Combining plot-scale indicators and farm-scale simulation to support the design of novel grassland-based beef systems

Guillaume Martin, Jean Pierre J. P. Theau, Olivier Therond, Marie-Angélina Magne, Roger Martin-Clouaire, Michel M. Duru

▶ To cite this version:

Guillaume Martin, Jean Pierre J. P. Theau, Olivier Therond, Marie-Angélina Magne, Roger Martin-Clouaire, et al.. Combining plot-scale indicators and farm-scale simulation to support the design of novel grassland-based beef systems. 9. European IFSA Symposium : Building sustainable rural futures. The added value of systems approaches in times of change and uncertainty, Jul 2010, Vienne, Austria. hal-02753833

HAL Id: hal-02753833
https://hal.inrae.fr/hal-02753833
Submitted on 3 Jun 2020

Combining plot-scale indicators and farm-scale simulation to support the design of novel grassland-based beef systems

Guillaume Martin[a,b], Jean-Pierre Theau[a], Olivier Therond[a], Marie-Angélina Magne[a],
Roger Martin-Clouaire[b] and Michel Duru[a]

[a] *INRA, UMR 1248 AGIR, F-31326 Castanet Tolosan, France; gmartin@toulouse.inra.fr*
[b] *INRA, UR 875 UBIA, F-31326 Castanet Tolosan, France*

Abstract: *The design of sustainable cropping and livestock systems has become a research priority. Model-based design approaches have been criticized e.g. for being too complex to stimulate farmers' learning and lead to effective innovation. This article presents an approach combining plot-scale diagnosis and farm-scale simulation tailored to support the design of novel grassland-based beef systems. Because of its intelligibility and transparency, diagnosis is expected to constitute a suitable entry point for the subsequent model-based design. Diagnosis determines the way in which the timing and intensity of farmer's practices on a grassland plot are suited to the productive potential of this grassland or its assigned function. Based on these elements, it suggests adjustments to grassland use enabling novel systems to be devised. Simulations of current and novel systems provide daily variation of standing herbage, forage stocks and animal performance for different weather patterns. The simulated behaviour of current and novel systems can then be compared. The approach is applied to two grassland-based beef systems in the French Pyrenees. Simulations reveal that improvement of forage self-sufficiency pinpointed by the plot-scale diagnosis was impractical at the farm scale due to weather and management constraints. Compared with diagnosis, simulations contributed to deeper learning of both scientists and farmers because of their level of integration and dynamic representation. Nevertheless, and as expected, diagnosis constituted a key stage in conditioning farmers to learning during the subsequent design and farm-scale model-based evaluation.*

Keywords: *design, farming system, farm management, grassland, diagnosis, modelling, learning*

Introduction

As highlighted by the "Farming Systems Design" symposiums (2007, 2009), the design of sustainable cropping and livestock systems has become a research priority. The overall objective is to design innovative systems capable of satisfying the increasing demand for safe food with reduced environmental impacts and low vulnerability to adverse events (e.g. rising input/output price ratios, weather variability, climate change). To support the design enterprise, four types of approach can be distinguished: (i) diagnosis and prescription (e.g. Doré et al., 1997), (ii) *in situ* experimentation (e.g. Mueller et al., 2002), (iii) prototyping (e.g. Vereijken, 1997), (iv) modelling (e.g. Dogliotti et al., 2005). In each case, effective innovation requires learning (Leeuwis, 1999) by farmers and scientists in parallel with the development and application of the approach. In this way, farmers can understand, accept, adopt and adapt the farming systems designed at their convenience, and scientists can refine or expand their approaches to fit more closely the design objectives. Salience (relevance to decision makers), credibility (scientific adequacy) and legitimacy (fair and unbiased information production respecting stakeholders' values and beliefs) of information provided by scientists to farmers are key determinants of learning (Cash et al., 2003).

Modelling has probably been the approach most emphasized to support farming systems design. However, its expected continuing success has been quite disappointing (McCown, 2002; Sterk et al., 2006). To explain this, several reasons are advanced of which the following seem of key importance. Most mathematical models are inflexible (Jones et al., 1997) and neglect or ignore farm management i.e. farmer's decisions and actions (Garcia et al., 2005; McCown, 2002). The consequence is their inability to cope with different production and management contexts which compromises the practical benefit - indirectly the salience and legitimacy - that the models display in designing farming systems. Models are generally so elaborated that "the risk of getting lost in [their] complexity […] is ever-present" (Cacho et al., 1995). Finally, the design process of most model-based approaches is like a "black-box", lacking transparency. The consequence is that they are regarded as unintelligible and as a result neither salient nor legitimate by most farmers (McCown, 2002). All these facts compromise the capacity of modelling approaches to stimulate farmer's learning and as a consequence, innovation.

We believe a possible solution is to combine design approaches. In this article, we present an approach combining plot-scale diagnosis and farm-scale simulation tailored to support the design of novel grassland-based beef systems capable of coping more efficiently with weather variability. Through intelligible graphical representations and transparent interpretation processes, plot-scale diagnosis is expected to constitute a suitable entry point for strengthening the salience and legitimacy of the subsequent more integrative design and farm-scale model-based evaluation. These two components are complemented by a learning characterization framework. The approach was applied to two grassland-based beef systems in the French Pyrenees. It is discussed with particular emphasis on the features of its components (i.e. diagnosis and simulation) to which learning during the design phase may be attributable.

Description of the approach

Outline of the approach

In less-favoured areas, beef production involves the management of a wide diversity of semi-natural grasslands. Herbage production is highly variable in space and time (Pleasants et al., 1995) due to between-plot differences in vegetation types, soil conditions and topography and also to weather variability within and between years. A challenge for farmers lies in making efficient and sustainable use of production resources (grasslands, labour, etc.) over space and time in order to achieve their objectives and maintain their production project. The design of beef systems capable of coping with a wide range of weather conditions is thus a challenging issue, involving changes in the currently available production resources of the farms or in the farmers' current management strategies. In such areas, as already suggested by several authors (Andrieu et al., 2007; White et al., 2004), we believe that great potential for efficiency improvement lies in novel farmers' management strategies through better use of grassland and farmland diversity. Similar to Reflexive Interactive Design (Bos et al., 2009), the approach presented here aims at designing reflexively and interactively such novel management strategies with scientists and farmers. It consists of four successive steps: system analysis, plot-scale diagnosis, farm-scale simulation and characterization of learning of scientists and farmers.

Farming system analysis

System analysis is a prerequisite to the two subsequent steps. It mainly aims at gaining an understanding of the year-round operation of the whole farm by identifying management discontinuities (e.g. a change in the herd diet). These determine periods during which the farmer makes use of a similar type of food resource (e.g. growing herbage, standing non-growing herbage, hay) with quite stable parameters (e.g. grazing intensity, number of cows per unit area), to feed the herd batch according to a given objective for the period (e.g. cow fattening through spring grazing after calving). Such a division of the year helps formalizing the relations between the farmer's practices within or between such periods, e.g. precedence (A before B), concurrence (A or B) or conjunction (A and B) and priority. By enabling the organization of farmers' practices over time and space to be recorded, it also assists in characterizing the farmer's labour peaks over the year, a key element to keep in mind when designing new management practices.

Plot-scale diagnosis of farmer's practices

In the approach presented, the diagnosis aims at determining the way in which the farmer's practices on a grassland plot are suited to the productive potential of this grassland or its assigned function. It is tailored to consider the diversity of semi-natural grasslands in temperate areas and relies on a functional characterization of grassland communities and on a representation of the time scale by using thermal time.

The concept of functional diversity is based on the definition and measuring of plant traits, i.e. morphological, physiological and phenological plant characteristics, in response to availability of resources and perturbations (Diaz and Cabido, 2001). Following this approach, it has been shown that the leaf dry matter content of individual species as well as abundance-weighted mean leaf dry matter content across grass species are well correlated with agronomic characteristics that govern the dynamics of grass growth (Duru et al., 2009).

When comparing technical operations between plots and farms in less-favoured areas, a major problem is the time scale. Farmland is heterogeneous. Plots are at various altitudes, so that at any given date, herbage age and developmental stage will vary. To account for this variation, time is expressed as thermal time or growing degree-day sums, i.e. for semi-natural grasslands the accumulated daily mean temperature between 0°C and 18°C starting from the 1st of February (Ansquer et al., 2009). Air temperatures are assumed to fall by 0.6°C per 100 m of altitude compared with the reference daily mean temperature measured at a fixed altitude (Andrieu et al., 2007).

A functional characterization of grassland communities combined with thermal time thus offers a basis for taking into account grassland and farmland diversity. It provides information on the phenology (expressed against temperature sums) of grass species encountered in the grassland community from which growth rate, timing of production, accumulated biomass and nutritive value of herbage can be deduced (Ansquer et al., 2008). In this way, the farmer's practices on a grassland plot can be analyzed reflexively in the light of this knowledge to establish whether better compromises between harvested quantity and quality can be found, or whether higher efficiency of herbage use could be achieved on this plot, given the farmer's objectives (Chazelas and Theau, 2008) (Fig. 1, left part).

For instance, a functional characterization of the vegetation provides information about the date (in thermal time) at which stem elongation of grass species begins. It also marks the transition into the spring reproductive phase. Based on this, the opportunity for grazing before or after this developmental stage can be discussed given the farmer's objectives. After stem elongation, grazing results in the removal of the reproductive apical meristems, thereby allowing reproductive growth to be controlled. On the other hand, it reduces the quantities harvested later on. Thus, on the basis of such a diagnosis, through reflexive interactions between scientists and farmers (Fig. 2), novel practices on the plot scale (e.g. an earlier hay-making date) and hence novel management strategies on the farm scale can be designed objectively, with transparency and in keeping with the farmer's objectives.

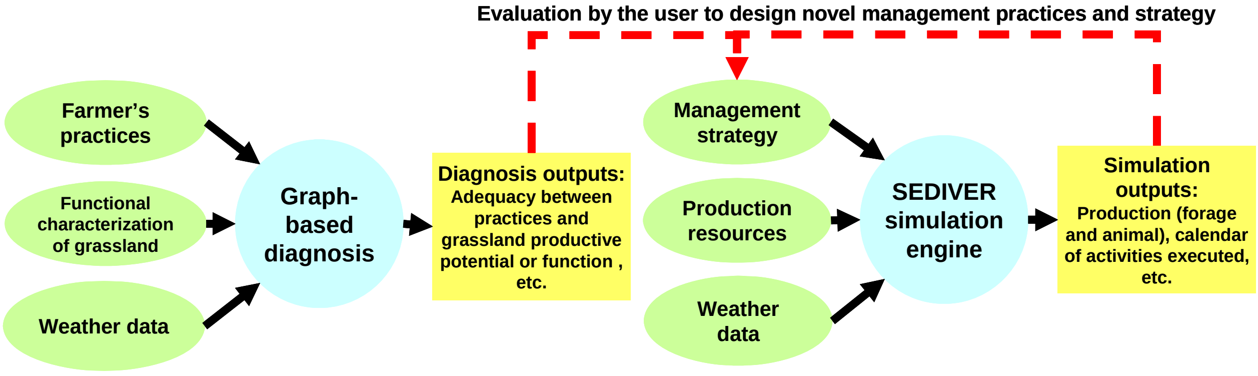

Figure 1. Overview of the design approach, inputs (ovals) and outputs (rectangle) of diagnosis and simulation.

Farm-scale simulation

SEDIVER (Martin et al., 2010) is a dynamic farm-scale simulation model that aims to assist in the evaluation of grassland-based beef systems. It is intended for use by researchers, possibly together with farm advisors and/or farmers, to investigate the suitability of the management strategy for the production system considered and also the expected performances under various weather conditions. Currently, the model is parameterized for grassland-based beef systems in European temperate areas with rustic beef cattle breeds (e.g. Salers, Gasconne). It simulates the behaviour of the biophysical system (i.e. daily variation in quantity and quality of forage stocks and standing herbage on the plots, performance of animals) in response to climatic factors and management actions that result from the progressive application of the farmer's management strategy (Fig. 1, right part).

The novelty of the approach lies in the explicit representation of grassland, animal and farmland diversity, its consequences for the dynamic heterogeneous nature of the biophysical processes occurring in the system and the subsequent constraints on herbage use and ultimately on system performance. As for the diagnosis, this relies on the concepts of functional diversity and thermal time. Another original feature concerns the modelling of the farmer's management on a daily scale through the planning and coordination over time and space of the activities whereby the farmer controls the biophysical processes occurring in the different components of the system. It takes into account any constraints and flexibility in the execution of these activities (time dependence, system-state-related constraints). SEDIVER then takes account of how the farmer copes with unpredictable and uncontrollable factors, and yields different sequences of actions depending on the conditions encountered. Such a representation of a given management strategy into a temporally-structured and flexible decision process suited to various weather conditions within and between years is facilitated by the preliminary farming system analysis.

Given that SEDIVER explicitly considers the management constraints faced by a farmer, it is suited to evaluating the feasibility of a novel management strategy. To perform such an evaluation, the model has to be used in two stages. First, it has to be particularized to the case study systems with the current management strategies to verify behavioural or representational accuracy of the simulated systems, i.e. that simulations provide realistic chronologies of farming activities and estimates of system state descriptors over several years. The extent of variation of uncontrollable factors (weather in particular) and the farmer's management strategies is considerable and precludes any systematic exploration or sensitivity analysis. Validation therefore mostly relies on common sense knowledge of experts or farmers in checking that the outputs are consistent for a range of simulation inputs (Cros et al., 2004), in addition to the comparison between the available observed data and simulated data. The considered outputs consist of a range of aggregate indicators (e.g. the quantity of food stocks harvested), production results (e.g. harvested yields) and a calendar of key events and farming activities (e.g. beginning of grazing, harvests). Then, the novel management strategies designed after the diagnosis have to be simulated, with their feasibility evaluated and their performance compared to those of the current management strategies. Both model validation and feasibility evaluation of novel management strategies constitute the support for further interactions between scientists and farmers (Fig. 2).

Learning characterization

The meaning of learning is restricted here to the cognitive change occurring when people act, receive feedback from their environment and as a result adapt their cognitions (Leeuwis, 2004). According to this same author, learning is made up, *inter alia*, of learning areas and levels. What people do or do not do is not only determined by their knowledge but also by their specific perceptions named areas of learning (e.g. a belief in own capacities, aspirations, risk perception; *vide* van Mierlo et al., 2010 for the whole list). For learning to take place, a change should occur in one learning area. The levels of learning refer to the degree of learning which can be "single loop", "double loop" or "triple loop" learning (Argyris and Schön, 1996), involving much more understanding of the current situation in each successive loop. Against this background information, to characterize and describe the learning effects, we used the grouping of learning areas and levels from van Mierlo et al. (2010) (Table 1). Interactions between scientists and farmers around the design of novel farming systems may lead to questioning about their current (scientific and farming) practices and possible opportunities. If stakeholders change for example their norms, perceptions or practices, learning is assumed to have taken place. Such changes have to be monitored and analyzed during the successive stages of the proposed approach.

Table 1. Indicators for learning effects according to area and level (van Mierlo et al., 2010)

Areas of learning / Level	Individual indicators
Aspirations and knowledge / single loop learning	Changes in problem definitions and perceived solutions that do not involve changes in pre-existing goals.
Aspirations and knowledge / double loop learning	Changes in goals, values, norms, or perceived interests, going along with radically new problem definitions and search directions.
Perception of own role and that of others	Increase in feelings of involvement, urgency and responsibility, or enhanced belief in own competencies and freedom of manoeuvre.
Action	Changes in behavioural patterns of individuals.

Application of the approach in the French Pyrenees

Case study farms

The studied grassland-based beef systems are in the French Pyrenees, in Ercé (latitude: 42°50N; longitude: 1°17E) between 615 and 1200 m.a.s.l. As the work was arduous and labour-intensive, we restricted our analysis to two farms selected because of their contrasting levels of forage self-sufficiency (Table 2). Also, they displayed different proportions of valley bottom grasslands, i.e. those suitable for mechanized harvest and often the most productive. Finally, both systems displayed comparable year-round operation of the whole farm.

Table 2. Main characteristics of the studied farms. Forage harvest and consumption are yearly averages.

Farm	Livestock units (LSU)	Area except summer grassland (ha)	Stocking rate (LSU/ha)	Forage harvest (tDM/LSU)	Forage consumption (tDM/LSU)
CC	42	70	0.59	2.25	2.27
MF	34	41.5	0.78	1.67	1.90

Several kitchen-table interactions between scientists and farmers took place during the application of the proposed approach (Fig. 2). They aimed at discussing the feasibility and relevance of management strategies proposed by scientists and the model validation. Beforehand, the two farms had been surveyed (1996-2001) to record the following information:

- the farmer’s production project: type and seasonality of production;
- the grasslands available: topography, mineral nutrition, functional characterization of grassland vegetation;
- the herd: size, renewal and batching policies, calving period, diet over the year;
- a forage calendar of planned and realized grassland uses (through hay-making or grazing) with justifications for the adjustments realized and *in situ* measurements e.g. herbage height after grazing;
- an evaluation of forage stocks availability at several times of the year;
- daily weather data (temperatures, rainfall, etc.).

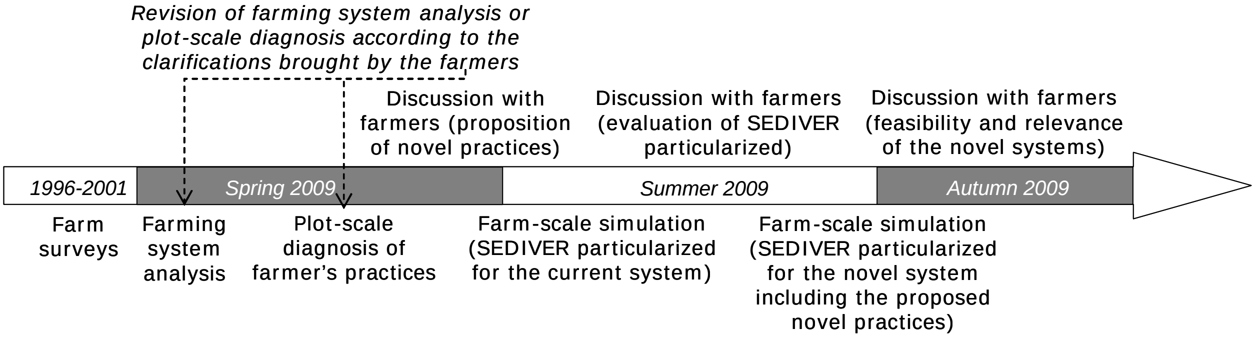

Figure 2. Successive steps and interactions with farmers during the application of the proposed approach.

Diagnosis of hay-making practices

Diagnosis can be done for both grazing and hay-making practices. For the sake of simplicity, only the diagnosis of hay-making practices is presented in this article. All the harvested plots displayed early and productive grassland communities dominated by early grass functional groups (according to Ansquer et al., 2004). With such grasslands, a first harvest aimed at maximising the quantity of forage harvested should occur around the peak of herbage production, just after flowering. After this stage, growth progressively stops and is exceeded by senescence. This is also true when light grazing at early spring precedes the harvest. Similarly, a second harvest, maximizing harvested quantity with adequate quality, should occur just after one leaf life-span, before growth is counterbalanced by senescence. Yet, in farms CC and MF, each year, numerous first harvests were taken after the end of the peak (Fig. 3), and second harvests occurred on average closer to two rather than one leaf life span. Thus, in each case, farmers harvested too late to benefit from the maximum quantity of harvestable herbage, and harvested hay was of poor nutritive value, being very rough. Bringing forward all the first harvests around the end of the peak and the second harvests just after one leaf life span seemed appropriate to increase quantity and quality of forage stocks. In addition, doing so was thought to enable a third harvest on each grassland plot on favourable years. A novel management strategy was then designed based on such thresholds.

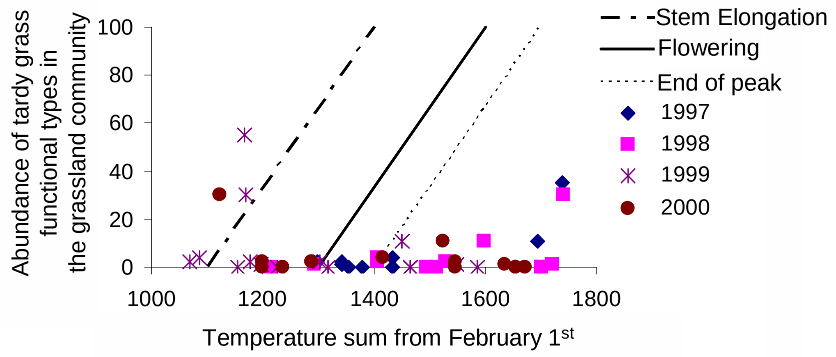

Figure 3. Characterization of the phenological stage at which first harvests occurred according to their date (in thermal time) and to the abundance of late grass functional groups in the grassland community for each plot harvested at CC farm between 1997 and 2000. The higher the abundance of such grass functional groups (at the expense of early grass functional groups), the later is the herbage phenology and the longer leaf life spans. Lines represent these different thresholds. Each symbol corresponds to the harvest of a plot in a given year and is located on the graph according to the phenological thresholds to illustrate the timing of harvests and their match with the productive potential of grasslands or their assigned function.

Simulations of current and novel management strategies

Simulations with current management strategies provided a consistent representation of the diversity of biophysical processes in space (or between animals) and time. For instance, when integrating between-plot differences in soil depth, mineral nutrition, altitude and grassland community type, simulated harvested quantities were close to those observed for first harvests (e.g.

at MF, n=46, $R^2=0.76$, $P<0.001$) and a little lower for second harvests (e.g. at MF, n=31, $R^2=0.65$, $P<0.001$). Forage harvested annually was on average overestimated by 7% at CC and underestimated by 13% at MF. Simulations reproduced consistently the extent and the nature (increase or decrease) of between-year variations of harvested forage. Yearly forage consumption and the distribution between types of food were also quite well simulated. Simulated daily forage stock consumption over time was very close to that observed, as was the duration of stay of animals at grazing (e.g. at MF, n=61, $R^2=0.67$, $P<0.001$), with a one day difference on average between simulations and observations. This confirmed that the dynamics of growth, senescence, available biomass, height, digestibility and fill value of herbage and intake capacity and intake of animals and the interactions between these factors were consistently and realistically simulated.

Simulations of current management behaviour of farmers also fitted with observations. Dates of key events (beginning of grazing, moving to summer grassland, etc.) were simulated with an average difference from observations of four days. Within the practical seasons, simulated dates of displacements of animals at grazing differed from observations by three days (e.g. at MF, n=61, $R^2=0.87$, $P<0.001$). Dates of harvests were simulated with a five-day difference (e.g. at MF, n=46, $R^2=0.89$, $P<0.001$). This confirmed that simulations consistently reproduced the farmers' decision processes as well as the relations between system state, decision-making and execution of actions.

With the novel management strategy, simulations revealed that resource availability (labour, machinery) and weather conditions limited the number of grassland plots on which harvests intended to minimize quantity and quality losses were possible. To bring forward all the harvests, given the area harvested, the speed of execution of harvests, and the high risk of rainfall in spring, it was necessary to begin harvests at 880°C.d^{-1}, i.e. mid-May, to complete the first harvests before the end of the peak. This led to proceed to the second and third harvests when herbage re-growth was between 700°C.d^{-1} and 1050°C.d^{-1}, and 660°C.d^{-1} and 930°C.d^{-1} respectively. Harvests were therefore made closer to the optimal threshold, such as one leaf life span for the second harvests. Still the above-mentioned constraints prevented farmers from harvesting all the plots at the optimal threshold to limit quantity and quality losses through senescence.

Simulation results showed that the yearly performance of current and novel management strategies was very similar for the whole set of aggregate indicators considered, except digestibility of harvested forage (Table 3). Indeed, the relative impact of change of management strategy on the other indicators was less than 5% and can be considered negligible, given the representational precision of the model. Simulated between-year variability of indicators was also in very good agreement with current and novel management strategies. With the novel management strategy, digestibility of harvested forage increased on average by 0.06 and 0.09 at CC and MF. This digestibility increase might have consequences by lowering forage fill value. If forage fill value decreases, animal daily intake might increase and as forage stocks remain constant, this might decrease forage self-sufficiency. Given that farms are currently not self-sufficient for forage, this supports the current management strategies with production of rough forage stocks and a simpler labour organization than that required by the novel management strategy. The plot-scale diagnosis remains valid but the hypothesis that great potential for efficiency improvement lies in novel farmers' management strategy is invalidated when keeping the production resources of the farms unchanged. Simulations assuming different material configuration of the production system (e.g. after investment in new machinery) might lead to different conclusions.

Table 3. Simulation results for the main aggregate indicators of system performance for both the current and novel management strategies on the two case study farms. Simulation runs are for years 1998 to 2000 and 2002.

Farm	Management strategy	Forage harvest (tDM/LSU)	Forage consumption (tDM/LSU)	Digestibility of forage harvested (kg/kg)	% of grazing in animal diet (%)	Herbage utilisation rate (%)
CC	Current	2.39	2.62	0.61	59	51
	Novel	2.30	2.58	0.67	59	53
MF	Current	1.34	1.71	0.63	60	74
	Novel	1.40	1.77	0.72	59	74

Characterization of scientists' and farmers' learning

On being presented with and discussing the plot-scale diagnosis, the two farmers changed the cognitive assumptions and norms that underlay their current practices at the plot scale. On seeing the output of the diagnosis, they realized the room for manoeuvre they had for increasing their self-sufficiency for forage with simple changes in their current management strategy e.g. by bringing forward their harvests. This resulted in changes in their aspirations and knowledge and learning of type "how to do things better", i.e. single loop learning. As this was in the middle of spring, learning immediately led to a change in farmers' actions as they tried to implement the novel practices e.g. for hay-making. Two months later, the simulation results were presented to the farmers. They found these to be consistent and realistic, given the simulated system and the weather time series considered. More importantly, their attempt to implement the novel practices on several plots confirmed the simulation results. Their room for manoeuvre appearing in the plot-scale diagnosis had proved to be actually impractical at the farm scale due to the scarcity of resources available (i.e. labour and machinery) and to the frequency of unfavourable weather conditions. This was considered valid for the studied year and most probably for years with different weather patterns. This confirmation led to changes of aspirations and knowledge for both scientists and farmers and induced higher level learning, i.e. double loop learning. Indeed, the learning occurring during this phase involved the abandonment of a shared norm, i.e. farmers actually had no room for manoeuvre for increasing their self-sufficiency for forage through better use of grassland and farmland diversity. As a result, problem definition and perceived solutions were revised. Available labour and machinery were identified as the main limiting factors to change in the currently available production resources of the farms instead of changes in the farmers' current management strategies. A simulation-based evaluation of the potentialities of investments into new machinery was identified as an interesting continuation of the work.

Discussion

In this article we have presented an approach combining plot-scale diagnosis and farm-scale simulation tailored to support the design of novel grassland-based beef systems capable of coping with weather variability. It was developed under the assumption that plot-scale diagnosis would constitute a relevant entry point for strengthening the salience and legitimacy of farming system design and farm-scale model-based evaluation, thereby stimulating learning. Plot-scale diagnosis stimulated single loop learning, whereas farm-scale simulations led to double loop learning. The two approaches, i.e. diagnosis and simulation, differed in terms of level of integration or spatial scale, i.e. plot-scale vs. farm-scale. Another distinction was that simulations were dynamic whereas the diagnosis was a static picture. These two differences, already identified as key points in previous studies (van Ittersum et al., 2004; van Paassen, 2004), had fundamental consequences on the type of learning stimulated. Indeed, the plot-scale diagnosis examines the farming system by taking it apart, i.e. plot by plot with their respective grassland communities and management practices. Actually, 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. Even if the diagnosis is valid at the plot scale, such interactions might give rise at the farm scale to properties such as a bottleneck on some resources that were not apparent at the lower or higher level. Understanding the mechanisms and consequences of these emergent properties is of key importance in devising a management strategy that complies with the farmer's objectives and constraints. Scientists can then learn unexpected aspects of the management practices they promote. Simulations at the farm scale revealed such emergent properties of the systems, e.g. the impact of labour and machinery scarcity on proper implementation of novel management strategies, which were not identifiable without *in situ* or *in silico* experimentation.

Leeuwis (2004) emphasized the need for relevant feedback to support learning. The plot-scale diagnosis has the potential to easily provide confrontational feedbacks to farmers, i.e. feedbacks indicating the existence of a problem or potentialities for improvement (e.g. more efficient use of herbage production) in the farmer's practices. It specifies the nature of the problem and goes with clear and easily understandable graphic representations and interpretations. This is supported by reliable procedures for measurement and analysis based on well-tried scientific knowledge which ensure the credibility of the approach. Such a diagnosis constituted a powerful first step to condition farmers to learning. As farmers got into the mental process for diagnosis, they appropriated the novel management practices easily and tried to implement them. Understanding of the concepts involved in the resolution of the problem then positively affected some areas of learning such as action. Afterwards, confrontational feedbacks were provided by simulations. If seeing the simulated effects of novel management strategies can enhance the feedback which is the source of the learning process, an inadequate system representation, e.g. deficient definition of the system components or unknown initial states, can greatly reduce the salience and credibility of the model (McCown, 2002) and therefore compromise this learning. In the SEDIVER model, the farmer who controls the biophysical processes is not considered as standing apart from the production system but rather as a main subsystem. As a subsystem, he produces decisions and interacts with the biophysical system through control and data collection interventions according to a farm-scale management strategy. Compared with available models, SEDIVER is the result of consistent efforts to achieve salience by improving the realism of simulation models and getting closer to the problems, questions and expectations raised by farmers in practice. It explicitly considers the management constraints faced by a farmer, those inherent to the farm structure (e.g. whether plots are suitable for mechanization) and those encountered dynamically (e.g. time dependencies between activities). In addition, the model's structure is adaptable to a variety of contexts and farmers' management strategies to correctly reflect an individual production situation and to ensure salience and legitimacy of the approach. The mental procedures and calculations behind the simulations are more complex than what is behind the diagnosis. Still, as farmers had been conditioned by the diagnosis, they were receptive to the simulation results. Their reactions and the confirmation of simulation results through on-field trials proved their interest and understanding, and the capacity of the farm-scale model to support high-level learning.

Two characteristics of the interactions between scientists and farmers were identified as key factors influencing learning. The increasing occurrence of rainless summers had led farmers to question their way of making forage stocks. Indeed, periodically, management processes must change when old ones are no longer adequate. In this kind of situation, new practical uncertainties emerge for farmers. Consequently they are usually more interested in information from the outside (McCown, 2002; Sterk et al., 2006). Perceived usefulness of the approach played an important role in bringing farmers to think that the approach application could be efficient. This was also related to the regularity of the contacts between farmers and scientists before the beginning of the simulations. Farmers provided regular feedback and progressively built trust in the research approach, in the scientists' understanding of the simulated system and in their capacity to produce salient and legitimate information. The project helped to develop a mutual understanding between farmers and scientists.

Conclusions

Following Sterk et al. (2007), the work presented in this article emphasizes the potentialities of combining approaches to support farming system design. Complementarities between plot-scale diagnosis and farm-scale simulation were evident to progressively access the complexity of the studied systems and thereby stimulate learning. If the number of farms considered in the application remains limited, both the diagnosis and simulation approaches have respectively been tested in other contexts or on different systems (Chazelas and Theau, 2008; Martin et al., 2010). Learning characterization proved to be an insightful complement to reflexively adapt the previous steps in order to make a more thought-provoking and constructive environment to support the design of farming systems able to cope with challenges of the near future, such as climate change.

Acknowledgements: This study was partly funded by the French ANR ADD and VMC programs in the framework of the projects TRANS (TRANSformations de l'élevage et dynamiques des espaces, ANR-05-PADD-003) and VALIDATE (Vulnerability Assessment of LIvestock and grasslanDs to climAte change and exTreme Events, ANR-07-VULN-011). We thank the farmers involved in this research for their fruitful collaboration, and Alan Scaife for the English revision.

References

Andrieu, N., Poix, C., Josien, E. and M. Duru (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.

Ansquer, P., Theau, J.P., Cruz, P., Viegas, J., Al Haj Khaled, R. and M. Duru (2004) Caractérisation de la diversité fonctionnelle des prairies à flore complexe: vers la construction d'outils de gestion. *Fourrages* 179: 353-368.

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

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

Argyris, C. and D. Schön (1996) Organizational learning II: Theory, method and practice, Reading, Mass: Addison Wesley.

Bos, A.P., Groot Koerkamp, P.W.G., Gosselink, J.M.J. and S. Bokma (2009) Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. *Outlook on Agriculture* 38: 137-145.

Cacho, O.J., Finlayson, J.D. and Bywater, A.C. (1995) A simulation model of grazing sheep: II whole farm model. *Agricultural Systems* 48: 27-50.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J. and R.B. Mitchell (2003) Knowledge Systems for Sustainable Development. *Proceedings of the National Academy of Sciences of the United States of America* 100: 8086-8091.

Chazelas, L. and J.P. Theau (2008) Appréhender la diversité fonctionnelle des prairies pour mieux les gérer. In: Cruz, P., Jouany, C., Theau, J.P., (Eds.). *Les Cahiers d'ORPHEE* 1. INRA-SAD, Toulouse, France, pp. 289-299.

Cros, M.J., Duru, M., Garcia, F. and R. Martin-Clouaire (2004) Simulating management strategies: the rotational grazing exemple. *Agricultural Systems* 80: 23-42.

Diaz, S. and M. Cabido (2001) Vive la difference: Plant functional diversity matters to ecosystem processes. *Trends in Ecology and Evolution* 16: 646-655.

Dogliotti, S., van Ittersum, M.K. and W.A.H. Rossing (2005) A method for exploring sustainable development options at farm scale: A case study for vegetable farms in South Uruguay. *Agricultural Systems* 86: 29-51.

Doré, T., Sebillotte, M. and J.M. Meynard. (1997) A diagnostic method for assessing regional variations in crop yield. *Agricultural Systems* 54: 169-188.

Duru, M., Al Haj Khaled, R., Ducourtieux, C., Theau, J.P., de Quadros, F.L.F. and P. Cruz (2009) Do plant functional types based on leaf dry matter content allow characterizing native grass species and grasslands for herbage growth pattern? *Plant Ecology* 201: 421-433.

Jones, J.W., Thornton, P.K. and J.W. Hansen (1997) Opportunities for systems approaches at the farm scale. In: Teng, P.S., Kropff, M.J., ten Berge, H.F.M., Dent, J.B., Lansigan, F.P. and van Laar, H.H., (Eds.). *Applications of Systems Approaches at the Farm and Regional Levels*, Vol. 1, Kluwer Academic Publishers, The Netherlands, pp. 1-18.

Leeuwis, C., 1999. Science and integral design in agriculture and resource management. Identification of issues and organisation of the book. In: Leeuwis, C. (Ed.). *Integral design: innovation in agriculture and resource management*, Mansholt studies 15. Mansholt Institute, Wageningen, pp 1-11.

Leeuwis, C. (2004) Communication for rural innovation: rethinking agricultural extension. Communication for rural innovation: rethinking agricultural extension. Blackwell Publishing Ltd., Oxford, United Kingdom, 412 p.

Martin, G., Martin-Clouaire, R., Rellier, J.P. and M. Duru (2010) A simulation model to design grassland-based beef systems. Submitted to *Environmental Modelling and Software*.

McCown, R.L. (2002) Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agricultural Systems* 74: 179-220.

Mueller, J.P., Barbercheck, M.E., Bell, M., Brownie, C., Creamer, N.G., Hitt, A., Hu, S., King, L., Linker, H.M., Louws, F.J., Marlow, S., Marra, M., Raczkowski, C.W., Susko D.J. and M.G. Wagger (2002) Development and implementation of a long-term agricultural systems study: challenges and opportunities. *Horttechnology* 12: 362-368.

Pleasants, A.B., McCall, D.G. and G.W. Sheath (1995) The management of pastoral grazing systems under biological and environmental variation. *Agricultural Systems* 48: 179-192.

Sterk, B., van Ittersum, M.K., Leeuwis, C., Rossing, W.A.H., van Keulen, H. and G.W.J. van de Ven (2006) Finding niches for whole-farm design models - contradictio in terminis. *Agricultural Systems* 87: 211-228.

Sterk, B., van Ittersum, M.K., Leeuwis, C. and F.G. Wijnands (2007) Prototyping and farm system modelling– Partners on the road towards more sustainable farm systems? *European Journal of Agronomy* 26: 401-409.

van Ittersum, M.K., Roetter, R.P., van Keulen, H., de Ridder, N., Hoanh, C.T., Laborte, A.G., Aggarwal, P.K., Ismail, A. B. and A. Tawang (2004) A systems network (SysNet) approach for interactively evaluating strategic land use options at sub-national scale in South and South-east Asia. *Land Use Policy* 21: 101-113.

van Mierlo, B.C., Leeuwis, C., Smits, R. and R. Klein Woolthuis (2010) Learning towards system innovation: Evaluating a systemic instrument. *Technological Forecasting and Social Change* 77: 318-334.

van Paassen A. (2004) Bridging the gap: computer model enhanced learning about natural resource management in Burkina Faso. *Tropical Resource Management Papers* 49, Wageningen University and Research Centre, Wageningen, The Netherlands.

Vereijken, P. (1997) A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. *European Journal of Agronomy* 7: 235-250.

White, T.A., Barker, D.J. and K.J. Moore (2004) Vegetation diversity, growth, quality and decomposition in managed grasslands. *Agriculture, Ecosystems & Environment* 101: 73-84.