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Modelling small ruminant systems in Mediterranean areas

M. Jouven*, R. Baumont, S. Ingrand*** and F. Bocquier***

*INRA-SupAgro, UMR ERRC, 2 place Viala, F-34060 Montpellier (France)
**INRA, URH, Theix, F-63122 St Genès Champanelle (France)
***INRA, UMR-1273 METAFORT, Theix, F-63122 St Genès Champanelle (France)

Abstract. This paper examines the issues and requirements of simulation models for small ruminant systems in Mediterranean areas. Due to the few published models suited to these systems, we analyze the features of existing models designed for other species and other geographical areas, but focussed on similar issues (adaptive abilities of the females, feed self-sufficiency of the farm, sustainable use of rangeland). The applicability of their equations and conceptual representations to small ruminant systems is discussed. Flock and land heterogeneity, but also resource variability between seasons and years, should be given high interest, since they are typical of Mediterranean systems. Setting precise modelling objectives in relation to the final users, and exploiting complementary sources of information including expert knowledge are basic conditions for building a model of the farming system.

Keywords. Model – Livestock system – Grazing – Mediterranean – Small ruminants.

Modélisation de systèmes d'élevage de petits ruminants en zones méditerranéennes

Résumé. *Cet article traite des enjeux et des cahiers des charges pour des modèles de simulation de systèmes d'élevage de petits ruminants en zones méditerranéennes. Comme peu de modèles publiés sont adaptés à ces systèmes, nous analysons les caractéristiques de modèles existants conçus pour d'autres espèces et d'autres régions, mais traitant d'enjeux similaires (capacités adaptatives des femelles, autonomie alimentaire de l'exploitation, utilisation durable des parcours). L'applicabilité de leurs équations et de leurs représentations conceptuelles aux systèmes de petits ruminants est discutée. L'hétérogénéité du troupeau et des ressources fourragères, mais aussi la variabilité des ressources entre saisons et entre années, sont des éléments importants, car typiques des systèmes méditerranéens. Pour construire un modèle du système d'élevage, il est nécessaire d'une part, de définir des objectifs de modélisation en rapport avec les utilisateurs finaux, et d'autre part, d'avoir recours à des sources d'information complémentaires dont l'expertise d'acteurs de terrain.*

Mots-clés. *Modèle – Système d'élevage – Pâturage – Méditerranée – Petits ruminants.*

I – Introduction

A model is an abstraction which simplifies the real system, keeping only the components which are essential to the issue which interests the modeler (Coquillard and Hill, 1997). In this broad definition, the model is a description of reality oriented towards the resolution of a problem: before constructing a model, one should state a sound question.

Constructing a model enables to integrate knowledge about isolated components of a system in order to bring out its global functioning and its emerging properties (Lemaire *et al.*, 2005). During the last 20 years, considerable progress has been made in the understanding of biological mechanisms. To draw practical lessons, this knowledge often needs to be integrated at farm scale. Building a farm-scale model implies defining specific questions that can be appraised at this scale, and simplifying models built at smaller scales. In fact, the more complex the model will be, the more errors might be cumulated, and the more results might prove difficult to interpret due to the high number of parameters and equations.

Recently, research has made much effort to develop simulation models, especially at farm scale. Simulation consists in making a model evolve with time, which allows a better understanding of both the functioning and the dynamics of the system (Hill, 1993, in : Coquillard and Hill, 1997). Simulation models are useful to represent evolutionary trajectories or time-dependent interactions. Today, it can take only a few minutes to simulate the functioning of a farm or the evolution of a land for decades, while these scales of space and time are difficult to tackle with on-field experiments. Controlling the components of the system modelled enables to simulate extreme or innovative scenarios.

This paper examines the issues and requirements of simulation models designed for small ruminant systems in North Mediterranean areas. Due to the lack of published models for these systems, a few examples of existing models designed for other species and other geographic areas are presented. Their structure and objectives are discussed relatively to the issues of small ruminant systems. We end by proposing a conceptual and methodological framework to build models adapted to the characteristics of farming systems in North Mediterranean areas.

II – Major issues of small ruminant systems in Mediterranean areas

Small ruminant systems including a pastoral component are a major source of animal products and land use in Mediterranean areas (Bocquier *et al*., 2006). These systems exploit rangelands, which are poor and heterogeneous forage resources such as garrigue, shrubland or woodland. The income of farmers, despite subsidies, is low compared to their farm production sectors (Rancourt *et al.*, 2006). To secure their economic and environmental sustainability, farmers need to manage accurately the biological components of the system (animals, grassland and rangeland), in order to produce efficiently with minimum use of bought feed and fertilizer. When faced to biological, technical or socio-economic constraints, farming systems can adapt by changing the management rules and objectives, or by relying on the biological adaptations of the animals.

1. Take advantage of the adaptative abilities of the females without damaging reproductive performance

The ability of the animals to survive, grow and reproduce in a given environment plays a major role in the sustainability of livestock systems. The adaptative abilities of the females over seasons and years are most important, since they determine the number of offspring (through fertility, prolificacy and mortality) and their growth (through suckled milk yield). In Mediterranean systems, the high variability of forage production between seasons and years often results in periods of restricted feeding (insufficient quantity) or of relative underfeeding (insufficient intake due to low quality) occurring when the females have their highest nutritional requirements (*i.e*. pregnancy and lactation).

Two strategies of adaptative response to underfeeding can be interpreted from scientific observations on ruminant females (Blanc *et al*., 2006). The first gives priority to individual survival, with decreased milk production and long anoestrus periods, thus lowering or delaying the periods of high nutritional requirements. The second gives priority to maternal investment, with mobilization of body reserves in order to keep milk production high in early lactation, which is at risk for the survival of the female, but beneficial for its offspring. For a given species, the dominant strategy varies among breeds. A few breeds are well adapted to wintering outdoors and walking, and show good reproductive abilities and maternal behaviour.

In Mediterranean regions, feeding practices can rely on the ability of the females to mobilize and rebuild their body reserves. Up to certain limits, body reserves act as a buffer against the variability of feed resources (Molénat *et al.*, 1993). At the scale of the production cycle, it has been shown that mobilizing and rebuilding body reserves has a lower energetic cost than maintaining body condition constant (Atti *et al.,* 2004). In large flocks, a major issue is how to take advantage of this adaptative response without overcoming the limits of individual biological regulations, that is without compromising reproductive performance or survival. Other management practices aimed at securing flock production might include grouping the animals according to their physiological status (Bocquier *et al*., 1995) or accepting a lower performance for a part of the flock (Agus and Bocquier, 1995).

Simulation models taking into account the variability between individuals can help investigating the dynamic response (short, medium and long term) of adaptative processes to management decisions. The easiest way to introduce heterogeneity within a flock or herd is to simulate separately animal categories (ex. lactating *vs* dry females, young *vs* adult animals, males *vs* females…). While models of high-productive systems often concentrate on the animals directly related to the product sold (*e.g*. lactating females in dairy systems or young growing animals in feedlots), it is essential that models of extensive systems consider also the non-productive animals, which play a role in resource utilization (Jouven and Baumont, 2008) and in the long-term production at farm scale (Ingrand *et al*., 2002). Modelling the heterogeneity of individual performance is also useful in order to understand the dynamics of herd or flock production (Ingrand *et al*., 2002; Cournut and Dedieu, 2004). Since the mechanisms of biological adaptation are still under study, models can also be built and used to investigate them further (Blanc *et al*., 2006).

2. Secure system feed self-sufficiency with complementary forage resources

Feed self-sufficiency is a common objective among farming systems with a pastoral component, because : (i) feeding the flock on natural resources is much cheaper than harvesting or buying feed (Benoit *et al*., 1997); (ii) the production rules for protected geographical indications include the utilization of the pastoral territory (Quetier *et al*., 2005); and (iii) from an environmental point of view, aiming for feed self-sufficiency prevents from over-exploiting the natural resource, since feed production and animal requirements are balanced (Jouven and Baumont, 2008). The challenge of feed self-sufficiency is to find a dynamic equilibrium between the availability of the forage resource and the productive cycle of both ewes and lambs (Moulin *et al*., 2004). In Mediterranean areas, this requires a set of tactical (short-term) and strategic (long-term) management rules to adapt grazing management to the high variability of forage production, which mainly depends on climatic conditions.

In this context, management plays a major role. Conserved forage can be harvested during periods of high feed availability, and distributed in periods of low feed availability. Distant forage resources can be exploited directly with transhumance: in summer, moving to upper areas enables to avoid drought, and in winter, moving to lowlands enables to avoid snow. The association of complementary vegetation types (*i.e*. broad-leaved grasslands which produce high quality forage in the early season, fine-leaved grasslands which quality is maintained longer, and bushland or woodland which provide good quality feed and shade in the late season) can be an efficient means of increasing feed self-sufficiency (Guérin and Gaultier, 2004).

The management of the flock is often adjusted, in order to align the periods of high energy requirements of the flock with those of high forage availability, or to assign the best forage resource to the animals with the highest requirements (Bellon *et al*., 1999). In fact, if dry animals will usually cover their energy requirements at low forage availabilities, milk production might be reduced for lactating animals (Osoro *et al*., 2000). The flock can be divided into groups managed separately, according to their production objectives. If the resource is chronically insufficient to feed the flock, the production objectives (frequency of reproductive cycles,…) can be decreased for the whole flock or for a group.

Simulation models exist, which predict the daily functioning of the forage system and the responses of its biological components (animal and vegetation) in terms of production levels.

These models can help finding combinations of management rules which allow a high feed self-sufficiency, constant through years (Jouven and Baumont, 2008). Since the best solution might strongly depend on the environmental and socio-economic context (Lasseur, 2005), different scenarios should be tested and discussed with farmers and advisory services.

Most of the existing models have been developed for high-productive systems based on improved pastures (Cacho *et al.,* 1995; Coléno and Duru, 1999; Delaby *et al.,* 2001) or at least grass-based sytems (Moore *et al.,* 1997; Baumont *et al.,* 2002a; Romera *et al.,* 2005abc; Jouven and Baumont, 2008). Very few models include shrub vegetation, which growth would be difficult to model mechanistically (Milne and Sibbald, 1998). Both spatial heterogeneity and shrub vegetation are essential to small ruminant farms, and need to be investigated further in order to produce models suited to pastoral systems.

3. Ensure a sustainable use of forage resources, and especially rangeland

The utilization of Mediterranean rangeland by small ruminants is a useful protection from fire risk, and a way to maintain social and economical dynamism in rural areas (Rancourt *et al*., 2006). Preserving rangeland from fire and encroachment serves also biodiversity conservation and nature-oriented tourism. From an agricultural point of view, repeated under- or over-utilization of portions of rangeland might lead to a decrease in the abundance and quality of the forage resource for animal production (Balent *et al*., 1999). For these reasons, a sustainable use of Mediterranean rangeland should be based on a moderate and homogeneous utilization by grazing, in order to avoid localized risks of degradation.

Herbivores are able to exploit heterogeneous resources such as rangelands (Meuret, 1997; Agreil *et al*., 2005). In order to meet their nutritional requirements, they are able to graze selectively areas and plant parts which provide abundant and/or high-quality feed, and to increase their feeding time, their intake rate within a meal or the number of meals (Baumont *et al*., 2005). Selective behaviour depends on animal species, and might depend on breed and physiological status (Rook *et al*., 2004). It is the result of a learning process with peers, and especially with the dam (Dumont and Boissy, 1999). In large paddocks, these adaptations and the spatial utilization of the feed resource are constrained by group forces (social attraction, leadership, dominance) and by the distance to water (Bailey *et al.,* 1996). Management and equipments (water points, fences, feed supplementation) can impact the spatial distribution of grazing (Bailey, 2005).

Simulation models can predict the distribution of grazing pressure through time and space, and therefore help identifying the risks of rangeland degradation. A few models differentiate between species or plant parts within the vegetation of a paddock (Armstrong *et al.*, 1997a ; Moore *et al.,* 1997; Jouven *et al*., 2006a) and use this typology to predict selective grazing (Armstrong *et al*., 1997b ; Freer *et al.*, 1997; Jouven *et al.*, in press). Those models can predict the distribution of grazing pressure between paddocks. Very few models (Baumont *et al*., 2002a; Chirat *et al*., 2007) spatialize this heterogeneity within the paddock, because it requires modelling a high number of vegetation units but also the movements of the flock or herd, which depend on social behaviour, memory and feeding preferences. Mechanisms of animal behaviour are not fully known, and modelling can also help testing functional hypothesis about them (Dumont and Hill, 2001).

III – A few examples of models dealing with similar issues

1. A model of the functioning of a suckler herd with emphasis on nutrition x reproduction interactions

SIMBALL (SIMulateur de Bovins ALLaitants, Ingrand *et al.*, 2002, Fig. 1) is a model of the functioning of the suckler beef herd designed as a decision support tool for extension services and breeders. Its objective is to evaluate the impact of changes in the management rules, on animal performance, herd composition and marketing distributions. These changes may occur either within a particular production project or during a shift from one production project to another. A production project is defined by specific objectives regarding the categories, proportions and periods of animal marketing.

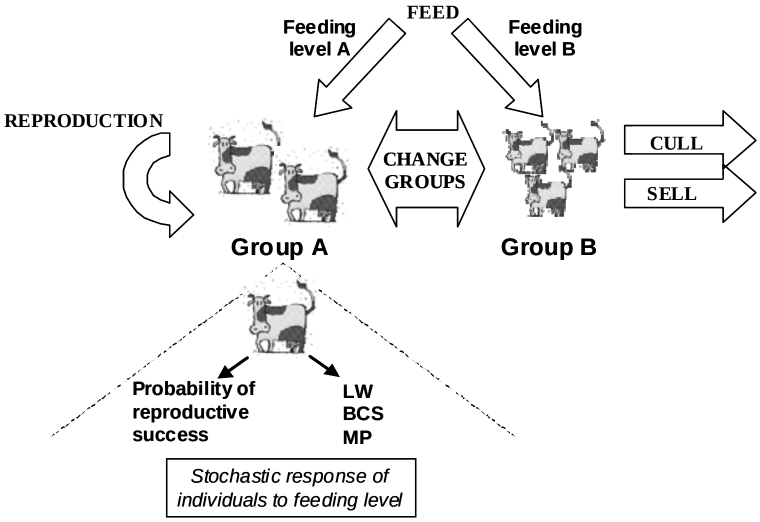

Fig. 1. Conceptual model for SIMBALL. The herd is divided into groups, where each animal is characterized by its state and potential performance. Management rules act upon group composition, feeding level, reproduction, culling and sales. LW: live weight, BCS: body condition score, MP: milk production.

The model is made of a biological sub-model, representing the animals, and a decisional sub-model, representing the farmer. The biological sub-model (Agabriel and Ingrand, 2004) predicts the body condition score, milk production, and reproduction (cyclicity and fertility) of the cows, and the growth of the young cattle (calves, steers and heifers), depending on the level of energy intake. To simulate heterogeneity within the herd, animal performance comprises a stochastic component. The decisional sub-model manages two cohorts of animals: the females, which are given a calving date, and the products, which are given objectives in terms of number and categories of animals sold. The level of energy intake is set for winter and summer. Management rules include criteria for culling cows and keeping replacement heifers. Given these rules and the initial state of the herd, the drift through years of marketing distribution and herd composition is predicted.

A first prototype of the model was built for research purposes, but has not until now been extensively used. The statistical distributions of animal performance were tested against available data, and a few outputs (culling rates, calving distribution based on feeding level) were validated by experts and compared to reference data from experimental farms and farm surveys. A second prototype, based on case studies and designed as a decision tool, is being built. In this objective, management rules have been refined and management scenarios have been identified with 12 farm surveys in the Charolais breeding area (Ingrand *et al*., 2003). SIMBALL is used in a training course for master students to introduce them to systemic modelling and to evaluate the discrepancies between farmers' practices and recommendations (Agabriel *et al*., 2007).

SIMBALL focuses on the relationship between system performance (distribution of marketed animals) and management of animal groups, and considers explicitly the heterogeneity of animal performance within the herd. The issue is of high interest for breeders, who are asked to produce year-round homogeneous groups of animals. Though, given the complexity of the actual version of the model, it is best suited for research purposes, among which testing the impact of the adaptative abilities of the females (productive and reproductive responses to feeding levels). The repeated interactions with farmers and extension services during model development should help discussing the results with field actors. In this perspective, a subsequent study has been undertaken in order to formalise the information system of beef cattle farmers (*i.e*. understand what type of information they mobilise, where and for what purpose) (Magne and Ingrand, 2005).

2. A model of the farm-scale dynamics of grassland utilization by the herd

SEBIEN (Simulateur d'Elevages Bovins en Interaction avec l'ENvironnement, Jouven and Baumont, 2008, Figs 2 and 3) is a deterministic model of the forage system designed to stimulate discussions between researchers and extension services about sustainable utilization of grassland in beef suckler systems based on permanent pasture. The objective is to understand how management and farm structure (grassland types, size and composition of the herd) influence system production and floristic diversity at farm scale. The model was designed and calibrated for the area of Massif Central, France.

The functioning of the forage system is predicted at a daily time scale, with simulation runs lasting 1 to 10 years. Paddocks, animal groups and animal categories within groups are the management units. The model is made of three sub-models which interact at multiple time scales. The grassland resource sub-model (Jouven *et al*., 2006a) predicts grass growth and quality at the paddock level, from soil quality, vegetation functional traits and climatic data. The animal sub-model (Jouven *et al.*, in press) calculates selective intake at pasture from the biomass and digestibility of plant parts. It also predicts weight gain and milk production from energy intake, for each animal type within each group. These biological sub-models have been tested with sensitivity analysis and validation on experimental data (Jouven *et al*., 2006b; in press). The management sub-model comprises a strategic component (management plan) and a tactical component (management rules). Herd management works mainly on a preplanned schedule. Utilization of paddocks is also planned, but can be revised at fixed dates depending on the total grazeable herbage on the farm. Management rules adjust feed availability for the herd, through grazing rotations, hay harvests, and supplementation with forage and concentrate to achieve production objectives (calf weight at sale, cow body condition score at calving). The management sub-model, based on farm surveys, has been validated by experts.

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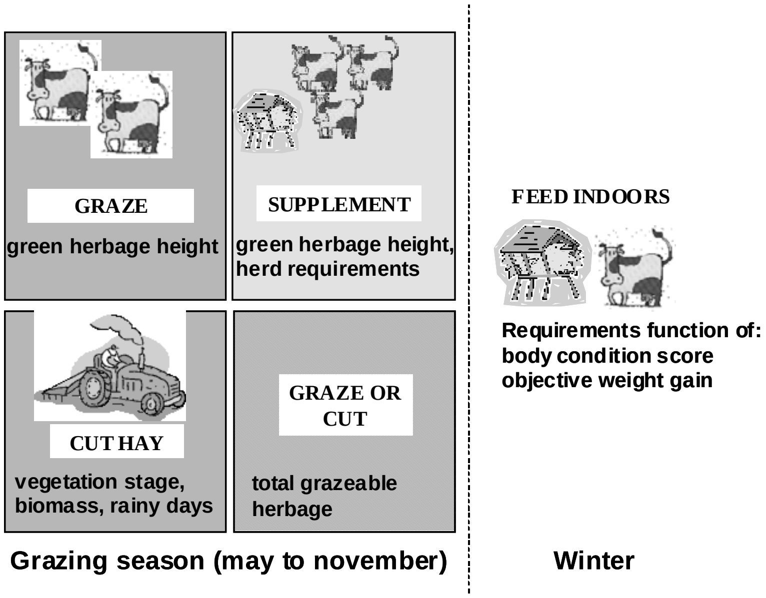

Fig. 2. **Management of the herbage resources (divided into paddocks) and of the herd (divided into groups) in SEBIEN. During the grazing season, the height of green herbage determines grazing rotations and supplementation of animal groups. The herbage is cut depending on sward state and climatic conditions; the surface cut can be modified if there is too much or too little herbage available for grazing. The conserved forage is fed to the herd mainly in winter, as a function of animal production objectives.**

SEBIEN has been used to test biodiversity-friendly management rules such as late hay harvest and low grazing intensity, for three case studies based on real farms (Jouven and Baumont, 2008). To characterize the production-biodiversity trade-offs at farm scale, model outputs were converted into an indicator of system production based on animal sales and forage self-sufficiency, and into an indicator of floristic diversity based on soil fertility and grassland utilization rates on each paddock. Results showed that the balance between grassland productivity and stocking rate was determinant for both biodiversity conservation and forage self-sufficiency. For all farms production remained unchanged when intermediate levels of biodiversity-friendly management rules were applied, but the pattern and amplitude of the responses differed between farms. At farm scale, an increase in floristic diversity on a few paddocks sometimes led to a decrease on other paddocks, which confirms that farm-scale analysis are needed to evaluate the effects of field-scale environmental policies. The model has recently been used to investigate the impact of the frequency and distribution of dry climatic years (unfavourable to grass production) on the forage system of a typical farm. After analysing model predictions for animal production and grassland utilization dynamics, changes in cutting and grazing management were tested in order to improve system resilience to climatic variability (Baumont *et al.,* 2008). In this set of experiments, the model was used beyond its initial scope, which implied modifying a few equations.

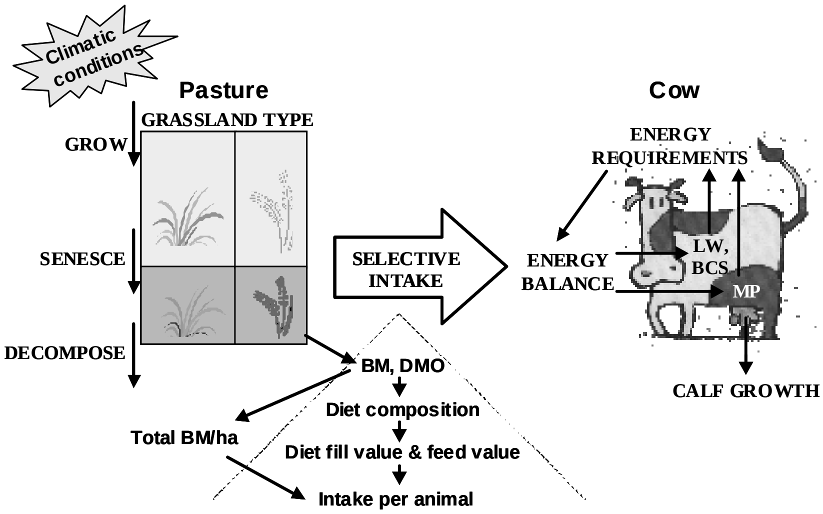

Fig. 3. Biological sub-models in SEBIEN. The biomass, structure and quality of herbage on each paddock depend on grassland type, climatic conditions and defoliations. The animals ingest selectively plant parts in relation to their abundance and digestibility. The energy balance of the animals determines their state and performance the following day.

SEBIEN focuses on the dynamics of forage utilization at farm scale, for all seasons, in situations where grassland resources are heterogeneous between paddocks. It develops a simple representation of farm functioning, with technical variables easily understandable by extension services and farmers. In this objective, the construction and validation of the model were based on farm surveys, and punctuated with meetings between researchers of different disciplinary fields and extension services. A rather detailed representation of the biological components was chosen for research purposes. A real effort of validation was made, because the objective was not the model itself, but model use and the discussion of model predictions with field actors. Model precision was estimated for the biological sub-models, and the validity domain of the whole-farm model was described. Given the many underlying hypothesis, and the site-specific calibration, model predictions can be compared and discussed between simulated scenarios, but are probably not directly applicable to the field.

3. A model of the spatial utilization of heterogeneous grasslands at paddock scale

PARIS (PAsture – Ruminant Interaction Simulator, Baumont *et al*., 2002a b; Carrère *et al*., 2002, Fig. 4) is a spatial multi-agent model of plant-animal interactions designed for researchers. The objective is to gain understanding about the impact of ruminants on the evolution of semi-natural grasslands, and about how to control it with grazing management (paddock size and shape, intensity and frequency of grazing).

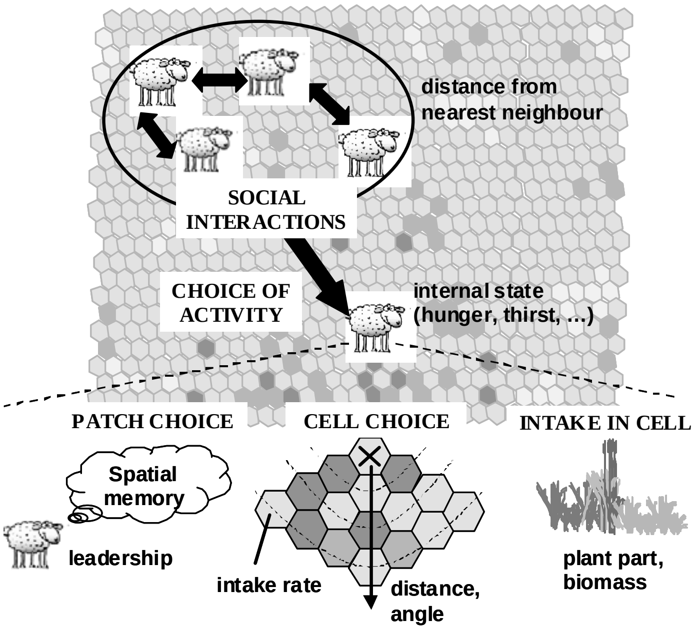

Fig. 4. Conceptual model for PARIS. Social interactions determine the dispersion and position of the flock. The internal state of the animals influences the choice of activity. When the activity is grazing, each animal chooses a cell in its visual field, and ingests selectively plant parts. The leader animal possesses spatial memory and induces long movements towards preferred patches.

The animal-plant interface is modelled at small spatial and temporal scales: vegetation heterogeneity is assessed with cells of 0.1 m^2 and animal behaviour is predicted individually, for sequences of a few minutes. The model is composed of three sub-models: (i) the vegetation sub-model simulates the growth and evolution of the grass cover in each cell; (ii) the animal sub-model simulates the physiological functions (intake, digestion) and the proximate feeding choices (cells grazed); and (iii) the flock sub-model simulates the spatial utilization of the paddock depending on social interactions (leadership, group cohesion) and spatial memory. The vegetation sub-model has been validated at paddock scale (1 cell = 1 paddock) in the context of the whole-farm simulator SEBIEN (Jouven *et al*., 2006b). The physiological functions of the animal sub-model had been previously validated with experimental data about feeding patterns of sheep fed hay indoors (Sauvant *et al*., 1996). The feeding choices have been validated for sheep with experimental data about short-term (30 min) binary grazing tests (Baumont *et al*., 2002b). Sensitivity analysis has been performed on spatial memory and social interactions, and the acquisition of memory within the first days on a paddock has been tested against experimental data about individual sheep searching for pellet bowls scattered in a pasture (Dumont and Hill, 2001).

PARIS has helped testing hypothesis about feeding choices (predicted cell choices based on intake rate were closer to observations compared to those based on green leaves content), identifying research questions which are now tackled with field experiments (*e.g.* the effect of plot size x stocking rate on the spatial utilization of a paddock). Once the simulator will be validated as a whole, it will be used to analyze the biological processes which explain the spatial utilization and the dynamics of vegetation under different grazing regimes. The effect on grassland utilization of paddock size, spatial distribution of vegetation sites and animal characteristics such as live weight, gregarity and selectivity, will be tested.

PARIS considers explicitly the spatial heterogeneity of the vegetation, and the spatial pattern of grazing, which are both of high interest in the objective of a sustainable utilization of grazing lands. This simulation model might prove difficult to use as a whole because of its complexity and because of the small scales simulated. To obtain average results, many simulations have to be run because several variables in the model are stochastic. Though, the model and its sub-models remain interesting and useful as research tools. The results of simulation experiments could help detecting the major variables influencing the grazing patterns. These variables could thereafter be used as indicators for grazing management, or included in a simple model adapted to extension services.

IV – Conceptual and methodological framework for modelling small ruminant systems in Mediterranean areas

1. Characteristic features of small ruminant systems and consequences for a modelling approach

A. Heterogeneity within large flocks

Small ruminant systems involve large numbers of animals; in France, flock size would usually range 200-2000 sheep, while herd size would rarely exceed 100 heads. In large flocks, with limited human intervention, the variability of animal production can be high, especially when feed resource is scarce and reproduction is not controlled with hormones. The heterogeneity of animal performance within the flock can be explained by inter-individual differences in: (i) genetic production potential; (ii) feeding behaviour (in relation to the knowledge of the environment); and (iii) amplitude of the adaptative response to feeding levels. Points 2 and 3 might vary according to the age of the animal. These factors strongly impact the amount and the distribution of the animal products sold and thus farm monthly income.

Individual variability has been introduced in simulation models with stochastic functions modifying randomly the biological response within a range of possible values (Ingrand *et al.,* 2002 for cattle; Cournut and Dedieu, 2004 for sheep). The weakness of such procedure, especially if based on a mechanistic approach, lies in the difficulty of calibrating the input parameters for each individual, and of interpreting the mass of outputs. An alternative solution could be to model heterogeneity between groups of animals. This has also been done in previous models, but has often raised the problem of limited data and equation availability to build intake and growth functions for non-productive animal categories (*e.g*. replacement lambs). Although the diversity of animal performance can be considered as a characteristic feature of Mediterranean small ruminant systems, its impact on predictions might strongly depend on the modelling objectives (variables considered, scales of time and space). As a rule, a complexification should not be introduced in a model unless it improves predictions substantially in relation to the utilization objective.

B. Spatial heterogeneity of the forage resources

In pastoral or agro-pastoral systems, the forage resource is very heterogeneous, with highly productive cultivated fields and low-productive rangelands, which are themselves spatially heterogeneous and might contain shrubs and trees (Fig. 5). The vertical and horizontal distribution of the vegetation determines the accessibility of the preferred forage resource to the animals. The relative abundance and quality of the various components, which vary with seasons and defoliations, influence animal feeding preferences (Dumont *et al*., 1995; Osoro *et al*., 2000). Adjusting the diversity of the forage resource to the dynamics of animal feed requirements is considered as a crucial adaptation to climatic variability and as a way of reconciling animal production with sustainable utilization of rangelands.

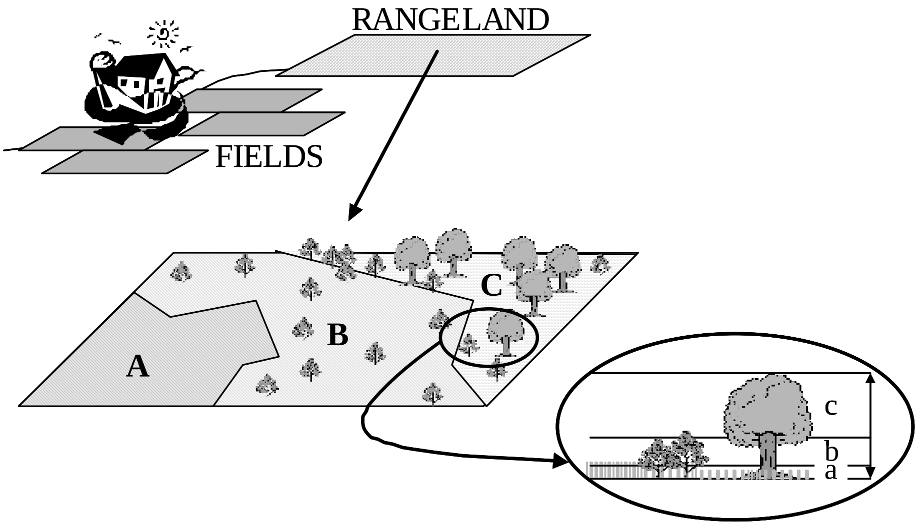

Fig. 5. Scales of resource heterogeneity in agro-pastoral systems. Resources are composed of fields (cultivated in different species or cultivars) and rangeland. Rangeland is spatially heterogeneous due to the coexistence of vegetation types (A, B, C) differing in species composition and abundance of ligneous species, and to the vertical distribution of forage resource: grass and fallen fruit in the lower layer (a), leaves and fruit of bushes and trees in the upper layers (b and c).

The heterogeneity of the forage resource, and especially that of rangeland, has been modelled either simply, with separate growth equations for resource components such as grass and shrub vegetations, or with complicated ecological models predicting the life cycle of each species. A detailed approach to resource heterogeneity and dynamics would be best suited to small spatial scales (< whole farm), to research models aimed at understanding mechanisms, and to utilization objectives focussed on the response of vegetation communities to different grazing management. Conversely, an integrated approach considering macro-heterogeneity within or between paddocks would be best suited to whole-farm models aimed at simulating the functioning of the forage system in response to grazing (and cutting) management. The level of detail should be coherent with that of the animal component : in the first case, animals would be modelled individually (see Arsenos *et al*., 2000 for an example where animals vary in their requirements, ability to discriminate feed and selectivity); in the second case, considering groups of animals or the flock as a whole would be sufficient.

C. Temporal heterogeneity of the forage resources

Mediterranean areas are characterized by summer drought and by a high variability of climatic conditions, and thus of forage production, between seasons and years. This raises two practical questions for simulation models. First, most existing models of forage growth are not adapted to extreme climatic conditions, because they do not consider explicitly plant reserves and seed dynamics. To solve this problem, either complex mechanistic models can be built (see Moore *et al*., 1997) or rangeland production can be modelled empirically and variation can be introduced with stochastic functions. Second, management needs to be flexible, with rules modifying system functioning depending on the current state of the herd and of the forage resources. This aspect has been investigated in previous models for cattle (Andrieu *et al.*, 2007; Jouven and Baumont, 2008), which conceptual framework should be easily applicable to small ruminant systems although the content of the management rules might be different.

2. Specifications of the models depending on the users

In a research context, models are a means of integrating current knowledge, and of producing new knowledge by testing functional hypothesis. Conceptual modelling describes the point of view of the scientist on the system studied; simulation models are useful to study time-dependent interactions. A simulation model for research is mainly aimed at understanding processes. Therefore, mechanistic models with many input parameters and output variables, which enable to monitor tightly system functioning, are preferred. An easy interpretation of model outputs, the precision of model predictions and their applicability to the field, are secondary. The construction of the model is an objective per se, which increases the knowledge of the modellers, points out gaps in the understanding of the system and stimulates exchanges between disciplinary fields.

The issues are different when simulation models are constructed as teaching aids for students or decision support systems for farmers and advisory services. Moulin *et al*. (2004) argue that in most cases, research models are not suited to pedagogic goals. Simulation models for students should be flexible and simple, focused on one pedagogical objective and easily understandable in a short period of time. Such models are useful as teaching tools because they enable a quick understanding of biological mechanisms. Students can explore system behaviour, or even take part to model construction, which helps them having a critical view of model predictions (Moulin *et al*., 2004).

Sterk *et al*. (2006) analyzed farmers position about a few whole-farm models built to help them exploring alternative, promising farming systems (in the Netherlands). They found that simulation models designed as decision support tools were often not based on specific objectives, were not adapted to answering farmers' questions, and were ready too late. The function of such tools is called into question, when farmers declare to be more interested in discussing and comparing their practices and results with other farmers, rather than exploring new management practices though simulation (Sterk *et al*., 2006). Therefore, models for farmers should be simple and use variables readily understandable by professionals, in order to stimulate discussions. Since individual farms and production objectives vary widely among farmers, the issue is to show the range of possible technical results (*e.g*. conciliating production and environmental objectives) rather than to support technical solutions.

3. Possible sources of information at each stage of model development

Models of farming systems make reference to different fields: animal and plant science for the biological functions, technical knowledge for the management of the flock and the forage resource. Therefore, different sources of information (research and field experts, existing equations, farm surveys, experimental data) should be mobilized at each stage of model development (Fig. 6).

Ideally, the objectives of the model and its requirements should be defined with the final users. For example, if a model is intended for extension services, the input parameters, the output variables and the aimed validity domain should be discussed with extension services, in order to ensure that the final product will meet their expectations, and therefore be useful. Discussions with experts and farmers are advisable during the development of the conceptual model, to ensure that the essential entities and interactions have been taken into account.

The construction of the model includes putting together biological equations and technical operations in a dynamic time frame, and calibrating them. Equations can be either adapted from published references, or constructed based on experimental or field data. Technical operations and the timing of their application can be discussed with extension services and with farmers. The latter can participate indirectly through farm surveys, or directly by giving their opinion on the model and its behaviour.

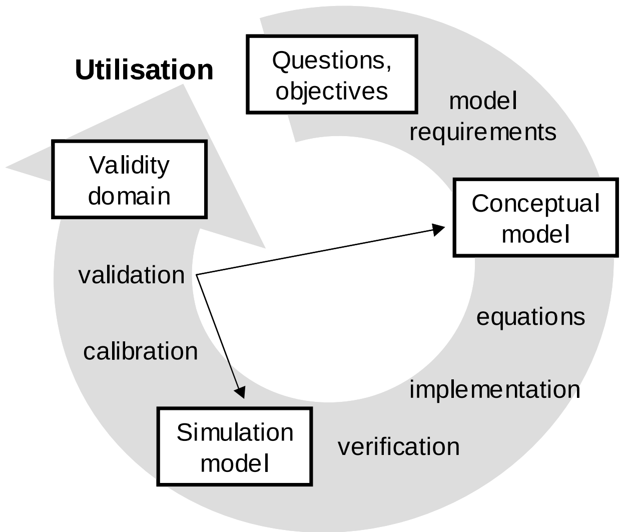

Fig. 6. Stages of model development (simulation model).

Model validation is aimed at determining whether or not the simulation model [of the farming system] is adapted to its utilization objectives. It consists in a series of tests to evaluate model quality, which includes (Scholten and Udink ten Cate, 1999): (i) meeting model specifications (correctness); (ii) performing the intended function with the required precision (reliability); and (iii) little effort required to learn, operate, prepare input and interpret output (usability).

A non-correct model would miss important entities or interactions in the representation of the system, or would not be able to reproduce its typical behaviour. A non-reliable model would have utilization objectives out of its validity domain, or would predict system functioning with an unacceptable amount of error. A non-usable model (common pitfall in research models) would be understanded almost only by the modeller, would include input difficult to fill in based on field data, or would be too complex to allow easy interpretation of output. Model correctness and reliability can be assessed using validation techniques such as sensitivity analysis (study of model behaviour in response to sequential variations of one or two parameters at a time), validation based on experimental data (statistical comparison of experimental measures and model predictions in similar conditions) and validation based on expert opinion at the scale of the farming system. Usability needs to be tested directly with a representative sample of users.

Conclusions

Modelling small ruminant systems in Mediterranean areas should help answering technical questions related to the following issues: (i) taking advantage of the adaptative abilities of the females without altering their reproductive performance; (ii) securing the feed self-sufficiency of the system by exploiting the diversity of forage resources; and (iii) ensuring a sustainable use of rangelands.

Very few published models deal with small ruminant farming systems in Mediterranean areas. The common theme of models dealing with similar issues (but for other species or other areas) is to analyze the relationship between decision making and flock or resource heterogeneity, at different scales of space (animal, animal group or paddock, whole-farm) and time (day, grazing season, year, decade). These aspects are of major importance for Mediterranean farming systems, which are characterized by large flocks and exploit a diversity of forage resources, which quality and abundance vary widely with time, and should therefore be taken into account during model development.

The content and form of the model will strongly depend on the final users and their demand. Whereas the construction of complicated mechanistic models can be a research objective per se, model utilization becomes most important for pedagogic goals and to support technical discussions. In these objectives, simulation models are interesting because they enable to test scenarios and to discuss possible options. The precision of model predictions for field use is often not the most important criteria. It is secondary compared to the user-friendliness of the simulation tool, which includes few inputs easy to collect, an unambiguous utilisation procedure and few easily-understandable outputs.

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