical strategies. In contrast, the simulation approach makes the evaluation of realistic strategies possible, is not impeded by the complexity of the underlying decision and biophysical processes, and takes the essential role played by uncontrollable events (especially the weather) into account. By simulating the application of a strategy on a range of hypothetical weather conditions (Racsko et al., 1991), it is possible to assess its robustness, that is, its ability to give acceptable results in most of the situations that might be encountered. The criteria to look at are defined by the simulation user. They might be based on production performance, resource use, environmental impact or a combination of these. Therefore, the worth of a strategy can be evaluated with respect to a particular risk attitude. Finally, simulation makes it possible to perform virtual experimentation under repeatable conditions (see Bywater and Cacho (1994) for some insights about simulation models). Physical experiments over a sufficient number of years would of course be impossible given the size of the sample that is required in order to take variability into account and to study the robustness of strategies. To effectively provide the above-mentioned benefits, the simulation models must be consistent and reasonably accurate with respect to their intended use. Validation is required to gain confidence in the correspondence of the behaviour of the model with reality or the behaviour expected by knowledgeable people.

3.2. Desirable features of a simulation tool

Despite its popularity in industrial contexts, simulation is still in its infancy in the agricultural management domain. In particular, the dynamic aspect of the decisional part has not yet been addressed in depth. Most simulators (Jones et al., 2003; Stöckle et al., 2003) deal with crop response to uncontrolled inputs (e.g., solar radiation, temperature, rain) and controlled ones generated on the basis of relatively static management rules. These rules usually convey pre-established sequences of technical operations and sometimes support a reactive behaviour under particular conditions. The farmers' management abilities are crudely modelled in such systems since no provisions are made for simulating the coherent anticipatory and adaptive decision trajectory that farmers should have in order to orient production according to their objectives and to reduce the impact of the fluctuations of the uncontrollable factors as much as possible. Due to their oversimplified view of the management task and the strong hypotheses regarding the availability of information on the biophysical variables, these simulation-based systems are too far from the real context of farmers' decision-making and their practical usefulness as decision support tools is limited although they can definitely help in facilitating analysis and learning of complex interrelationships in agricultural production processes (McCown, 2002).

The major aim of our research is consequently to promote and develop the use of structured languages for representing management strategies in interactions with biophysical systems. Similar ideas about the interaction between decision-making, biophysical aspects and weather conditions have been investigated for the management of winter wheat (Papy et al., 1988), conserved forage production (Gibon et al., 1989) and greenhouse tomato production (Rellier et al., 1998). In order to increase the chance of effectiveness of a simulation tool, it seems necessary to impose some design constraints on the modelling capabilities and computational framework of the simulators. These include:

- a proper level of detail and of precision of the biophysical model with respect to the intended use. The biophysical model must be able to respond dynamically to the actions determined by the decision-making system and it must be able to provide the kind of information used to make decisions;
- openness and flexibility of the formal language used to represent the production system and more especially the management strategies;
- usability of the simulation tool: ease of simulating the consequences of applying a strategy in different uncontrollable contexts;
- efficiency to cope with repeated simulations covering a range of hypotheses about the external (uncontrollable) environment.

The following section focuses on the rotational grazing problem introduced in Section 2.2 and illustrates how strategies are represented in a specifically developed formal language that is interpretable by the constructed simulator.

4. Simulating rotational grazing management with SEPATOU software

The simulation approach discussed in the previous sections has been applied to the case of a pasture-based dairy system. SEPATOU software (Cros et al., 2001a) has been developed in this spirit. Section 4.1 outlines the biophysical model included in the simulation system and shows where the management strategy lies within this model. Section 4.2 presents how a rotational grazing strategy is represented and interpreted by the simulation mechanism. Section 4.3 briefly illustrates the kind of management strategies that can be simulated and the kind of results obtained.

4.1. The biophysical model

Many papers (e.g., Woodward, 1999) have been published on grassland models, which address only the herbage growth or vegetation dynamics aspects. Few grazing models (e.g., Herrero et al., 1997) dealing with the plant/animal interaction are reported in scientific literature, especially when management is the central concern. Unlike most typical research models that focus on understanding a limited number of physiological or ecological processes, the model developed for the SEPATOU system (Cros et al., 2003a) is at farm scale and integrates knowledge from different areas of expertise (crop science, animal science, farming systems research) and from a farm management perspective at the seasonal scale. The highest level the SEPATOU simulator operates at is the grazing system, that is, the farm level. The lowest levels in the model are the plots and the cows that constitute a single mob. The model is made up of three submodels that deal with the soil, sward and animal components. It includes control variables that are the main factors that farmers can control (nitrogen fertiliser rate, defoliation frequency and intensity, composition of cows' diet). It accounts for the influence of climatic factors such as rainfall, temperature and solar radiation. See Fig. 2 for a sketch of the biophysical model.

Given a set of grazing fields and a dairy herd, the model makes it possible for the day-to-day dynamics of biophysical processes such as herbage growth and senescence or cow intake and milk production to be simulated. This model integrates existing and new submodels, either process-based or empirical, and tailored to the simulation task that covers a period of several months from the beginning of February to the end of July. The model provides realistic estimates of variables such as the daily milk yield, the intake of the different feed types and the herbage mass and digestibility on each field. Besides playing a role in the biophysical mechanisms at work, these variables might also be subject to requests by the decision-making system if they are relevant to the making of a decision. When analysing the simulation results, they may also be involved in the evaluation of the management strategy applied. Also of primary importance is the ability to compute dates of occurrence of key events such as the turnout to grass, the start of night and day grazing and the end of the first grazing cycle, that are functions of biophysical state conditions (see Section 4.3). These events happen as a consequence of the management strategy applied to the biophysical system. In other words, the biophysical system must respond convincingly to management operations and environmental factors in such a way that it can interact with the decision-making system and enable the value of management strategies fed into the decision-making system to be assessed.

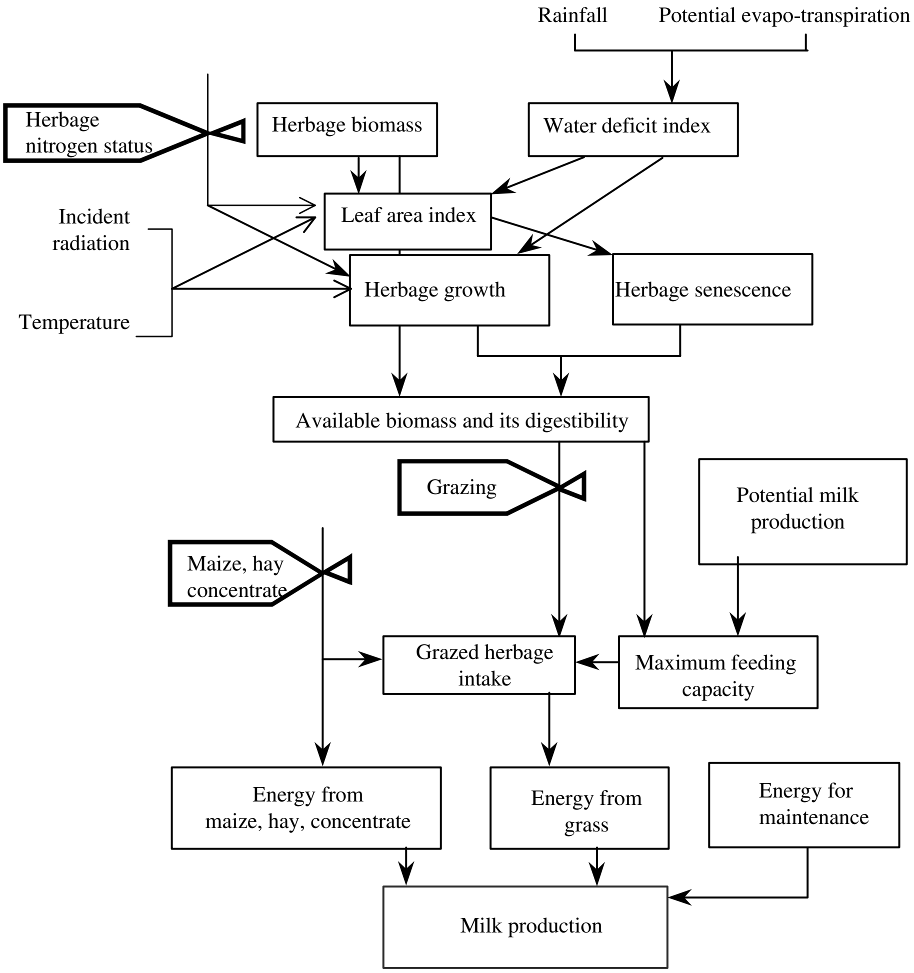


Fig. 2. A simplified schematic view of the biophysical model: ▭⊲ management variables; ▭ state variables.

4.2. The management model

The management behaviour of the dairy farmer is fully specified through his management strategy that conveys, in a structured way, what to do conditionally in response to some states and events. In the SEPATOU system, a strategy is represented using a specific and dedicated representation language called LnU. In this language (Cros et al., 2001a), a strategy is defined by:

- planning rules that set up the different tasks involved in the production process over the temporal horizon of interest;
- acting rules that expand, for each active task, the planned trajectory so as to generate situation-dependent actions;

Table 1
The tasks and the corresponding plan and action variables

Task	Plan variables	Action variables
ConservedFeed	?FeedConcentrate ?FeedMaize ?FeedHay	?ConcentrateAmoun ?MaizeAmount ?HayAmount
Grazing	?FieldsToGraze ?GrazingDuration	?GrazedField ?GrazingLengthOfField
Cutting	?FieldsPlannedForSilage ?FieldsPlannedForHayCutting	?FieldsCutForSilage ?FieldsCutForHay
Fertilization	?FieldsToFertilize ?Nlevel	?FertilizedFields ?Nrate
Coordination	?TaskOrdering	?ActionOrdering

- temporal landmarks that are involved in the planning and acting rules and that are associated with monitored events;
- interpretation functions that are needed to inform the condition parts stated in the planning and acting rules.

Five tasks have been identified (see Table 1): distribution of conserved feed, allocation of the herd to a grazing field, cutting a field, fertilisation of the fields, coordination of the above tasks. A set of plan variables and a set of action variables are associated with each task. The planning rules are responsible for assigning values to the corresponding plan variables for a given period over which these values remain constant, except if an adaptation is required (which would be carried out by bringing another planning rule into play). The planning rules guide the production system by restricting the possibilities for future actions. They have a triggering part made of either a single landmark or a logical combination of landmarks using conjunction and disjunction operators. A planning rule is applicable as soon as the events that occur satisfy the trigger. The action rules are used to completely determine what actions to perform in the task under consideration. Interpretation functions are essentially used to provide past and present synthesized information about the external environment and the biophysical system. They can also be used as a predictor of future states. In practice, interpretation functions are also used to synthesize data that are useful for the analysis of simulation results.

The above notions are illustrated in Table 2. The first planning rule that defines the plan for the grazing task specifies the set of fields allocated to grazing for periods delineated by landmarks and the grazing time per day (diurnal only or day and night). The landmarks are defined in terms of a number of days of offered herbage per cow if fed only with this resource. Such numbers are computed from the biophysical model by interpreting the herbage dry matter amount that is currently available. The second planning concerns the grazing tasks as well. It performs adjustments of the set of fields in the grazing plan at the ending date of the first cycle as a function of the herbage available. The acting rule given in Table 2 is based only on a residual sward height condition. This is actually a simple version of the kind used in

Table 2
Examples of grazing strategy components using the LnU language

Strategy components	Meaning in natural language	Coding in the LnU language
Planning rule (plan setting, adaptation)	The grazing plan is composed of three periods delineated by February 1st, the turnout date, the day and night grazing date and July 31st. In each period the set of grazing fields is the set of all fields.The grazing length is 0 in the first period (no grazing), diurnal time in the second one and day and night in the last one.	PLANNING RULE : CreateGrazingPlan TRIGGER : !February1st { FROM !February1st TO !TurnOut DO { ?FieldsToGraze = AllFields ?GrazingLength = “0”} FROM !TurnOut TO !DayNightGrazing DO { ?FieldsToGraze = AllFields ?GrazingLength = “day”} FROM ! DayNigthGrazing TO !July31st DO { ?FieldsToGraze = AllFields ?GrazingLength = “day-night”} }
	At the end of the first cycle, *field10* should be taken out of the set of grazing fields, if the offered herbage per cow covers more than 8 days of a solely grazing herbage diet.	PLANNING RULE : AdaptGrazingPlanAtEnd1stCycle TRIGGER : !EndFirstCycle IF HerbageMassAvailability(?FieldsToGraze) > 8 THEN ?FieldsToGraze = ?FieldsToGraze − Name(“field10”)
Acting rule	The field to graze today is either the current one if grazing it another day would leave a residual sward height higher than 5 cm, or the grazing field that is the oldest in the grazing sequence.	ACTING RULE : DefineFieldToGraze IF SwardHeigth(CurrentField) > 5 THEN ?GrazedField = CurrentField ELSE { %GrazableFields = Grazable(?FieldsToGraze) − CurrentField ?GrazedField = OldestNonUsed (%GrazableFields)}
Landmark	The turnout time is reached when the offered herbage per cow covers more than 4 days of a solely grazing herbage diet.	LANDMARK : !TurnOut CONDITION : HerbageMassAvailibility(?FieldsToGraze) > 4
	The date of closing of the maize silage silo is reached when the offered herbage per cow covers more than 4 days of a solely grazing herbage diet, and the average herbage growth rate is greater than 40 kg of dry matter per ha and per day.	LANDMARK: !CloseMaizeSilo CONDITION HerbageMassAvailibility(?FieldsToGraze) > 4 AND HerbageGrowth > 40
Interpretation function	The average herbage growth rate is the average of growth on the set of grazing fields in a week.	FUNCTION : HerbageGrowth CODE : AverageGrowthRate (?GrazingFields)

the strategies effectively simulated where different, time-varying and sometimes multiple criteria have been used. Examples of criteria are the maximum sward height to allow grazing of a field or the soil-bearing capacity. Only a few adaptation and acting rules are used in the case of a simple farm model (single soil type, single grass species, etc.). More sophisticated cases can be modelled, requiring more rules.

The discrete event simulator at the core of the SEPATOU software works as follows. Every day it is checked to see whether a noticeable event has occurred and, if so, the plans attached to the activities are eventually created or adapted, using planning rules. By using action rules, the general instructions specified in the plans are then transformed into executable actions that depend on the current situation of the biophysical system (more precisely on the decision maker's perception of the current situation), the external environment and the current date. The changes that the actions cause to the biophysical system are then computed, resulting in the total milk production for this particular day and an updating of the biophysical state that corresponds, at this point, to the situation at the beginning of the next day. The simulator then considers the next day and performs similar processing. The iterations are pursued until the end of the simulated period.

4.3. Examples of strategies and simulation results

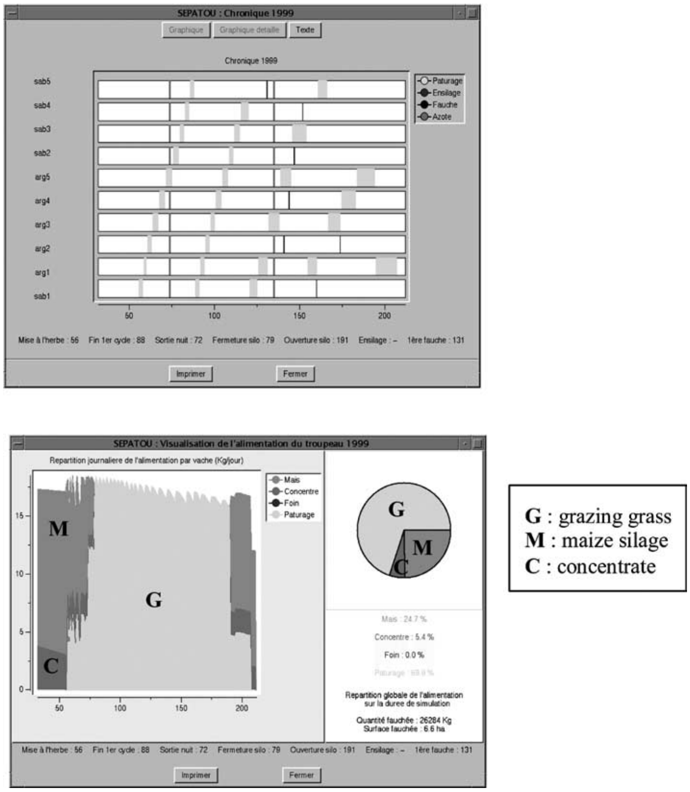
In this section, three examples of management strategies are considered for dairy production systems in Brittany (western France). They have been defined by extension service agents who are specialists in the area of grazing for feeding dairy cows (Thébault et al., 1998). They were synthesized from observed management practices based on farm surveys and specific cases monitored in the setting of advisory activities. The complete elicitation of the strategies, their coding in LnU and simulation using SEPATOU have been carried out in collaboration with these agents (Cros et al., 2001b). The main differences between the three strategies concern the grazing season length (70, 100 and 150 days, respectively, of an exclusive grazing herbage diet over the year) and the land resources in the corresponding dairy farms (0.26, 0.35 and 0.48 ha, respectively, per cow).

For the strategy, "100 days of exclusive grazing herbage diet" (100-grazing-day strategy, for short), the typical dairy farm considered was assumed to have the following characteristics:

- 31 dairy cows, each having a milk production potential of 7500 kg per year and having calved on October 15th of the previous year.
- The grazing area for the dairy cows equals 11 ha of perennial rye-grass split into 10 paddocks.
- The actually simulated strategy implemented a particular management behaviour that essentially presents the following features:
- Grazing can start as early as February 15th. The length of the feeding transition phases is conditioned by the amount of offered herbage available per cow and by the rate of herbage growth. All fields have to be grazed at least once. The set of fields allocated to grazing is revised every week as a function of the offered herbage availability.

- All the fields that have been left aside for grazing and that have a sward higher than 18 cm are harvested.
- The distribution of conserved feed during the transition toward the full grazing diet evolved in a three-step process: (i) at turn out, cows are given 10 kg of maize silage and half of the concentrate ration provided daily before turn out, (ii) as soon as overnight grazing starts, cows get 5 kg of maize silage and 1 kg of concentrate, (iii) at the end of the maize silage feeding period, conserved feed is no longer provided. During the mixed feed period, the amount of maize silage is temporarily increased by 5 kg and that of concentrates by 1 kg if the herbage growth is insufficient to cover the demand.
- Finally, a high herbage nutrient status (nitrogen index around 90) has to be maintained by nitrogen fertilisation.

An example of simulator output (Cros et al., 1999), for this 100-grazing-day strategy under the 1999 climatic scenario is given in Fig. 3. The upper and lower parts show display windows of the grazing calendar for each field and the feeding diet per cow, respectively. These types of representations are commonly used by extension service agents and are therefore highly suitable for communication and validation purposes.



Mise à l'herbe : 56 Fin 1er cycle : 88 Sortie nuit : 72 Fermeture silo : 79 Ouverture silo : 191 Ensilage : – 1ère fauche : 131

Mais : 24.7 %
Concentre : 5.4 %
Foin : 0.0 %

Repartition globale de l'alimentation sur la duree de simulation

Quantité fauchée : 26284 Kg
Surface fauchée : 6.6 ha

Fig. 3. Display windows of a grazing calendar (plots used vs. time) and a feeding diet calendar (daily intake vs. time in kg of DM per cow).

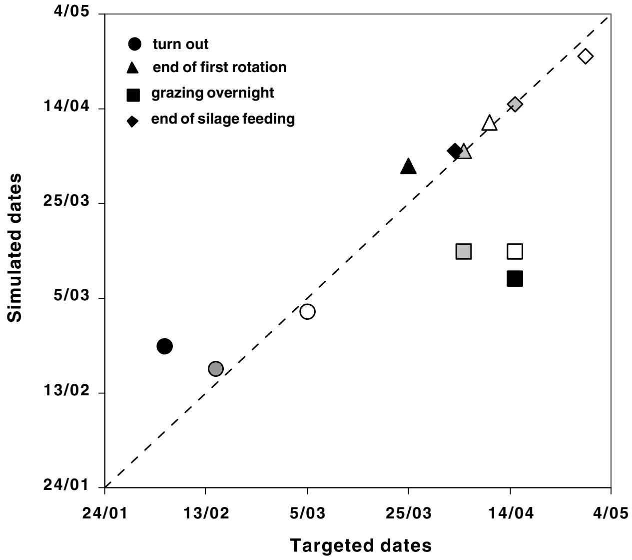


Fig. 4. Comparison of target key event dates with simulated ones for the 70 (black), 100 (grey) and 150 (white) grazing-days strategies.

The objective of the strategy, "70 days of exclusive grazing herbage diet", in which the grazing area is smaller, is to close the maize silo for two months: May and June. This strategy was expressed within the same framework using different thresholds. The strategy, "150 days of exclusive grazing herbage diet", requires more grassland area per cow but allows more flexibility. This is obtained by using rules making versatile feeding transitions possible to allow frequent variations of the herd diet. Useful insights about the robustness of the strategies can be derived by comparing simulation results obtained under various climatic scenarios. Fig. 4 shows the average of 17 climatic years obtained for the occurrence of four key event dates in spring: turnout, start of day and night grazing, end of the first grazing rotation and stopping of the maize silage supply. As expected, the three strategies produce different behaviours with respect to the timing of these events. Fig. 4 also compares the simulated dates and the target ones given by grazing experts (Thébault et al., 1998). A rather good fitting was observed, except for the timing of the day and night grazing event. The temporal order between the three strategies is consistent for each type of the key events. These comparisons and others have contributed to the validation process (Cros et al., 2003a).

5. Conclusion

The changes in the economic, technical and legal context of farming require innovation or at least adaptation of the way to use the resources (how to produce) and, consequently, the way to manage the enterprise throughout the production period. In many cases, what was appropriate is no longer sufficient or appropriate to new constraints and objectives. In order to support this necessary adaptation of the farm enterprise management and cope with the difficulty of finding new solutions to new problems, we have advocated a modelling approach of the response of the biophysical processes to farmers' technical operations and of the articulated logic underlying the choice of these operations. The dynamic simulation of this process makes it possible to evaluate management practices and understand why and in which cases they may perform acceptably well or fail. Simulation can support the design of new management strategies. The representation framework and simulation tools of the kind discussed in this paper can enhance creativity and intuition of those willing to explore management alternatives. It can also facilitate communication between farmers and extension services by enforcing a common vocabulary for the domain and providing a framework for joint discussions. For the above reasons, the kind of simulation approaches advocated here, that realistically combine biophysical and management considerations, have great potential to enhance the learning process of the various dimensions of agricultural production systems (Walker, 2002).

The practical usefulness of the simulation is demonstrated in this paper by the SEPATOU system that is devoted to the problem of managing the feeding resources in a dairy production system. The SEPATOU simulation model makes it possible to describe the complex relationships and interactions between decision-making choices (e.g., turnout date, length of mixed feeding period, residual sward mass target), climatic factors and production performances such as the milk yield, and to support learning and elucidation of these interactions by trial and error. SEPATOU has been designed for use by grazing experts as a means of training extension agents (or dairy farmers) in the operational management of rotational grazing systems and to help them test and therefore discover innovative management strategies. By providing the opportunity to formulate alternative management behaviours and dairy farm configurations, SEPATOU allows virtual experimentation that can then serve as a tangible basis for discussion of issues and as a way of making the complexity of interactions between pasture, animal and management understandable. This capability makes it valuable for disseminating knowledge and improving management practices at the empirical level. SEPATOU does not aim to support on-farm decision-making for any particular farm but rather to provide a comprehensive view of the impact that management decisions might have on typical production systems considered over a given season and under different weather scenarios. No attempt has been made to closely match any existing system, which would require an extremely intensive modelling and data collection effort. Modelled production systems are artificial representative examples of real cases that are slightly simplified but realistic as regards management. SEPATOU has been validated empirically (Cros et al., 2003a) for this use by a panel of experts (farming system scientists and extension services).

In this paper, the management of only a part of the farm (a single enterprise or a combination of a few interdependent ones) has been considered. However, this excludes the problem of finding the most profitable mix of crops and livestock products to produce from the available resources at the farm scale. The problem of managing a whole farm is more complex for several reasons: it must be addressed with a time horizon of several years, it involves many situations of concurrence on the use of resources (machinery and labour) and it is much harder to build a comprehensive model supporting the study of biophysical, social, economical and managerial aspects. However, dealing successfully with the management of a combination of interdependent production system components gives encouraging insight into the general principles (Cros et al., 2003b) to be taken into account in order to tackle the whole farm management problem.

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