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Diagnosis and simulation: a suitable combination to support farming systems design

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Abstract. Designing or improving farming systems requires understanding their dynamics so as to predict their behaviour in response to management. Simulation tools can potentially support the process by which farmers and scientists might obtain such an encompassing understanding. The usability of these tools is, however, partially inhibited by the inherent complexity of the interactions at work in farm-scale models. Whereas such models are generally used in isolation, here we present an approach in which a field-scale diagnosis method complements a farm-scale simulation model. This diagnosis method lends itself easily to an intelligible presentation of field-specific knowledge that can be fed to the simulation tool for more encompassing considerations. Our approach is used to support the design of novel management strategies in grassland-based beef systems and proved to be effective when applied to two farms in the French Pyrenees. Thanks to the integrative representation of the various processes, including the management ones, simulation contributed to deeper learning of both scientists and farmers about room for manoeuvre for increasing self-sufficiency for forage. The diagnosis phase enhanced the learning process by providing a simpler framework in which elementary problems at field scale could be considered separately before being examined concurrently at farm scale in the simulation phase.

Additional keywords: design, farm management, farming system, grassland, learning, modelling.

Introduction

As highlighted by the ‘Farming Systems Design’ symposiums (Donatelli *et al*. 2007; Hatfield and Hanson 2009), the design of sustainable cropping and livestock systems and their management strategies has become a research priority. The overall objective is to design innovative farming 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 approaches 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), and (*iv*) *in silico* experimentation (e.g. Dogliotti *et al*. 2005).

Diagnosis attempts to determine why some fields or farms do not achieve their expected or potential level of performance, and in particular which features of field or farm management are responsible for reduced performance (Doré *et al*. 1997). Based on the conclusions of diagnosis, adaptations of management strategies are elaborated to get closer to the expected or potential level of performance of the field or farm. *In situ* experimentation relies on the establishment of farming system trials at experimental stations to identify, among the systems tested, the one which performs best given a range of objectives (Mueller *et al*. 2002). It can be preceded by a prototyping phase, that is, a methodical and participatory way of designing, laying out, testing and improving prototypes of farming systems with the support of experts, e.g. farm advisors and farmers (Vereijken 1997). Finally, *in silico* experimentation allows virtual experimentation through two kinds of approaches, optimisation and simulation. Both involve the creation of a simplified description of a farming system which is generally expressed in mathematical terms. Optimisation determines, for an objective function, the best possible system from a set of alternatives (e.g. Dogliotti *et al*. 2005). Simulation explores the dynamics of the system to evaluate its behaviour under a range of external conditions (e.g. weather) (e.g. Martin *et al*. 2011*b*). It is the responsibility of the model user to progressively modify the simulated system to tend towards the ‘best’ system. Both optimisation and simulation can involve different degrees of stakeholders’ (e.g. farm advisors, farmers) participation (Sterk *et al*. 2006; McCown *et al*. 2009).

With each of the four design approaches, in parallel with the development and application of the approach, effective innovation requires learning (Leeuwis 1999) by farmers and scientists (or farm advisers). This learning concerns the dynamics of interrelated physical, biological, and human decision-making processes in the farming systems so as to create greater understanding of outcomes, or to predict the behaviour of farming systems in response to management. In this way, farmers can understand, accept, adopt and adapt the farming systems designed at their convenience, and scientists

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(or farm advisers) 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 promoting learning (Cash *et al*. 2003).

In silico experimentation has probably been the most common approach used to support farming systems design. However, its expected success has been quite disappointing (Sterk *et al*. 2006; Woodward *et al*. 2008). 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. the farmer's decisions and actions (Garcia *et al*. 2005). The consequence is that mathematical models are unable to cope with different production and management contexts. This compromises the practical benefit – indirectly the salience and legitimacy – that the models display in designing farming systems. Indeed, in essence, farming systems are located in different production and management contexts. 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 model-based approaches are regarded as unintelligible and as a result neither salient nor legitimate by most farmers (Woodward *et al*. 2008; McCown *et al*. 2009). All these facts compromise the capacity of *in silico* experimentation approaches to stimulate farmers' learning and as a consequence, innovation.

We believe a possible solution is to combine design approaches. In this paper, we present an approach combining field-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 (Fig. 1). Through intelligible graphical representations and transparent interpretation processes, field-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 characterisation framework. The approach has been applied to two grassland-based beef systems in the French Pyrenees. The application is discussed with particular emphasis on the features of its components (i.e. diagnosis and simulation) to which learning effectiveness in the design phase may be attributable.

Material and methods

An approach combining diagnosis and simulation

Outline of the approach

In many regions across the world, livestock 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-field 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 over the short- and the long terms. The design of livestock 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. As already suggested by several authors (White *et al*. 2004; Andrieu *et al*. 2007), we claim that great potential for efficiency improvement lies in novel farmers' management strategies making better use of grassland and farmland diversity. The approach presented here aims at designing such novel management strategies based on reflexive (that is, by encouraging critical questioning about one's own practices) thinking of farmers and reflective interactions between scientists and farmers. It consists of three successive steps: field-scale diagnosis, farm-scale simulation and characterisation of learning of scientists and farmers. Here, the whole approach has been applied to two grassland-based beef farms in a semi-mountainous area. In the literature, all three steps have respectively been tested in other contexts or on different systems (e.g. Chazelas and Theau 2008; van Mierlo *et al*. 2010; Martin *et al*. 2011*b*).

Field-scale diagnosis of farmers' practices

In the approach presented, the diagnosis aims at determining why some grasslands in a farm do not achieve their expected or potential productive potential, or assigned function (e.g. production of good quality hay). It focuses especially on the role of farmers' practices in such performance gaps. Based on the conclusions of diagnosis, adaptations of grassland management practices are discussed with the farmer (Fig. 1, left part). This diagnosis approach is tailored to consider the diversity of semi-natural grasslands in temperate areas and relies on a functional characterisation of grasslands and on a representation of the time scale by using thermal time.

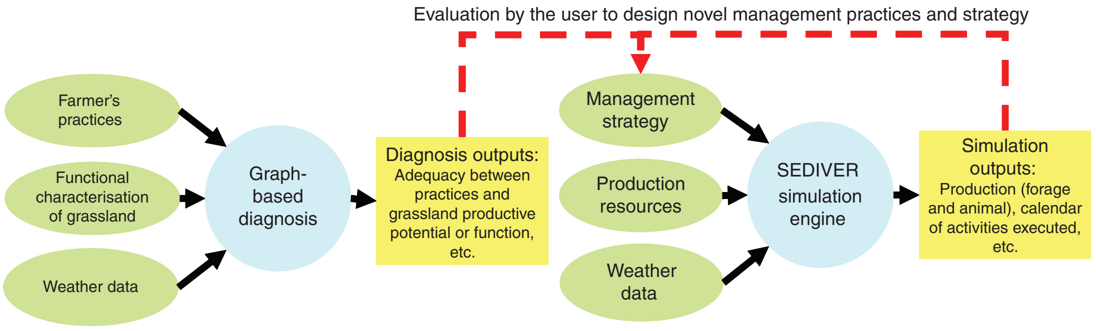

Fig. 1. Overview of the approach, inputs (ovals) and outputs (rectangles) of diagnosis and simulation.

The concept of functional diversity is based on the definition and measuring of plant traits, i.e. morphological, physiological and phenological plant characteristics, characterising the response of plants to availability of resources and perturbations (Diaz and Cabido 2001). Categorisations of grasslands can be built from differences in trait values (McIntyre 2008). 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 (e.g. beginning of stem elongation, flowering, biomass peak) that govern the dynamics of grass growth (Duru *et al.* 2010*b*).

A categorisation of grasses into functional types based on plant trait values has recently been proposed (Cruz *et al.* 2010). The resulting functional types display differences in the timing of development stages (beginning of stem elongation, flowering, biomass peak and leaf life span), and in growth rate and nutritive value (Cruz *et al.* 2010; Duru *et al.* 2010*b*). Based on this categorisation of grasses, a simplified method for functional characterisation of grasslands has been proposed (Duru *et al.* 2010*a*; Theau *et al.* 2010). It first consists of a simplified botanical survey consisting in a visual characterisation of the abundance of grasses in the grassland community, and the respective abundance of each dominant grass species. Along a transect in the surveyed field, 20 10 × 10-cm plots distributed equidistantly are sampled. Each plot is exhaustively sorted and a score from 0 (species present but not dominant) to 6 (species representing the total biomass present) is given to the species sampled (Theau *et al.* 2010). From the results of the botanical survey, a spreadsheet (Duru *et al.* 2010*a*) displays the relative abundance of each grass functional type in a grassland, and related information about the weighted mean agronomic characteristics (growth rate, timing of production and nutritive value) of this grassland.

When comparing technical operations between fields and farms in mountainous areas, a major problem is the time scale. Farmland is heterogeneous. Fields are at various altitudes, so that at any given date, herbage age and developmental stage will vary. In addition, in a farm, the frequency of grazing or mowing might vary between fields. This requires a time-scale representation accounting for seasonal variations of herbage development. To account for the two abovementioned factors, time is expressed as thermal time or growing degree-day sums, i.e. for semi-natural grasslands the accumulated daily mean temperature between 0 and 18°C starting from 1 February (Ansquer *et al.* 2009*a*). 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 characterisation of grasslands combined with thermal time thus offers a basis for taking into account grassland, farmland and management diversity. It provides information on the phenology (expressed against temperature sums) of grass species encountered in the grassland from which growth rate, timing of production, accumulated biomass and nutritive value of herbage can be deduced (Ansquer *et al.* 2009*b*; Duru *et al.* 2010*b*). 'Early' and 'late' grasslands can be distinguished as regard to thresholds defined based on the timing of agronomic characteristics, for instance the beginning of stem elongation, flowering or the biomass peak (Fig. 2). The farmer's practices on a grassland field can then be analysed in the light of this knowledge. According to a nomogram (Fig. 2), it is possible to establish whether better compromises between harvested quantity and quality can be found, or whether higher efficiency of herbage use is reachable and as a consequence whether the expected or potential productive potential, or assigned function could be achieved on this field, given the farmer's objectives (Chazelas and Theau 2008).

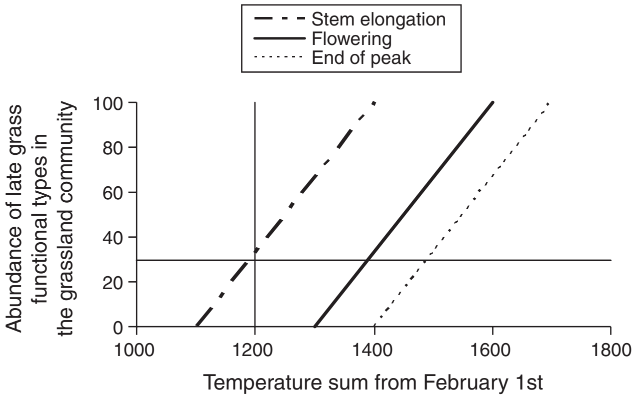

Fig. 2. Example of a nomogram to diagnose field-specific harvest at spring. It enables estimation of herbage phenological stage using: (*a*) field-specific relative abundance of 'late' maturing grass functional types, and (*b*) thermal time based on nearest temperature recording site. Relative abundance of 'late' grass functional types is used as an herbage maturity index. A horizontal line at the level of some calculated maturity index of a given field (e.g. 30% here) intersects the functions for stem elongation, flowering and end of biomass peak. Vertical lines from the intersects indicate the date (in thermal time) of each event (e.g. stem elongation here) for that field. Using such a nomogram, herbage phenological stage at harvest can be evaluated for specific fields, and the match with the productive potential of the grassland or its assigned function can then be discussed.

For instance, a functional characterisation of grasslands indicates whether they are dominated by 'early' or 'late' grass functional types (according to Ansquer *et al.* 2009*b*). This provides information about the date (in thermal time) at which stem elongation of grass species begins and the peak of herbage production, just after flowering occurs. Stem elongation of grass species 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. Similarly, a first and a second harvest aimed at maximising the quantity of forage harvested should occur around the peak of herbage production (Fig. 2) and just after one leaf life span, respectively, in both cases before growth is exceeded by senescence (Ansquer *et al.* 2009*b*). Thus, on the basis of such a diagnosis, through reflexive thinking of farmers and reflective interactions between scientists and farmers, novel practices on the field 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 (Fig. 3).

In addition to its core objective, by enabling the organisation of the farmer's practices over time and space to be recorded, the

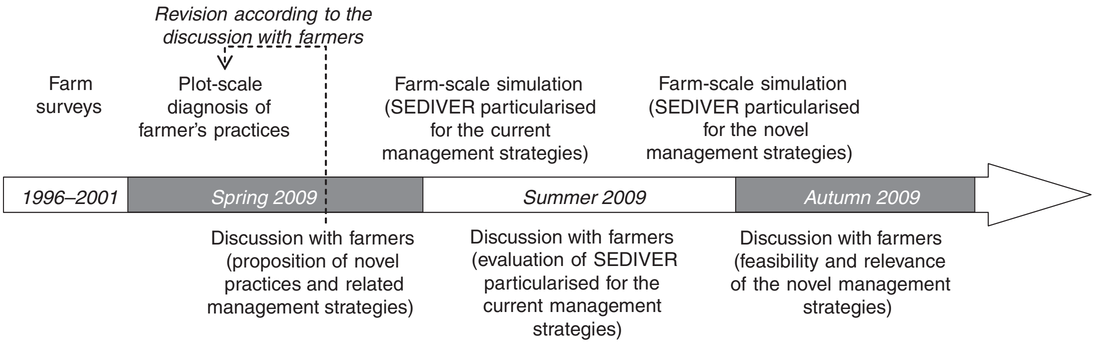

Fig. 3. Successive steps and interactions with farmers during the application of the proposed approach.

diagnosis assists in gaining an understanding of the year-round operation of the whole farm. It also assists in characterising the farmer's labour peaks over the year, a key element to keep in mind when designing new management practices.

Farm-scale simulation

SEDIVER (Martin *et al*. 2011*a*, 2011*b*) is a dynamic farm-scale simulation framework that aims to assist in the evaluation of grassland-based beef systems. The models that can be built with the SEDIVER framework simulate the behaviour of the biophysical system (i.e. daily variation in quantity and quality of forage stocks and standing herbage on the fields, 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). Such models investigate the suitability of a management strategy for a given farming system and also expected performances under various weather conditions. Currently, the SEDIVER framework is parameterised for grassland-based beef systems in European temperate areas with rustic beef cattle breeds (e.g. Salers, Gasconne).

The novelty of the SEDIVER 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-based models then take 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 is facilitated by the preliminary understanding of the year-round farming operations gained through the diagnosis.

Given that SEDIVER-based models explicitly consider the management constraints faced by a farmer, they are suited to evaluating the feasibility of a novel management strategy. To perform such an evaluation, the models have to be developed in two stages. First, the SEDIVER framework has to be particularised (instantiated in programming language) into models of the investigated grassland-based beef systems with the current management strategies. It aims at verifying the 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 outputs considered 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. 3).

Characterisation of scientists' and farmers' learning

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 and practices (Leeuwis 2004). According to Leeuwis, 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 more details). 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', i.e. learning of type 'how to do things better', or 'double loop' i.e. learning involving the relinquishing of basic certainties, goals and values, inducing the revision of problem definition and overall of perceived solutions (Argyris and Schön 1996; Leeuwis 2004). The levels of learning involve much more understanding of the current situation in each successive loop. Against this background information, to characterise 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 analysed during the successive stages of the proposed approach.

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 detailed and labour-intensive, we restricted our analysis to two farms. These two farms were selected because they were representative of the farms in the region regarding criterion such as farm size, stocking rate, land use, productivity, year-round operation, etc. Representativeness was verified using the description of synthesised typical farms provided for the study region by Réseaux d'Elevage (2011). Also, the two farms displayed contrasting levels of forage self-sufficiency (Table 2), and different proportions of valley bottom grasslands, i.e. those suitable for mechanised harvest and often the most productive.

Several kitchen table interactions between scientists and farmers took place during the application of the proposed approach (Fig. 3), discussing the feasibility and relevance of management strategies proposed by scientists and model validation. Beforehand, the two farms had been surveyed (1996–2001) to record the following information, which, based on discussions with farmers, proved to accurate for use in 2009 including:

(1) The farmer's production target: type and seasonality of production;
(2) The grasslands available: topography, mineral nutrition, botanical surveys that enabled functional characterisation of grassland vegetation;
(3) The herd: size, renewal and batching policies, calving period, diet over the year;
(4) A calendar of planned and realised grassland uses (through hay making or grazing) with justifications for the adjustments realised and *in situ* measurements e.g. herbage height after grazing;
(5) An evaluation of forage stocks availability at several times of the year; and
(6) Daily weather data (temperatures, rainfall, etc.).

Results and discussion

Design and evaluation of novel grassland-based beef systems

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 paper. All the harvested fields displayed 'early' (considering the seasonality of production) and productive grassland communities dominated by 'early' grass functional types (according to Ansquer *et al*. 2009*b*). 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, maximising harvested quantity with adequate quality, should occur just after one leaf life span, before growth is counterbalanced by senescence (Ansquer *et al*. 2009*b*). Yet, in farms 1 and 2, each year, numerous first harvests were taken after the end of the peak (Fig. 4), 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 and very rough. The 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 field on favourable years. A novel management strategy was then designed based on such thresholds.

Simulations of current and novel management strategies

Over the four simulated years (1998, 1999, 2000, 2002), 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-field differences in soil depth, mineral nutrition, altitude and grassland community type, simulated harvested quantities were close to those observed for first harvests (e.g. in farm 2, $n = 46$, $R^2 = 0.76$,

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 competence and freedom of manoeuvre
Action	Changes in behavioural patterns of individuals

Table 2. Main characteristics of the studied farms

Forage harvest and consumption are yearly averages. tDM and LSU mean t of forage dry matter and livestock unit, respectively

Farm	LSU	Area except summer grassland (ha)	Stocking rate (LSU/ha)	Forage harvest (tDM/LSU)	Forage consumption (tDM/LSU)
1	42	70	0.59	2.25	2.27
2	34	41.5	0.78	1.67	1.90

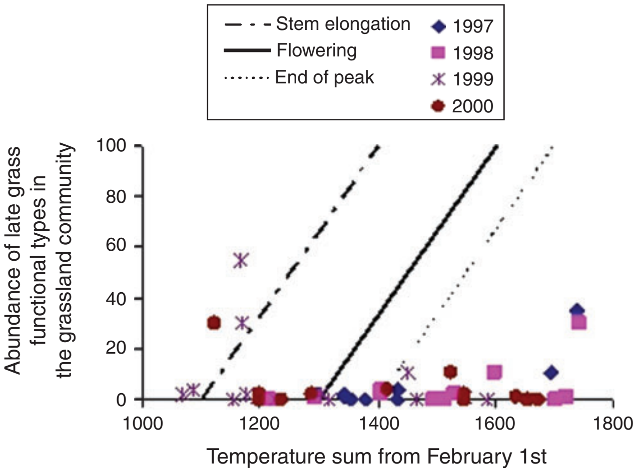

Fig. 4. Based on the nomogram of Fig. 2, characterisation of the phenological stage at which first harvests occurred for each field harvested in farm 1 (left graph) and farm 2 (right graph) between 1997 and 2000. Each symbol corresponds to the harvest of a field in a given year. Explanations on how to read the graph are provided in Fig. 2.

$P < 0.001$) and a little lower for second harvests (e.g. in farm 2, $n = 31$, $R^2 = 0.65$, $P < 0.001$). Forage harvested annually was on average overestimated by 7% in farm 1 and underestimated by 13% in farm 2. 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. in farm 2, $n = 61$, $R^2 = 0.67$, $P < 0.001$), 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 animal movements at grazing differed from observations by three days (e.g. in farm 2, $n = 61$, $R^2 = 0.87$, $P < 0.001$). Dates of harvests were simulated with a five-day difference (e.g. in farm 2, $n = 46$, $R^2 = 0.89$, $P < 0.001$). 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 (over the 4 simulated years) limited the number of grassland fields on which harvests intended to minimise quantity and quality losses were possible. To bring forward all the harvests, given the area harvested, the time needed to harvest, and the high risk of rainfall in spring, it was necessary to begin harvests at 880 degree-days, 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 regrowth was between 700 and 1050 degree-days, and 660 and 930 degree-days, respectively. Harvests were therefore made closer to the optimal threshold, such as one leaf life span for the second harvests. Still the abovementioned constraints prevented farmers from harvesting all the fields 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). With the novel management strategy, it increased on average by 0.06 and 0.09 in farms 1 and 2. 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. 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 organisation than that required by the novel management strategy. The field-scale diagnosis remains valid but the hypothesis that great potential for efficiency improvement lies in novel farmers' management strategy is invalidated when

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. tDM and LSU mean t of forage dry matter and livestock unit, respectively

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

keeping the production resources of the farms unchanged. Simulations assuming different material configuration of the farming system (e.g. after investment in new machinery) would almost certainly lead to different conclusions.

Scientists' and farmers' learning in the application

Observed scientists' and farmers' learning

Designing or improving farming systems requires that farmers and scientists (or farm advisers) understand and most often learn about the dynamics of interactive physical, biological, and human decision-making processes in the systems. It is a prerequisite to understanding key drivers of desirable or undesirable facts, or predicting the behaviour of such systems in response to management.

In the study region as well as in most French regions where livestock farming is present, the traditional knowledge about grassland use has progressively been lost over the past 50 years. As a consequence, on being presented with and discussing the field-scale diagnosis, the two farmers changed the cognitive assumptions and norms that underlay their current practices at the field scale. On seeing the output of the diagnosis, they realised what room for manoeuvre they had for increasing their forage self-sufficiency by simple changes in their current management strategy e.g. by bringing forward their harvests. This resulted in changes in their aspirations 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 four weather time series considered. More importantly, their attempt to implement the novel practices on several fields confirmed the simulation results. Their room for manoeuvre appearing in the field-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 revision for both scientists and farmers, and induced higher level learning, i.e. double-loop learning. Indeed, the learning that took place 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.

Suitable and complementary features of diagnosis and simulation

The two approaches, i.e. diagnosis and simulation, differed in terms of level of integration, i.e. field- *v.* 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.

Field-scale diagnosis examines the farming system by taking it apart, i.e. field by field 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 field 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) emphasised the need for relevant feedback to support learning. The field-scale diagnosis has the potential to easily provide thought-provoking 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 established scientific knowledge which ensure the credibility of the approach. Such a diagnosis constituted a powerful first step to frame farmers' minds towards 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 and reasoning involved in the resolution of the problem then positively affected some areas of learning such as action.

Afterwards, thought-provoking 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 (Woodward *et al*. 2008) and therefore compromise this learning. In the SEDIVER model, the farmer who controls the biophysical processes is not considered as standing apart from the farming 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 fields are suitable for mechanisation) and those encountered dynamically (e.g. whether or not the feasibility conditions of an activity are satisfied). 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 considered in simulation are more complex than those in diagnosis. Still, as farmers' mind had been framed towards learning by the diagnosis, they were receptive to the simulation results, especially after corroboration through on-field trials. The farmers' reactions proved their interest and understanding, and the capacity of the farm-scale model to support high-level learning. Complementarities between field-scale diagnosis and farm-scale simulation were then evident to progressively access the complexity of the studied systems, i.e. from the field to farm scale, and thereby stimulate learning. The work presented in this article then emphasises the potentialities of combining approaches to support farming system design.

Features of farmer–scientist interactions involved in 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 who, consequently, become more interested in information from the outside (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. A significant contributing factor was 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 and concordance between farmers and scientists.

Conclusions

Whereas farming system design approaches are generally used in isolation, the approach presented in this paper combined field-scale diagnosis and farm-scale simulation to support the design of novel grassland-based beef systems capable of coping with weather variability. It was developed under the assumption that field-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. Application of the approach to two farms in the Pyrenees showed that simulations contributed to deeper learning of both scientists and farmers about room for manoeuvre for increasing self-sufficiency for forage. Diagnosis constituted a key preliminary stage in framing farmers' mind to learning during the subsequent design and model-based evaluation. This result suggests that instead of mobilising design approaches in isolation, potentialities of combining these are promising in order to make a more thought-provoking and constructive environment to support a credible and salient design of sustainable farming systems able to cope with challenges of the near future, such as climate change.

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