A conceptual model of grassland-based beef systems

Guillaume Martin, Roger Martin-Clouaire, Jean-Pierre Rellier, Michel M. Duru

A Conceptual Model of Grassland-Based Beef Systems

Guillaume Martin, INRA, UMR 1248 AGIR, F-31326 Castanet Tolosan, France

Roger Martin-Clouaire, INRA, UR 875 UBIA, F-31326 Castanet Tolosan, France

Jean-Pierre Rellier, INRA, UR 875 UBIA, F-31326 Castanet Tolosan, France

Michel Duru, INRA, UMR 1248 AGIR, F-31326 Castanet Tolosan, France

ABSTRACT

Fulfilling the production objectives of a grassland-based beef system requires a robust management strategy to secure the best practicable use of forage resources with regard to the cattle demand. To address the challenging issue of designing such strategies, this article describes the application of an ontology of agricultural production systems to the generic conceptual model SEDIVER, which supports the representation and dynamic farm-scale simulation of specific grassland-based beef systems. The most salient and novel aspects of SEDIVER concern the explicit modeling of (a) the diversity in plant, grassland, animal and farmland, and (b) management strategies that deal with the planning and coordination of activities whereby the farmer controls the biophysical processes. By using the SEDIVER conceptual framework, part of the subjective and context-specific knowledge used in farm management can be captured and, in this way, enable scientific investigation of management practices.

Keywords: *Conceptual Model, Diversity, Flexibility, Grassland, Livestock System, Management, Simulation*

INTRODUCTION

In temperate less-favored areas, beef farming involves the management of a wide range of semi-natural grasslands. Such systems are increasingly threatened by rising input/output price ratios and the growing uncertainty surrounding production due, for example, to year-year weather variability. These problems add to the known difficulties in managing grassland-based systems. In such systems, herbage production is very heterogeneous and variable in time and space (Parsons, 1988). This is partly because of the variation in vegetation types in relation to management intensity and environmental factors, mainly soil conditions and topography, and partly because of weather variability within and between years. The management challenge is thus to make efficient use of grassland production, and to secure the feeding of the herd in accordance with desired, attainable and currently usable herbage production. Of primary importance for farmers is the development of greater flexibility in farm management, enabling them to take advantage

DOI: 10.4018/jaeis.2011010102

of opportunities, reduce vulnerability to adverse events, or cope with their consequences, in order to preserve the sustainability of their production enterprise.

Farmers have long relied on their intuition and on lessons resulting from analyzing other farmers' experiences to make strategic decisions (Jiggins & Röling, 2000). Now, when management processes must change or be adapted, the ability to use experience and history to discern patterns is still helpful, but given the limitations of human intellect and the increase in the pace and scale of change and uncertainty, it can hardly be used to shape robust decisions that perform consistently across a range of possible situations (McCown, 2002). The traditional reductionism of agronomic analysis, which examines a production system by taking it apart and understanding its constituent elements, is also inappropriate (Antle et al., 2001). Indeed the parts interact in complex and non-linear ways in response, in particular, to the manager's actions that are inherently discrete. These interactions are highly significant in the overall functioning and performance of the system. They might give rise to phenomena such as a bottleneck on some resources. Understanding the mechanisms and consequences of these emergent phenomena is of key importance in devising a management strategy that complies with the farmer's objectives and constraints.

The idea that farming systems should take greater consideration of plant, grassland, animal, and farmland diversity, both biological and functional, is generally agreed (e.g. Altieri, 1999; Andrieu, Poix, Josien, & Duru, 2007; White, Barker, & Moore, 2004). Such an approach encourages more flexible and efficient use of natural resources including herbage production. For instance, it enables functional complementarities and synergisms to be promoted between grassland plots that are suitable for different and sometimes multiple uses that depend on context-specific grassland production, and the feeding requirements of different animal categories (e.g. cows vs. heifers) characterized by different and fluctuating animal intake rates (Duru & Hubert, 2003; White et al., 2004). In addition, all four types of diversity constitute a potential source of flexibility that can be used in management choices to cope with uncertainty about uncontrollable factors such as weather. For instance, on a farm scale, farmland and grassland diversity bring organizational flexibility into farm management, i.e. freedom in the implementation and modification of a management strategy, e.g. a switch in the type of grassland use on a field, depending on the actual conditions encountered. On a field scale, plant species diversity makes it possible to take advantage of timing flexibility in grassland management (Martin et al., 2009), i.e. the extent to which the use of a given grassland may be brought forward or deferred at various times of year. More generally, plant and/or animal diversity enhances operational flexibility, i.e. the farmer's ability to modify the target performance or the state of the plant and/or animal material.

The properties and behavior of agricultural production systems which exhibit such an organized complexity may be studied through modeling and computer simulation. Simulation does not replace intuition or lessons learned from other farmers' experiences but rather supplements it by revealing emergent behavior. Research has produced several simulation-oriented farm models for designing beef systems (e.g. Andrieu et al., 2007; Jouven & Baumont, 2008; Romera, Morris, Hodgson, Stirling, & Woodward, 2004). These models suffer from two main limitations. None of them integrates plant, grassland, animal and farmland diversity, and its consequences on the dynamic heterogeneity of biophysical processes into a single all-embracing model. None considers the flexible and dynamic exploitation of this diversity with sufficient emphasis on the planning and situated, i.e. situation-dependent, coordination over time and space of the farming activities. The contribution of the present work lies in a more detailed and explicit integration of these aspects into a new model. It raises an interdisciplinary challenge of knowledge integration (Bammer, 2005) which concerns among others agronomists, animal scientists, production management scientists and artificial intelligence modelers.

Consistent with this special issue on Intelligent Systems for Engineering Environmental Knowledge and EcoInformatics, this article addresses particularly complex and challenging ecological systems, i.e. agroecosystems in temperate European areas. It presents how an ontology general to the domain of agricultural production systems (Martin-Clouaire & Rellier, 2009) was employed to engineer knowledge particular to grassland-based beef systems. The resulting conceptual model supports the SEDIVER (Simulation-based Experimentation on livestock systems with plant, grassland, animal and farmland DIVERsity) simulation project that aims to design flexible grassland-based beef systems (including radically different ones) and management strategies capable of coping with a wide range of system states and conditions through increased consideration for plant, grassland, animal and farmland diversity. A conceptual model is a non-software description of a computer simulation model (Robinson, 2004). Conceptual modeling is about moving from the recognition of a problem situation, through model requirements to the determination of what is going to be modeled and how. This process makes explicit the link between science and design (Nassauer & Opdam, 2008) thereby constituting the common ground for the interdisciplinary approach. First, it involves identifying relevant concepts and scientific and expert knowledge and determining the appropriate level of detail of the model through the entities, behavior and interactions to be included in it. Then it requires finding areas of overlap to articulate this knowledge in a coherent systemic representation. Finally, it implies clarifying assumptions and simplifications that have to be formulated given the project rationale. In summary, it consists of making choices regarding complexity, uncertainty and imperfection (Bammer, 2005) of the model. The design of the conceptual model is very important because it affects all aspects of a simulation study, in particular the data requirements, the speed with which the model can be developed, the speed of experimentation and the confidence that can be placed in the model results. The approach to beef farming taken in this research is introduced. We then outline the conceptual model of the biophysical and the decision systems and discuss the key modeling choices. We also briefly present how to move from such a conceptual model to simulation-based experimentation.

BEEF FARMING AS THE EXPLICIT MANAGEMENT OF BIOPHYSICAL ENTITIES AND PROCESSES

A Systemic Dynamic Approach

This research relies heavily on a systemic dynamic view of beef farming. The production system is a structured organization to transform system resources, i.e. land, animals, equipment, labor and know-how, into animal products, i.e. meat and milk. It responds to internal purposeful drivers, mainly the farmer's interventions and external factors such as weather conditions. The production system is complex and can be broken down into interacting or interdependent subsystems made up of interacting or interdependent entities, in particular the fields, the forage stocks and the animals, which form a complex whole. Controlling these interactions by appropriate and timely interventions to achieve his goals despite environmental and biological variation is the main concern of the farmer. Production management is thus considered as a flexible dynamic process rather than solely a function. Indeed, in making decisions, the farmer is able to take a variety of directions which define different system configurations and dynamic resource allocation, given the potentialities and limitations of his farm.

As has long been done in industrial production management (Schneeweis, 1995), production process design involves planning, coordinating and controlling biophysical and decision-making processes at the production system, i.e. farm, level, whilst most existing investigation approaches tend to address one at the expense of the other. To be relevant to real world decision-making and day-to-day management, one must therefore capture and analyze both the sequence and timing of decisions and feasible actions, and their consequences on the state of the system's entities and their relationships. Emphasizing a farm level approach might reveal the flexibility available to a farmer faced with environmental and biological variation, and might even uncover emergent phenomena or system properties. This is especially needed, given that most experimental field research assumes idealized conditions. The data obtained are informative about the potential production of biological entities, e.g. grasslands, but are of limited practical interest due to the management importance of other factors such as, in particular, weather variability or resource restriction aspects.

The Biophysical System as a Set of Managed Entities and Interacting Processes

The biophysical system is composed of a well-structured and ever-changing set of interacting entities. The changes result from biophysical processes and actions taken by the farmer. On the production year scale, the achievement of production objectives calls for skillful management decisions about types of actions, their timing, frequency and extent as a means of influencing the biophysical processes and the interactions between them. As an example, herbage growth on a plot might be affected by the displacement of animals on this plot for grazing to an extent determined by the number of animals, their intake rate and the duration of their stay. For each type of entity, within- and between-entity biological or functional diversities can be distinguished. For instance, grassland diversity exists within a plot through a range of plant species, and between plots through different grassland communities. These within- and between-entity diversities lead to a dynamic heterogeneity of biophysical processes within a farm, in particular for herbage dynamics.

Semi-natural grasslands are complex agro-systems composed of a wide variety of plant species. Their composition depends mainly on management intensity, soil moisture, and nutrient availability (Grime, 1973; Lavorel & Garnier, 2002). Grassland plant species and consequently grasslands exhibit a variety of growth and senescence patterns (Duru et al., 2009), determined by local (i.e. plot-scale) weather conditions, mineral and water nutrition and timing, frequency and extent of herbage use. These patterns have strong practical consequences on the kinds of versatile and profitable herbage use achievable. The trade-off between growth and senescence, which depends on phenological stages and leaf life span (Duru et al., 2009), has major consequences on herbage digestibility (Duru, Cruz, & Theau, 2008) and the related nutritive value, i.e. fill value, intake rate, and energy content, all closely correlated with digestibility (INRA, 2007). In practice, grassland use by grazing or mowing can hardly be synchronized on all plots at a time to exploit the optimum trade-off, but there is a range around this optimum trade-off that does not result in great losses of one property at the expense of another (Ansquer, Duru, Theau, & Cruz, 2008). At the grassland plot scale, there is a time window for using herbage whose duration depends on herbage availability and nutritive value and herd feeding objectives. Inappropriate grazing such as late use can lead to immediate undesirable effects such as low herbage nutritive value, and indirect delayed effects on availability and nutritive value of herbage for subsequent growth cycles. Inappropriate grazing can even compromise the persistence of the grassland over the long term by affecting the dynamic equilibrium between plant species.

The herd is a set of animals characterized by a category (e.g. heifer or cow), a physiological status (e.g. gestating or non-gestating cows), a productive function (e.g. fattened heifers for slaughter or replacement heifers) possibly with a production target and a breed. Feeding requirements and intake and performance patterns vary according to such characteristics.

Intake and induced animal performance are regulated by the farmer's decisions and actions. For example he might occasionally opt to underfeed in a situation of acute shortage of feeding resources. The animal component of the production system can further be structured into herd batches that group together animals that are managed in the same way. The determination of the size and composition of the herd batches is a key management decision.

The spring herbage production peak constitutes about half of the yearly production. However, cattle feeding requirements do not follow this trend and display a more regular pattern over the year. Thus, despite the wide literature on the topic, we believe that in grassland-based beef systems, stocking rate is less of a key management issue than the planning and situated coordination over time and space of the encounters between cattle and standing or conserved (e.g. hay) herbage, and the associated distribution of grassland use for grazing or mowing consistent with production potentialities and the likely growth pattern of grasslands, the allocation of animals to appropriate fields according to their feeding requirements, and the frequency and intensity of defoliation likely to result in favorable conditions for the rest of the year. As a consequence, the dynamic heterogeneity of biophysical processes has strong practical implications in the planning and coordination of activities by the farmer. It generates constraints and opportunities for herbage use and animal feeding, which have strong consequences on system performance.

The Manager as an Explicit System that Produces Decisions and Implements Actions

The dynamic system view of the beef system includes the farm manager. Indeed, the farmer who controls the biophysical processes should not be considered as standing apart from the production system but rather as being a main subsystem. As a subsystem he produces decisions and interacts with the biophysical system through control and data collection interventions.

The manager has a management strategy that drives the in-situation management decisions that are both plan-based (anticipatory) and reactive. A strategy reflects the farmer's personal practices, which can be seen in his monitoring and observation behavior, in his understanding of the way the biophysical entities should be operated throughout the season, and in his appreciation of what events are important and how they should be reacted to. As farmers have accumulated experience and advice, they have learned to develop their own temporal organization of farming activities consistent with the overall objective and peculiarities of their production systems. In any particular production system the manager must repeatedly:

- Monitor the occurrence of new events and scrutinize salient aspects of the current state of the production system;
- Revise the management strategy in situations recognized beforehand to require such adaptations;
- Determine the sets of activities that are deemed relevant for execution according to the plan included in the strategy.

As a system, the manager has states and internal dynamics that respond to the passing of time and the influence from other parts of the production system as well as from exogenous factors. The decision-making behavior can be scrutinized, in particular with respect to its ability to cope with uncertainty. This concerns in particular the robustness of the strategy, defined as its capacity to satisfy the multidimensional objectives of the farmer across a range of external factors.

Analyzing the sequence of actions performed on the main biophysical entities e.g. grasslands, may reveal failure or potential improvement in the organization of the production activities over time and space. Such analyses constitute the basis of plan design which focuses on the interdependence between the production activities, whose coordination should achieve the desired outcome, and the feasibility periods and contextual conditions enabling their implementation. The timing of any management operation on biophysical entities, mainly grasslands and animals, depends on their current state. In practice, for any operation there is an ideal time window for its execution. As pointed out by Kemp and Michalk (2007) “farmers can manage more successfully over a range than continually chasing optimum or maximum values”. Thus, in contrast with most of the literature on the topic, we believe the vagueness of a plan is not a fault, but, on the contrary, provides the flexibility needed to cope with the huge number of actual circumstances unfolding during its situated enactment, especially in agriculture where uncontrollable factors play a key driving role. Despite its flexibility, a plan may encounter situations where the initial intention is beyond its bounds as particular events occur (e.g. drought); the production system may then require some adjustments affecting for instance the configuration of some herds or the feeding policy, or call for changes of part of the initial plan of activities (e.g. switching the use of a field from haymaking to grazing when there is a shortage of grazing). Such adaptation capabilities need to be incorporated in the strategy. The necessity to expand or modify the strategy in this respect can be revealed by evaluating the application of the strategy in individual scenarios.

Towards the Conceptual Model

The conceptual modeling effort aims at structuring and organizing the pieces of knowledge about the system under study in a coherent systemic representation enabling the issue at stake to be tackled. The key decision regards the granularity required in the model to ensure predictive efficiency rather than fundamental mechanistic certainty (Antle et al., 2001). We do not need to model everything, but to include in the model only those events, processes and processed entities essential to efficiently predict the behavior of the studied system at the time and spatial scales of analysis required by the problem. In this case, because our focus is on the role of temporal aspects and timeliness of the decisions, it consists of evaluating at the farm scale the behavior over years of a farming system configuration and the associated management strategy by simulating the operational level. Day-to-day management is the appropriate level to represent realistically a flexible activity plan faced with environmental variability and its consequences on biophysical processes and on the performance of the farm.

In the present project, the design of the conceptual model is greatly supported by the use of the modeling framework DIESE (DIscrete Event Simulation Environment) that itself relies on a generic conceptual model of agricultural production systems (Martin-Clouaire & Rellier, 2009). This modeling framework provides a specific set of constructs that help to represent and articulate the structural, behavioral and dynamic features of the target system. It involves regarding an agricultural production system as an entity situated in and influenced by what is called the external environment. It can be divided into three interactive subsystems: the manager (decision system), the operating system and the biophysical system (Figure 1). The operating system is simply the system that transforms the manager’s decisions into actions and executes them using the available resources. Three fundamental concepts are used for the modeling of this dynamic system: entity, process and event. These represent the structural, functional and dynamic aspects of a system respectively (Rellier, 2005). An entity describes a kind of material or abstract item in the area of interest. The state of a system at a given moment in time is the value of the slots of the entities it comprises. A process is a specification of the behavior of a system, i.e. of the entities composing it. A process causes a change in state when a particular event occurs. Thus, events determine the timing of process triggers.

A CONCEPTUAL MODEL OF THE BIOPHYSICAL SYSTEM

Overview

The model of the biophysical system (Figure 2) is composed of four main types of entity: farmland, herd, food storage units and stable. Stable is just considered a physical location which does not include any process. For reasons of clarity, it is not represented in Figure 2 nor mentioned later in the text. The farmland is a set of groups of grassland plots determined according to the proximity between plots. A plot is made up of two interacting components, soil and herbage, the latter being a set of herbage compartments representing groups of plants within the herbage. Food storage units are a set of food storage units in which food stocks coming from harvested herbage such as hay are stored. The herd is a set of animals structured into herd batches and animal groups. Herd batch is a functional managed entity that can contain different types of animals such as replacement heifers and cows constituting animal groups. The herd is fed based on herbage available on the plots or food stocks contained in food storage units. The state of the system entities and the running of the biophysical processes are modified by weather, e.g. temperature and rainfall, and the farmer through his actions. These processes, which determine soil and herbage state i.e. availability and nutritive value, animal feeding and animal state or performance, are modeled at the lowest entity levels, i.e. soil-, herbage- or animal-scale, with a daily time step (Figure 2). Such a level of granularity is required to account for within- and between-entity biological or functional diversity and its consequences on dynamic heterogeneity of biophysical processes such as the variation in time and space of standing herbage. These processes interact: For example, the updating of herbage state on a plot interacts with the animal feeding process particular to each type of animal composing the herd batch grazing on that plot.

Farmland

On the farmland, accounting for groups of grassland plots or land islets is necessary, given that the spatial structure of the farm greatly

Figure 1. Production system view in the SEDIVER model

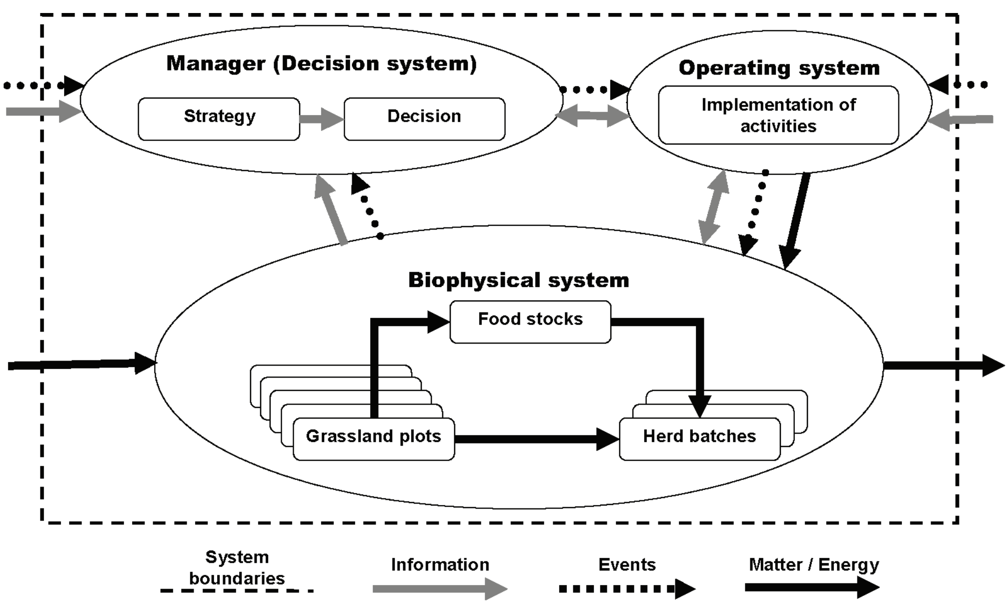
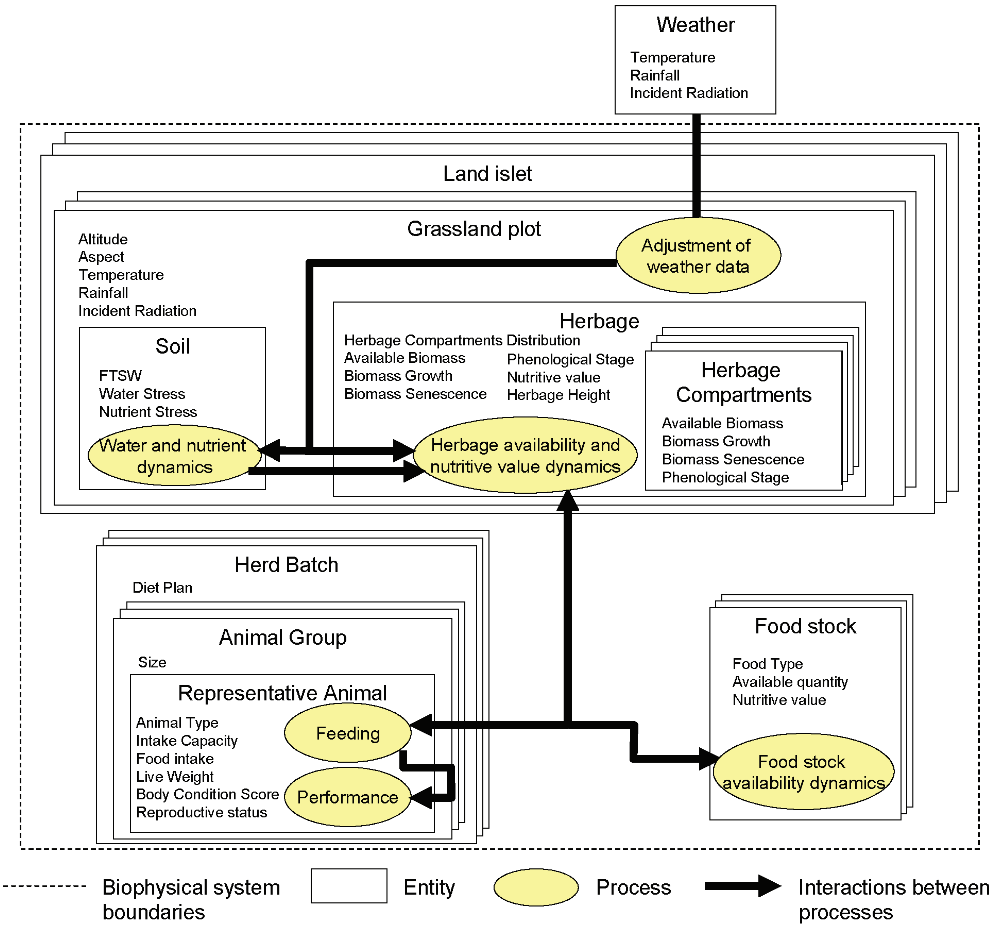


Figure 2. Main entities and processes in the biophysical system, and interactions between them



influences system organization, for example due to the ease of herd batch displacements. The key processes to be modeled on the plot for the purpose of the project are those underlying the dynamics of herbage availability and nutritive value (Figure 2). They depend on so-called defining factors, i.e. weather conditions and plant species characteristics that determine the potential herbage production and nutrient and water availability as limiting factors that determine attainable herbage production (van Ittersum & Rabbinge, 1997). These factors are described here for the case of semi-mountainous grassland-based beef systems such as in Martin et al. (2009).

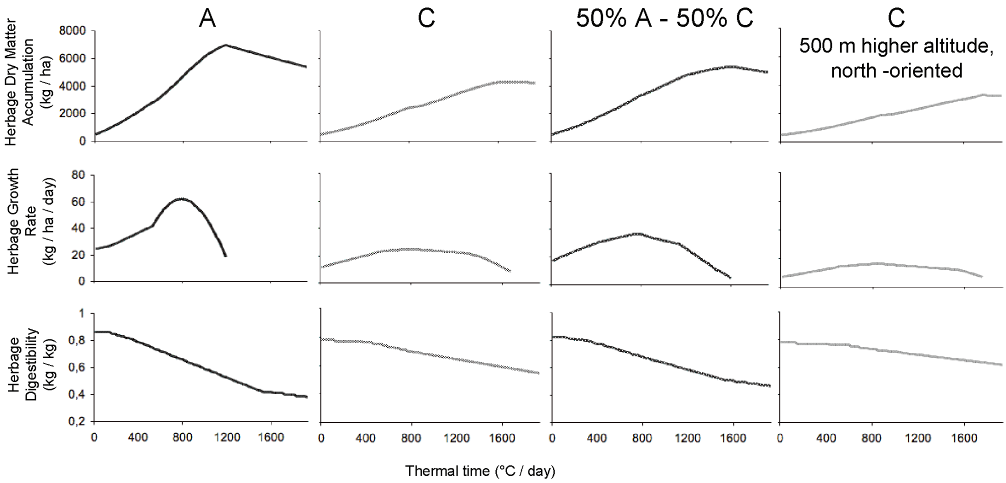
Plant species characteristics are defined as a model input including the range of plant species characteristics found in such grasslands. To account for this diversity, the concept of functional diversity defined in plant ecology is quite helpful. In this approach, species are classified into groups, here named herbage compartments, that relate directly to function (primary production) based on shared biological characteristics (plant traits) for plant morphology, physiology and phenology. Functional diversity is based on the identification and measuring of these plant traits in relation to environmental conditions and perturbations (Diaz & Cabido, 2001). A reason for emphasizing a functional ecology approach is that traits are universal whereas species and taxonomic groups are restricted in distribution. Plant traits such as the leaf dry matter content (LDMC) weighted at plant community level are well correlated with agronomic characteristics like herbage digestibility (Al Haj Khaled, Duru, Decruyenaere, Jouany, & Cruz, 2006) and plant phenology (Ansquer et al., 2009), characterized by the beginning of reproductive phase, flowering and leaf life span, all expressed in thermal time units. Plant phenology governs the dynamics of grass growth and nutritive value. LDMC provides a powerful generic (i.e. with a large validity domain) descriptor of a grassland community for characterizing the within- and between-effect of plant functional composition, or relative abundance of each herbage compartment, for the dynamics of biomass availability and nutritive value, the timing of grassland use on a phenological basis, and timing flexibility through time windows for suitable use (Ansquer et al., 2008). Previous studies such as that of Meot, Hubert, and Lasseur (2003) already identified field functions but missed such key vegetation characteristics to qualify what distinguishes fields for dynamically allocating grassland use.

Accessing grassland community characteristics through weighted mean plant traits provides the information to represent variability of herbage state and dynamics between plots (Figure 3), or to characterize the thermal time windows for grassland use. Between-field functional diversity spreads the peaks of herbage dry matter over time. Indeed, differences in phenological stages can reach 400 degree days between two vegetation types (Figure 3, 1st and 2nd columns) which can correspond at a given moment to differences of 50% in above-ground herbage mass (calculation based on Duru et al., 2009) and by 15% in digestibility (calculation based on Ansquer et al., 2008). Within-field functional diversity softens the changes in herbage growth and digestibility decrease rates (Figure 3, 1st and 3rd columns) (Ansquer et al., 2008). Herbage digestibility is needed to properly evaluate herbage nutritive value and animal intake as it determines the fill value of the forage and thus the forage quantity that the animal can eat. This information constitutes the basis for allocating grassland use over time and space.

Weather takes the form of incoming energy and material, i.e. rainfall, radiation and temperature. Given that each plot displays particular topographic peculiarities, upcoming weather data from the reference weather station have to be adjusted in an additional process (Figure 2) according to plot altitude and aspect. These factors can modify temperature by 0.6°C per 100 m of altitude and daily incident radiation by 1% per 100 m of altitude and by -17% when the plot is north-oriented, and by +18% when the plot is south-oriented (Andrieu et al., 2007). Ignoring these corrections to the reference weather data can lead to over- or underestimating daily herbage growth by 50% (Figure 3, 2nd and 4th column; calculation based on Duru et al., 2009). On the other hand we assume that for a given farm, daily rainfall can be regarded as uniform.

Plant water and nutrient stress are driven from the soil component. In the soil, water and nutrient dynamics are governed by inflow from fertilization, excreta or rainfall and outflow - mainly uptake by the plant and drainage. A water stress index (Merot, Bergez, Wallach, & Duru, 2008) and a plant nutrient index (Lemaire & Gastal, 1997) representing the extent of water and nutrient limitation experienced by the plant in achieving the potential growth permitted by local weather conditions can be calculated with simple characterization of soil properties such as the fraction of transpirable soil water (FTSW). Based on such indices, 0.2 water and nutrient stresses (both on a scale from 0 to 1) induce 25% and 27% shortfalls in the potential growth (calculations based on Duru et al., 2009) and 5% to the potential digestibility (calculation based on Duru et al., 2008). Available mechanistic models for nutrient dynamics in grasslands have been calibrated for particular areas (e.g. Scholefield, Lockyer, Whitehead, & Tyson, 1991) and would require considerable effort for a recalibration.

Figure 3. Examples of processes occurring at spring (thermal time starts on the 1st of February as recommended by Ansquer et al., 2009) on four grassland communities with different vegetation types (A vs. C vs. A and C mixed; see Ansquer et al., 2008 for further details) or topographic conditions (last column with vegetation type C growing in a north-oriented plot of higher altitude). From the top to the bottom are the dynamics of herbage dry matter accumulation, daily growth rate (calculations based on Duru et al., 2009) and digestibility (calculations based on Duru et al., 2008).



The models of Duru et al. (2008, 2009) include all the above-mentioned factors and have been slightly modified, in particular to account for within-plot diversity of plant functional types, or relative abundance of each herbage compartment, and for the modeling of the biomass in the ungrazable strata, e.g. below 5-6 cm for cows. Indeed, indicators used in day-to-day management such as herbage height have to be modeled accurately. Residual centimeters after grazing should not be neglected given the remaining grazing days they could provide (between 100 and 500 kg of dry matter per cm and per hectare according to the type of grassland community) and given that they are essential to ensure the quality of later herbage regrowth (Parsons, 1988). When residual height after grazing is too low, growth is reduced due to a leaf area index that is too low for capturing most of the incident radiation, but beyond this threshold, reducing the intensity of use, either by lengthening the interval between defoliation or grazing, or by increasing the residual height after grazing, results in greater losses from senescence and hence reduced stocking density (Duru & Hubert, 2003).

Interactions between the dynamics of herbage availability and its use take into account day-to-day interactions between processes. Dynamics of herbage availability are modeled on a daily time step as available herbage growth models are not accurate enough to consider shorter time scales. The effects of grazing animals on standing herbage are also modeled on a daily time step. We assume that vegetation characteristics of herbage are uniform on the plot scale.

Food Storage Units

Food storage units contain food stocks, i.e. hay, bale-silage, silage and sometimes concentrates. In grassland-based beef systems, food stocks play a key role in the feeding of the herd. According to the area (e.g. semi-mountainous vs. temperate) they fulfill different functions such as winter feeding for several months or a buffer to compensate for feed shortages at grazing due, for instance, to drought. The importance of food stocks is also related to the farmer's desire for forage self-sufficiency. As a consequence, choices related to food stock management greatly influence the organizational and day-to-day management of grazing, given that the timing, frequency and intensity of grazing depend on the concomitant hay and/or silage-making and distribution. To tackle this issue it is necessary to model food stock dynamics (Figure 2) taking into account the storage capacity of the food storage equipments, which can be a limiting factor. Nutritive value of the food stocks also has to be considered (Jouven & Baumont, 2008) given that different types of food stocks are suited to different animal categories. As with grazing, it is possible to match the availability and quality of the food stocks distributed to the feeding requirements of animal categories.

Herd

Accurately evaluating animal intake and performance, i.e. growth, weight variation, milk production, etc. requires accessing the diversity of animal types encountered on the farm, since different animal categories have different intake rates (INRA, 2007). Animal groups composing herd batches bring together animals of similar category, physiological status, productive function or production level target and breed. Intake can be modified by up to 400% between young grazing calves and cows, up to 30% between lactating and non-lactating cows, 9% per point of body condition score, about 30% between replacement heifers and heifers for slaughter and 8-10% between breeds (calculations based on INRA, 2007). Two processes, animal feeding and performance, are then modeled for a representative animal of each group (Figure 2).

A diet plan is assigned to each herd batch, defining the content of the diet over the seasons. At the animal scale, we do not mechanistically model the act of prehension (grazing), bolus mastication during rumination or the rumen motility cycle. We only model the daily intake process. Indeed, since we consider a representative animal for a group, we cannot simulate individuals' feed preferences through animal behavior at grazing and the related spatial variation consisting of patches of ungrazed vegetation and nutrient excretion. The corresponding quantities of material are then deducted from food stocks or standing herbage mass of grassland plots assuming cattle is not selective at grazing. Given the size of the animal group, animal intake at animal group level is evaluated and finally aggregated at herd batch level. In previous models (Andrieu et al., 2007; Jouven & Baumont, 2008), animal group and herd batch were not distinguished, making it impossible to model different animal categories mixed within a single herd batch. It is especially useful to the issue tackled, given that herd batch re-composition can be used as a regulatory process to adjust stocking rate for coping with variability in herbage availability. As varying herd size is another way of adjusting herd intake rate, accounting for population dynamics over years is essential to take into account the flexibility it constitutes, as regulated by reproductive events such as mating and calving date, and marketing aspects such as target state at sale.

Intake rate is dependent on the animal side on the energy invested in milk production, on live weight and body condition score, and on the fill value of the diet which is related to food digestibility (INRA, 2007). The partitioning of energy intake between displacement, maintenance, pregnancy and lactation and its consequences on live weight and body condition score is modeled as in Jouven and Baumont (2008) and Romera et al. (2004). As a consequence, the reproductive status of the animals and its impact on animal physiology are also modeled.

A CONCEPTUAL MODEL OF THE MANAGEMENT SYSTEM

Rationale

The need for process flexibility in the workflow and process technology communities as a critical quality of effective business processes to adapt to changing market demands and other business circumstances has long been recognized (Reijers, 2006). Several authors (e.g. Sawhney, 2006) suggested that manufacturing flexibility should be included as a key dimension of a firm's manufacturing strategy; researchers have posited that firms increase their manufacturing flexibility to allow them to respond to uncertainty in the environment, and that an appropriate match between business strategy and flexibility improves performance. Agricultural production systems are similarly concerned, although uncertainty does not affect production in manufacturing as much as in agriculture, where some key production drivers such as the weather are out of control.

There is an urgent need for more effective whole-farm analyses to address issues of productivity, profitability and sustainability, and the role played by flexibility. A key requirement for such an analytical framework is the capacity to accommodate weather variability and various kinds of uncertainty. Mathematical models of farm management based on static equilibrium conditions fail on several criteria. Dillon (1979) reflected on the scientific discipline of Farm Management research in Australia and concluded that it had lost touch with practical farming because of "logically attractive but largely inapplicable theory". He emphasized the management challenges created by uncertainty and dynamics, and the failure of existing mathematical models of farm management to capture these features adequately. McCown, Brennan, & Parton (2006) attempted to attract wider recognition of Dillon's criticisms of the mathematical model approach embodied in farm management. Following Dillon, they listed a number of reasons why static equilibrium models cannot be applied to the practice of farm management:

- Farm systems are complex and dynamic;
- Farming is conducted under conditions of uncertainty and performance depends very much on how uncertainty is dealt with;
- Individual farms are unique and farmers have different practices and preferences. A wide variety of so-called farming styles (van der Ploeg, 1994) exist.

Simulation-based approaches that explicitly incorporate production management processes seem to provide a more promising framework to take into account these aspects or highlight the issues they raise. The management system model should explicitly represent the decision-making process and the implementation of the technical actions resulting from this process.

As for the biophysical system, the conceptual model of the management system relies on the DIESE framework that includes specific constructs to represent various aspects relevant to the management functions (Martin-Clouaire & Rellier, 2009). Fundamental to our conceptual model is the commitment to understand things from a farmer's point of view. To be effective, management behavior must be specified by using constructs and language that are intelligible and conceptually close to those actually used in an agricultural setting. The typical approach to representing decision-making in simulation models is to express decision behavior through a set of decision rules. This approach is ontologically limited and becomes cumbersome as the number of rules grows beyond a certain limit; the meta-knowledge about the proper use of the rules, for example which should be applied first when several are applicable, is hard to represent and makes the rule-based approach hard to maintain and reuse.

Hence the basic unit of analysis in our approach is work activity, which is a common high level concept in production management.

An activity is a purposeful engagement driven by certain needs to achieve a certain purpose. Activities are contextual in the sense that actual circumstance condition their relevance and greatly affect the way the intended objective is achieved. Activities usually involve the use of resources (equipment, labor). Whenever a combination of activities must be undertaken with a view to achieving a pre-conceived result, a plan is needed to express how those composite activities should be coordinated. A work plan is the result of reflection on prior experiences and in anticipation of particular goals and likely occurrences of important events. Because of this, plans are not rigid in the sense of a definite and precise specification of the execution steps. Plans are flexible and adaptable to circumstances. A slightly more formal and encompassing conceptual description is given in the next subsection.

A Conceptualization of Production Management

In its simplest form, an activity, which we will call a primitive activity, denotes something to be done to a particular biophysical object or location, e.g. a herd batch, building, by an executor, e.g. a worker, a robot or a set of these. Besides these three components, a primitive activity is characterized by local opening and closing conditions, defined by time windows and/or predicates (Boolean functions) referring to the biophysical states or indicators. An indicator is a contextual piece of knowledge or information invoked, assembled, or structured to substantiate a decision-making step, e.g. appraisal of remaining forage amount on a field to decide withdrawal of the herd from it. The opening and closing conditions are used to determine at any time which activities are agronomically eligible for execution; they play a key role in defining the timing flexibility.

The "something-to-be-done" component of a primitive activity is an intentional transformation called an operation, e.g. the harvest operation. The step-by-step changes to the biophysical system as the operation is carried out constitute a functional attribute of the operation. These changes take place over a period of time by means of a process that increases the degree of achievement at each step of the operation until it is completed. An operation is said to be instantaneous if its degree of achievement goes from 0 to 1 in a single step, otherwise the operation is durative which implies that its execution might be interrupted. An operation may require resources such as a mower in case of cutting. In addition, the execution of an operation is constrained by feasibility conditions that relate to the biophysical state. Objects on which an operation is carried out can be individual objects, e.g. a field or a set of fields, or objects having numerical descriptors, e.g. an area. Speed is defined as a quantity e.g. number of items or area, which can be processed in a unit of time. The duration of the operation is the ratio of the total quantity to the speed. In order to have the effect realized the operation must satisfy certain enabling conditions that refer to the current state of the biophysical system, e.g. the field to be processed should not be too muddy, muddy being an indicator. The ability to reap the benefits of organizational and timing flexibility depends on execution competence determined by the involved resources (both operation resources and the executor). Careful representation of the resources and their availability might therefore be essential to get a proper understanding of the situation under study.

Activities can be further constrained by using programming constructs enabling specification of temporal ordering, iteration, aggregation and optional execution. To this end, we use a set of non-primitive or aggregated activities having evocative names such as *before*, *iterate*, and *optional*. Others are used to specify choice of one activity among several (*or*), grouping of activities in an unordered collection (*and*) and concurrence of some of them (e.g. *co-start*, *equal*, *include*, *overlap*). Formally a non-primitive activity is a particularized activity. As such it might also be given opening and closing conditions as well as other properties such as a delay between two activities involved in a *before* aggregated activity. In particular, it has a relational property that points to the set of the other activities directly involved in it (or constrained by it). In addition, it is equipped with a set of procedural attributes that convey the semantics of the change in status specific to each non-primitive activity. The opening and closing of a non-primitive activity depend on their own local opening and closing conditions (if any) and on those of the underlying activities. All the activities are connected; the only one that does not have a higher level activity is the plan. In addition to the timing flexibility attached to the opening and closing conditions of its activities a plan is made flexible by the use of composed activities that enable optional execution or choice between candidate activities. Whether an optional activity is executed and which alternative activity is chosen are context-dependent decisions relying on indicators or priorities between activities.

Besides the flexibility of the timing of the execution of activities it may be necessary to adapt the plan when particular circumstances occur. Indeed a nominal plan conveys the rough course of intended steps to go through under normal circumstances. The specification of when and what changes should be made to a nominal plan is called a conditional adjustment. The trigger for a conditional adjustment is either a calendar condition that becomes true when a specific date is reached, or a state-related condition that becomes true when the current circumstances match this condition. The adjustment can be any change to the nominal plan such as the deletion or insertion of activities. It can also affect the resources used in some activities. Actually a conditional adjustment can also specify a change to be made to conditional adjustments themselves. By this means, the management can be reactive, e.g. by modifying the management objective, and thus cope with unexpected (though still feasible) fluctuations of the external environment and various contingencies. For instance, a target beef production level might be reviewed in case of drought, and materialized by voluntary underfeeding of cattle.

Examples of Operations, Primitive and Composite Activities and Conditional Adjustments

The model includes a wide range of activities corresponding either to daily routine work e.g. distributing stored food, moving a grazing herd batch, etc. or to seasonal work, e.g. mating, weaning calves, selling animals, etc. Let us take the example of hay-making on a farm. This is composed of two steps, i.e. two primitive activities, first cutting the herbage of a grassland plot and, once it is dry enough, storing this new-mown hay. For the cutting activity, the object operated by the cut (the something-to-be-done component) is a plot, in particular the component herbage, and the executor is the farmer equipped with his tractor and mower. The speed of the something-to-be-done component is a harvestable area per unit time. Its effect is the creation of a harvested herbage, the initialization of a drying process on this harvested herbage, and the re-initialization of the herbage component of the plot with its descriptors updated (leaf area index, dry matter, growth cycle age, digestibility, etc.). For the storing activity, the object operated by the storage (the something-to-be-done component) is the harvested herbage, and the executor is the farmer equipped with his tractor, round-baler and trailer. The speed of the storage is a storable quantity of hay per unit time. Its effect is the crediting of the amount of hay stored in the barn by the harvested quantity minus some losses to the yield associated with the whole hay-making process. Storing of harvested herbage can occur only once cutting is complete. Thus hay-making is a sequence of two primitive activities which can be written:

hay-making = *before* (cutting:
operation: cut with mover
operated object: plot
performer: farmer
storing:
    operation: store with tractor, round-baler and trailer

operated object: harvested herbage created in cut
performer: farmer)

The opening of any hay-making activity, and consequently of the cutting activity, has to occur within a particular time range delimited by an earliest and a latest beginning date. In addition, the opening predicate refers to a minimum harvestable yield and a given phenological stage for the corresponding herbage, i.e. between stem elongation and flowering, to ensure a compromise between harvested quantity and quality. Once the opening predicate of the hay-making activity has been verified the feasibility conditions attached to the cut operation are examined. These feasibility conditions concern the bearing capacity of the grassland plot, sufficient free space in the barn to store additional hay, and a satisfactory expected air saturation deficit and rainfall in the coming days to ensure proper drying conditions in the field. No closing conditions are specified in this case to ensure completion of the hay-making activity. To summarize the hay-making aggregated activity is represented as follows:

hay-making = *before* (cutting, storing)
earliest beginning date = a date
latest beginning date = a date
opening predicates concerning:

- minimum yield to harvest = an amount expressed in kg / ha
- earliest phenological stage = stem elongation expressed in degree days
- latest phenological stage = flowering expressed in degree days

Farmers seldom make hay on a single field at a time. Typically, they do it on a set of fields that are close together, i.e. that belong to the same islet. This practice may be risky if too many fields are cut and long period of rainy weather occurs. A typical risk-limiting attitude is to make small groups of plots and harvest these groups in sequence. Bad weather during drying then harms only the plots in the last group treated. In the example of practice considered in this paper, hay-making on the plots of a group can only start if the last hay-making activity executed in the previous group is complete. Sometimes farmers may defer groups of activities for several days to make time for daily routine work not done on the busy days of hay-making. The grouping of activities enables management constraints to be attached to this set, such as the delay between the processing of the groups {Field1, Field2, Field3} and {Field4, Field5}. Using an *and* to make the grouping gives flexibility in the order of execution of the concerned activities, using for instance yield-based preferences. The sequence of hay-making on the two groups of fields can then be written:

before (*and* (hay-making Field 1, hay-making Field 2, hay-making Field 3),

and (hay-making Field 4, hay-making Field 5)
in-between delay = a number of days)

Due, for example, to particular weather conditions in a given year, such a plan might be unachievable. Conditional adjustments of the plan are then necessary to recover a consistent management situation. For instance, in a showery weather period, the farmer might decide to reverse the order of the groups of hay-making activities in the sequence (*before*) to take advantage of the lower drying requirements of herbage on fields 4 and 5. Another adjustment could be the changing of the delay between the processing of the two groups. This conditional adjustment would then change the above activity into:

before (*and* (hay-making Field 4, hay-making Field 5),

and (hay-making Field 1, hay-making Field 2, hay-making Field 3)

in-between delay = a number of days)

FROM THE CONCEPTUAL MODEL TO A SPECIFIC FARM MODEL AND ITS USE IN SIMULATION-BASED DESIGN

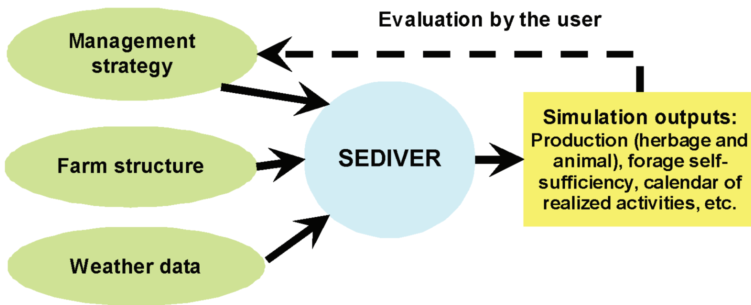
The implementation of the conceptual model in the DIESE modeling framework (Martin-Clouaire & Rellier, 2009) amounts to developing particularizations of some classes. For example, from the Entity class, particular cases such as "Plot" or "Herd" were created. From the Activity class, e.g. "Distributing stored food" and "Hay-making" were created. This work led to an implemented simulation model general to the domain of grassland-based beef systems. Going from this general model to a model of a particular beef system was achieved by instantiating the particularized classes, e.g. from the "Plot" class, creating "plot 1", and "plot 2"; or from the "Moving Herd Batch" class, creating "moving Herd Batch A to plot 1". Articulation of the instantiated primitive activities using non-primitive ones then led to "manually" constructed executable plans. The implementation of the conceptual model has been reported in related papers (Martin, Martin-Clouaire, Rellier, & Duru, 2011; Martin et al., 2010) with two simulation-based investigations of the merits and limitations of different management strategies applied to three grassland-based beef systems.

The openness and flexibility of the formal language used to represent the management strategies are suited to support a trial and error learning process (Figure 4) by rapidly exploring alternative configuration of the production system and management strategies, their performances and trade-offs between performance criteria at almost no cost. Assume a configuration of the system, both hard (physical layout, dimensioning) and soft (organizational infrastructure, decision logic). Flexibility and adaptability are inherent and built in beforehand in the considered management strategy. In beef systems, "manual" reconfiguration might concern the composition and dimensioning of land and animal resources. Other reconfigurable hard components include technology (e.g. hay drying) and resources (labor). The soft components modifiable in a "manual" reconfiguration are mainly the production plans in which activities can be added or removed, the timing flexibility attributes, the event-based adjustments, as well as the indicators used for decision making. The ability to switch appropriately between options is often more important than offering a large number of options, and sheds light on the key role of temporal aspects and timeliness of the decisions.

CONCLUSION

Keating and McCown (2001) suggested that challenges for farming system modelers are "not to build more accurate or more comprehensive models, but to discover new ways of achieving relevance to real world decision making and management practice." This applies in a wider sense to managed ecosystems. The ontology (Martin-Clouaire & Rellier, 2009) and the conceptual framework underlying SEDIVER are the result of consistent efforts to improve the representation of management strategies and get closer to the questions raised in practice. Using the integrative conceptual framework that we have described one can develop elaborate simulation models of managed ecosystems. It provides a common structure to help organize and frame monitoring and management activities that can be applied effectively and consistently across any such a system. Running a simulation model under various scenarios of external conditions helps to give a realistic view of the system's behavior and performance, its sensitivity to external factors and the quality of the tested management strategy as regards robustness and flexibility. We can use this approach to give a clearer meaning to the selection and prioritization of management activities by placing the management process in context. The present work and the related applications (Martin et al., 2011, 2010) are examples of the merits of ontology-based modeling to engineer knowledge about ecosystems and in fine to address complex management problems.

Figure 4. The iterative loop based on simulation, evaluation and re-configuration



Alternative modeling approaches such as linear programming models generally assume static equilibrium conditions or rely on farm- or ecosystem-averaged indicators. Thus they ignore the diversity within the system and its consequences on the variability of ecosystem processes in time and space. These approaches can hardly address challenges created by uncertainty and dynamics whereas it is essential that the model be able to reveal how fluctuations might be amplified and how the system may become unstable to large perturbations. Indeed, the complexity of the farmer's management task is not due to the number of components or possible states of the system but rather to the dynamic behavior of the different components which arise from their interactions over time and their dependence on uncontrollable driving factors. The dynamic complexity relates to human difficulty in dealing consistently with feedback effects, and multiple and delayed consequences of interventions. Much of the information about biophysical system functioning and the cognitive process involved in production management resides in the mental models of managers where it remains tacit. By using the conceptual framework set up in the present work, one can expect to capture part of this subjective and context-specific knowledge and, in this way, make it an object of scientific investigation. Improving our ability to make this knowledge explicit and usable for formal modeling and learning can have important effects on both research and practice. Researchers are in a better position to build more complete, accurate and insightful models and practitioners can increase their awareness and mastery of organizational and management issues.

ACKNOWLEDGMENTS

This study was partly funded by the French ANR ADD program in the framework of the project TRANS (TRANSformations de l'élevage et dynamiques des espaces, ANR-05-PADD-003) and by the French ANR VMC program in the framework of the project VALIDATE (Vulnerability Assessment of LIvestock and grasslanDs to climAte change and exTreme Events, ANR-07-VULN-011). The authors would like to thank J.P. Theau and O. Therond who, as specialists of beef farming systems, contributed to this research, and the three anonymous reviewers for their relevant comments.

REFERENCES

Al Haj Khaled, R., Duru, M., Decruyenaere, V., Jouany, C., & Cruz, P. (2006). Using leaf traits to rank native grasses according to their nutritive value. *Rangeland Ecology and Management*, *59*, 648–654. doi:10.2111/05-031R2.1

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture Ecosystems & Environment*, *74*, 19–31. doi:10.1016/S0167-8809(99)00028-6

Andrieu, N., Poix, C., Josien, E., & Duru, M. (2007). Simulation of forage management strategies considering farm-level land diversity: Example of dairy farms in the Auvergne. *Computers and Electronics in Agriculture*, *55*, 36–48. doi:10.1016/j.compag.2006.11.004

Ansquer, P., Al Haj Khaled, R., Cruz, P., Theau, J. P., Therond, O., & Duru, M. (2009). Characterizing and predicting plant phenology in species-rich grasslands. *Grass and Forage Science*, *64*, 57–70. doi:10.1111/j.1365-2494.2008.00670.x

Ansquer, P., Duru, M., Theau, J. P., & Cruz, P. (2008). Functional traits as indicators of fodder provision over a short time scale in species-rich grasslands. *Annals of Botany*, *103*, 117–126. doi:10.1093/aob/mcn215

Antle, J. M., Capalbo, S. M., Elliott, E. T., Hunt, H. W., Mooney, S., & Paustian, K. H. (2001). Research needs for understanding and predicting the behavior of managed ecosystems: Lessons from the study of agroecosystems. *Ecosystems (New York, N.Y.)*, *4*, 723–735. doi:10.1007/s10021-001-0041-0

Bammer, G. (2005). Integration and Implementation Sciences: Building a New Specialization. *Ecology and Society*, *10*(2), 6.

Diaz, S., & Cabido, M. (2001). Vive la difference: Plant functional diversity matters to ecosystem processes. *Trends in Ecology & Evolution*, *16*, 646–655. doi:10.1016/S0169-5347(01)02283-2

Dillon, J. L. (1979). An evaluation of the state of affairs in Farm Management. *South African Journal of Agricultural Economics*, *1*, 7–13.

Duru, M., Adam, M., Cruz, P., Martin, G., Ansquer, P., & Ducourtieux, C. (2009). Modelling above-ground herbage mass for a wide range of grassland community types. *Ecological Modelling*, *220*, 209–225. doi:10.1016/j.ecolmodel.2008.09.015

Duru, M., Cruz, P., & Theau, J. P. (2008). Un modèle générique de digestibilité des graminées des prairies semées et permanentes pour raisonner les pratiques agricoles. *Fourrages*, *193*, 79–102.

Duru, M., & Hubert, B. (2003). Management of grazing systems: from decision and biophysical models to principles for action. *Agronomie*, *23*, 689–703. doi:10.1051/agro:2003051

Grime, J. P. (1973). Competition and Diversity in Herbaceous Vegetation. *Nature*, *244*, 310–311. doi:10.1038/244311a0

INRA. (2007). *Alimentation des bovins, ovins et caprins. Besoins des animaux – Valeur des aliments*. Paris: Quae Editions.

Jiggins, J., & Roling, N. (2000). Adaptive management: potential and limitations for ecological governance. *International Journal of Agricultural Resources . Governance and Ecology*, *1*, 28–42.

Jouven, M., & Baumont, R. (2008). Simulating grassland utilization in beef suckler systems to investigate the trade-offs between production and floristic diversity. *Agricultural Systems*, *96*, 260–272. doi:10.1016/j.agsy.2007.10.001

Keating, B. A., & McCown, R. L. (2001). Advances in farming systems analysis and intervention. *Agricultural Systems*, *70*, 555–579. doi:10.1016/S0308-521X(01)00059-2

Kemp, D. R., & Michalk, D. L. (2007). Towards sustainable grassland and livestock management. *The Journal of Agricultural Science*, *145*, 543–564. doi:10.1017/S0021859607007253

Lavorel, S., & Garnier, E. (2002). Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. *Functional Ecology*, *16*, 545–556. doi:10.1046/j.1365-2435.2002.00664.x

Lemaire, G., & Gastal, F. (1997). N uptake and distribution in plant canopies. In Lemaire, G. (Ed.), *Diagnosis of the Nitrogen Status in Crops* (pp. 3–44). Berlin: Springer Verlag.

Martin, G., Hossard, L., Theau, J. P., Therond, O., Josien, E., & Cruz, P. (2009a). Characterizing potential flexibility in grassland use - An application to the French Aubrac region. *Agronomy for Sustainable Development*, *29*, 381–389. doi:10.1051/agro:2008063

Martin, G., Martin-Clouaire, R., Rellier, J.P., Duru, M. (2011). A simulation framework for the design of grassland-based beef-cattle farms. *Environmental Modelling & Software 26*, 371-385.

Martin, G., Theau, J.P., Therond, O., Carre, J., Cruz, P., Jouany, C., Magne, M.A., Duru, M. (2010). Bases et premier exemple d'application d'une démarche articulant diagnostic et simulation de systèmes fourragers pour évaluer et améliorer l'efficience d'utilisation de l'herbe. *Fourrages 201*, 47-56.

Martin-Clouaire, R., & Rellier, J. P. (2009). Modelling and simulating work practices in agriculture. *International Journal of Metadata. Semantics and Ontologies*, *4*(1-2), 42–53. doi:10.1504/IJMSO.2009.026253

McCown, R. L. (2002). Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agricultural Systems*, *74*, 179–220. doi:10.1016/S0308-521X(02)00026-4

McCown, R. L., Brennan, L. E., & Parton, K. A. (2006). Learning from the historical failure of farm management models to aid management practice. Part 1. The rise and demise of theoretical models of farm economics. *Australian Journal of Agricultural Research*, *57*, 143–156. doi:10.1071/AR05051

Meot, A., Hubert, B., & Lasseur, J. (2003). Organisation of the pastoral territory and grazing management: joint modelling of grazing management practices and plant cover dynamics. *Agricultural Systems*, *76*, 115–139. doi:10.1016/S0308-521X(02)00105-1

Merot, A., Bergez, J. E., Wallach, D., & Duru, M. (2008). Adaptation of a functional model of grassland to simulate the behaviour of irrigated grasslands under a Mediterranean climate: The Crau case. *European Journal of Agronomy*, *29*, 163–174. doi:10.1016/j.eja.2008.05.006

Nassauer, J. I., & Opdam, P. (2008). Design in science: extending the landscape ecology paradigm. *Landscape Ecology*, *23*, 633–644. doi:10.1007/s10980-008-9226-7

Parsons, A. J. (1988). The effect of season and management on the grass growth of grass sward . In Jones, M. B., & Lazenby, A. (Eds.), *The grass crop* (pp. 129–178). London: Chapmann and Hall.

Reijers, H. A. (2006, June 26-28). Workflow flexibility: The forlorn promise. In *Proceedings of the 15th IEEE International Workshops on Enabling Technologies: Infrastructures for Collaborative Enterprises,* Manchester, UK (pp. 271-272).

Rellier, J. P. (2005). *DIESE: un outil de modélisation et de simulation de systèmes d'intérêt agronomique. Internal report UBIA-INRA, Toulouse-Auzeville.* Retrieved from http://carlit.toulouse.inra.fr/diese/docs/ri_diese.pdf

Robinson, S. (2004). *Simulation: The Practice of Model Development and Use*. Chichester, UK: Wiley.

Romera, A. J., Morris, S. T., Hodgson, J., Stirling, W. D., & Woodward, S. J. R. (2004). A model for simulating rule-based management of cow-calf systems. *Computers and Electronics in Agriculture*, *42*, 67–86. doi:10.1016/S0168-1699(03)00118-2

Sawhney, R. (2006). Interplay between uncertainty and flexibility across the value-chain: towards a transformation model of manufacturing flexibility. *Journal of Operations Management*, *42*, 476–493. doi:10.1016/j.jom.2005.11.008

Schneeweis, C. (1995). Hierarchical structure in organisation: a conceptual framework. *European Journal of Operational Research*, *81*, 4–31. doi:10.1016/0377-2217(95)00058-X

Scholefield, D., Lockyer, D. R., Whitehead, D. C., & Tyson, K. C. (1991). A model to predict transformations and losses of nitrogen in UK pastures grazed by beef cattle. *Plant and Soil*, *132*, 165–177.

van der Ploeg, J. D. (1994). Styles of Farming: an Introductory Note on Concepts and Methodology. In van der Ploeg, J. D., & Long, A. (Eds.), *Born from within. Practice and perspectives of endogenous rural development* (pp. 7–30). Assen, The Netherlands: Van Gorcum.

van Ittersum, M. K., & Rabbinge, R. (1997). Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research*, *52*, 197–208. doi:10.1016/S0378-4290(97)00037-3

White, T. A., Barker, D. J., & Moore, K. J. (2004). Vegetation diversity, growth, quality and decomposition in managed grasslands. *Agriculture Ecosystems & Environment*, *101*, 73–84. doi:10.1016/S0167-8809(03)00169-5

Guillaume Martin holds a Master degree in Plant Science (2006) from Wageningen University (Netherlands) and a Ph. D. in Agronomy (2009) from Toulouse University (France). He is currently working as a research associate at INRA Toulouse. His research interests concern grassland ecology and grassland management as well as the development of methods (mainly model-based) for design and analysis of integrated farming systems.

Roger Martin-Clouaire holds a Masters degree in Biomedical Engineering (1982) from Saskatchewan Univ. (Canada) and a Ph. D. (1986) in Artificial Intelligence from Toulouse University (France). He joined INRA (Institut National de la Recherche Agronomique) in 1987 as a research scientist. His main research area concerns the modelling and simulation of agricultural production systems and, in particular, decision-making processes involved in production management. He is currently director of the laboratory "Unité de Biométrie et Intelligence Artificielle".

Jean-Pierre Rellier joined INRA in 1976. In his early career, he worked as a statistical analyst in the area of cropping systems. In the mid-eighties, he became a member of the national group on agricultural expert system development. Since 1988, he has been a software engineer in the "Unité de Biométrie et Intelligence Artificielle" where his main areas of interest concern the methodological aspects of complex system modelling and simulation.

Michel Duru is senior researcher at INRA Toulouse and head of the laboratory AGIR (Agrosystems and territorial development). His main research area concerns grassland management at field and farm levels through building sward indicators and decision support systems based on biophysical and decisional models.