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Original article

A biophysical dairy farm model to evaluate rotational grazing management strategies

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Abstract – This paper describes a biophysical dairy farm model developed as part of the SEPATOU system that simulates pasture-dominated feeding strategies in a dairy cow enterprise. It can reproduce the effects of various technical management options applied to a set of grazing fields on a daily basis over a period of several months. The model is made up of three submodels that deal with the soil (availability of water), sward and animal (cow intake and milk yield) components. It includes as driving variables the main factors that farmers can control (nitrogen fertilizer rate, defoliation frequency and intensity, composition of cows' diet) in order to attain some objectives such as the intended grazing herbage contribution in the cows' diet or the amount of milk produced per cow or per ha. The intended purpose of the SEPATOU system has led to several original developments. In order to simulate various defoliation regimes, growth and senescence processes are dissociated as there is no longer synchronization between them, and the effect of grazing intensity is expressed in terms of the ratio between the herbage mass after and before grazing. The animal intake submodel that can deal with mixed feeding combines two approaches, one based on energy requirements and the other on the relationship between herbage mass, herbage digestibility and intake. The model of herbage digestibility is based on herbage mass and takes into account its variation down the sward profile; this latter aspect plays a key role in the plant–animal interaction. The model has been validated using typical farm cases in Brittany. It provides realistic estimates of the state variables involved in the processes, such as herbage mass and daily milk yield, and it credibly predicts the timing of key events (e.g. date of turnout to grass, end of first grazing cycle).

simulation / decision / pasture / dairy cow

Résumé – **Un modèle biophysique d'atelier laitier pour évaluer des stratégies de conduite du pâturage tournant.** Cet article décrit un modèle biophysique développé pour le système SEPATOU qui simule l'application de stratégies d'alimentation d'un troupeau de vaches laitières, en particulier la gestion du pâturage tournant. Il peut reproduire sur une base journalière les effets du climat et de différentes opérations techniques résultant de l'application d'une stratégie de conduite sur un ensemble de parcelles pâturables durant une période de plusieurs mois. A cet effet, trois sous-modèles sont articulés : (i) le sous-modèle sol permet de simuler un indice de déficit hydrique ; (ii) le sous-modèle plante comprend un module de croissance fonction du niveau de nutrition azotée et du climat, un module de sénescence fonction de la biomasse résiduelle et un module d'évaluation de la digestibilité ; (iii) le sous-modèle animal permet de simuler les quantités ingérées en fonction des quantités d'herbe offerte et de sa structure. L'utilisation souhaitée du système SEPATOU a nécessité le développement de nouveaux modèles des processus biophysiques de croissance végétale (quantité et digestibilité) afin de rendre ceux-ci réactifs aux décisions de conduite telles que l'intensité de prélèvement par parcelle et de fréquence de rotation sur les parcelles. D'autre part, le besoin de simuler des alimentations mixtes (ensilage de maïs et herbe pâturée) au cours d'une journée a demandé certaines avancées sur la modélisation des processus d'ingestion animale. Le modèle a été mis à l'épreuve sur des cas types d'exploitation en Bretagne. Il fournit des estimations réalistes des variables d'état des processus biophysiques (par exemple, la quantité d'herbe disponible par parcelle ou la production laitière quotidienne) et des dates d'occurrence d'événements importants tels que la mise à l'herbe ou la fin du premier cycle de rotation sur les parcelles pâturées.

simulation / décision / prairie / vache laitière

1. INTRODUCTION

The economical viability of agricultural production systems depends more and more on the ability of farmers to cope with technical, social and economic pressures from increasing competition, new environmental targets, and increasing consumer requirements [1, 42]. The need is particularly relevant for French dairy enterprises because in

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many areas grazing can to some extent replace feeding of maize silage [59], thereby reducing pollution risks, at least during the period of rapid grass growth [68]. Moreover, grazed grass is less expensive than maize silage and presents a more attractive image of dairy produce to consumers [57, 74]. The current heavy use of maize silage can be explained by economic influences such as grants for maize silage. Another reason stems from the management difficulties associated with grazing. It is particularly hard to determine in advance appropriate rates for nitrogen fertilizer, amounts of hay or silage, the area to be allocated per cow and rotation policy. In order to obtain target milk output per cow, energy intake per cow needs to be high and regular, whereas the available amount [54] and quality [37] of grass are very sensitive to weather and sward management, particularly grazing pressure and rotation length. These difficulties may have contributed to the decline in the use of grazing for feeding cows [5].

Achieving objectives and controlling risks in a grazing system cannot happen by chance. It is necessary to devise and apply a coherent management strategy defined as a set of planned tasks adaptable to unforeseen weather changes. A complete strategy would indicate how to make decisions successively throughout the production period, depending on the situations encountered. Building satisfactory management strategies depends on the ability of farmers to anticipate the outcomes or consequences of a set of operational decisions under conditions of uncertainty [66]. We have developed the SEPATOU simulation model in order to describe the complex relationships and interactions between decision choices (e.g. turnout date, length of mixed feeding period, residual sward mass target), climatic factors and production performances such as the milk yield [8] and to support learning and elucidation of these interactions by trial and error. This software enables the dynamics of two interactive processes to be reproduced: the decision process that implements the management behavior of the farmer and the biophysical process that concerns the dynamic response of herbage and milk production to climatic factors and situation-dependent management operations (see [41] for an example of a related project). SEPATOU has been designed for use by grazing experts as a means of training extension agents (or dairy farmers) in the operational management of rotational grazing systems and helping them test and therefore discover innovative management strategies. By providing the opportunity to formulate alternative management behaviors and dairy farm configurations SEPATOU allows virtual experimentation that can serve as a tangible basis for discussion of issues and as a way of making understandable the complexity of interactions between pasture, animal and management. This capability makes it valuable for disseminating knowledge and improving management practices empirically. SEPATOU does not aim to support on-farm decision-making for any particular farm but rather to provide a comprehensive view of the impact that management decisions might have on typical production systems considered over a given season and under differen weather scenarios. No attempt is made to match very closely any existing system, which would require an extremely intensive modeling and data collection effort; the modeled production systems are artificial representative examples of real cases that are slightly simplified but realistic as regards management.

This paper is devoted to the presentation of the biophysical model underlying the SEPATOU system [10]. Given a set of grazing fields and a dairy herd it enables the day-to-day dynamics of biophysical processes such as herbage growth and senescence or cow intake and milk production to be simulated. This model integrates existing and new submodels, either process-based or empirical, and tailored to the simulation task that covers a several-month period from February to the end of July. The model must provide realistic estimates of the variables involved in the processes, which include for instance the daily milk yield, the intake of the different feed types and the herbage mass and digestibility on each field. Beside playing a role in the biophysical mechanisms at work these variables might also be subject to requests by the decision system if relevant to the making of a decision. When analyzing the simulation results they may also be involved in the evaluation of the management strategy applied. Also of primary importance is the ability to compute the dates of occurrence of key events such as the turnout to grass, the start of night and day grazing and the end of the first grazing cycle, that are functions of biophysical state conditions. These events happen as a consequence of the management strategy applied to the biophysical system. In other words, the biophysical system must respond convincingly to management operations and environmental factors in such a way that it can interact with the decision system and enable the value of management strategies fed into the decision system to be assessed. The validity of the model is judged by its ability to behave realistically in typical farm reference cases according to the judgment of a panel of experts.

Many papers [67 and 71, for example] have been published on grassland models which address only the herbage growth or vegetation dynamics aspects. Few grazing models [16, 18, 34 and 80, for example] dealing with the plant/animal interaction are reported in the literature, especially when the aim was concerned with management issues. The originality of the biophysical model of the SEPATOU system lies both in its purpose – to support the investigation of realistic management practices – and in the herbage growth and animal intake submodels that have been designed to cope with the possible range of situations encountered particularly in a French dairy farm management setting. The novel aspects of the biophysical model and rationale behind the modeling choices are surveyed in Section 2. Section 3 is dedicated to the detailed presentation of the model. The validation issue is addressed in Section 4.

2. SPECIFICITY AND JUSTIFICATION OF THE MODEL[1]

2.1. Design features and assumptions

Like many models, SEPATOU is an abstraction and a simplification of reality, determined by the objectives of the

[1] From now on, when there is no ambiguity the word “model” stands for “biophysical model”.

project. Unlike most typical research models that focus on understanding a limited number of physiological or ecological processes, the present model is on a farm scale and integrates knowledge from different areas of expertise (crop science, animal science, farming systems research) and from a farm management perspective on the seasonal scale (from the end of winter to mid-summer). The highest level the SEPATOU simulator operates at is the grazing system, that is, the farm level. The lowest levels in the model are the plots and the cows that constitute a single mob. Having more than one hierarchical level below the level of immediate interest (i.e. grazing system) would not necessarily serve the purpose any better because it leads to greater complexity [71]. Thus, we aimed at developing summary functions that combine several elementary processes into a single equation when appropriate. For example, photosynthesis, respiration and assimilate partitioning involved in the main processes of herbage growth have been merged, whereas growth and senescence processes have been separated to allow the simulation of contrasting defoliation regimes.

The choice of the processes to be modeled, the management variables to be considered and the level of detail must be determined by the intended use of the simulation model. Consequently, the model includes as driving variables the main factors that farmers can control (nitrogen fertilizer rate, defoliation frequency and intensity, composition of cows' diet) in order to attain some objectives such as the intended grazing herbage contribution in the cows' diet or the amount of milk produced per cow or per ha. Since the strategies to be evaluated refer to state variables, the model must provide accurate enough information about their current values. For grass growth as well as for animal intake we have therefore avoided static models (e.g. [40]) which, by definition, do not contain time as a variable and cannot make time-dependent predictions. The model must be able to react dynamically to external stimuli and to actions prescribed daily by the decision system. The main structural components of the dairy enterprise are herd, grass paddocks, available feedstocks at the end of winter (maize silage and hay) and inputs (concentrate and nitrogen fertilizer). Only fields which can be grazed are considered: plots used exclusively for silage or hay are not included. In other words, the model deals with a set of plots that can be used for grazing if necessary or else harvested, enabling management strategies exploiting such flexibility in the grazed area to be studied. The model is deterministic, although it responds to weather which can be generated randomly in simulation experiments.

Making the biophysical model as simple as possible is a design principle that has been followed as much as possible to facilitate model parameterization. It would be unwise to model some biophysical processes in great detail if the parameters involved could not be obtained in current conditions. This is the case of soil submodels that compute the soil water balance on the basis of water flow across hydraulic gradients. Using a more empirical model as in [59], requiring soil parameters for several soil layers (field capacity and wilting point) would still not be ideal, because the typical expected users usually only have estimates of these parameters for the whole soil profile. This is why we have used a simpler soil model than those currently found in the literature.

Modeling N uptake can potentially raise a similar parameterization difficulty in cases of large gradients in soil characteristics (soil texture and organic matter content). Soil nitrogen transformation models are classically based on N mineralization and reorganisation rates [82]. This requires parameters that are not easily obtained in actual situations at the farm level. Moreover, some of the soil processes involved are still incompletely understood; the after-effect of grazing management is difficult to take into account [27, 38, 81]. Consequently, we did not use a dynamic soil submodel linking the amount of N uptake to soil characteristics and the amount of N supply. Instead we have used an expertise-based and site-specific model that remains compatible with the intended use of the model.

Some restricting assumptions are made for the sward and animal components in order to stay within the current bounds of well-established scientific knowledge: the sward is a pure stand and each grazed plot is assumed to be uniform; all the cows are assumed to be identical, i.e. of the same weight, genetic potential for milk production and calving date. Consequently, there is only one herd in the model. The full herd is assumed to be allocated to a single grass plot for at least one full day, and usually for several days. Grazing two plots in one day is not possible. The grazing pressure (number of cows per ha) is assumed to be large enough to ensure uniform grazing over the field. Low grazing pressure could induce some heterogeneity in sward structure which is beyond the of scope of the study associated with this model (such aspects could possibly be dealt with using, for instance, some results of Parsons [54]).

Finally, the model incorporates some simplifications that concern aspects irrelevant to the kind of study it is designed to be used for. We have assumed that milk production only depends on energy fluxes since a pasture-based diet is rarely protein-limited. The period of simulation runs from 1 February to 31 July, on the assumption that the main problems for grassland management in France occur during this period.

2.2. Main processes in the model

We discuss below how the objective of the SEPATOU system led to requirements that the model should satisfy. From these requirements we derive what parts of published material could be kept and what had to be built from published data, new research results or expert knowledge. This section focuses on aspects that have been addressed especially for the SEPATOU system.

2.2.1. Herbage growth

The model should be able to simulate net herbage accumulation and herbage digestibility for swards submitted to a wide range of nitrogen rates and defoliation regimes, from high to moderate grazing pressure defined by variable grazing intervals and residual sward mass. We have chosen a model based on carbon balance [32, 69, 72] that is simpler than more mechanistic models based on the balance between structural or metabolic compartments, which include carbon and nitrogen partitioning (e.g. [67]). This type of model, which includes a radiation interception submodel and another for the

conversion of radiation into aerial biomass, has mainly been used for perennial grasses, but only for frequent defoliation regimes or high grazing intensity [3, 32]. Our model of the herbage growth process is similar to those elaborated in other works (see [4, 50], for example). However, variation in radiation use efficiency throughout growth is the net result of several processes (senescence, stem elongation, etc.) which are specific to a given species [53]. For grassland, as various defoliation regimes are possible, growth and senescence processes need to be dissociated as there is no longer synchronization between them. In other words, with either lenient or severe defoliation the growth rate is approximately the same whereas the senescence rate is significantly greater in the case of lenient defoliation. The parameters of growth submodels incorporate indexes to take into account the effects of nitrogen and water shortages on the one hand, and temperature threshold phenomena on the other hand. In order to take into account the effect of grazing pressure on net herbage accumulation, senescence is made dependent on residual sward mass. This differs from the approach taken in many grazing models [18, 52] where a constant grazing pressure is assumed. Some previous empirical studies have played an important role in shaping the approach to net herbage accumulation [20, 29]. Indeed, the herbage offtake on a given paddock leads to a sward structure that can fairly be conveyed by the residual leaf area index together with the residual herbage mass, that determine the growth rate and the senescence rate, respectively. Based on recent results showing an ontogenic relationship between sheath and lamina length [22], the effect of grazing intensity is expressed in terms of the ratio between the herbage mass after and before grazing. Alternatively, a ratio involving height before and after grazing could be used to decide when to move out grazing animals from a paddock.

2.2.2. Animal intake

The model must be able to take into account several foods in the daily diet because the management of the transition between indoor feeding and spring grazing is central in the design and in the evaluation of grazing management strategies. In the grazing models reported in the literature, it is not usually possible to combine grazing herbage and feedstuffs (silage or hay) in the daily diet. For modeling such complex feeding systems, three approaches [34] can be considered for the prediction of herbage intake. They are based on: (i) systems of energy requirements; (ii) grazing behavior measurements; or (iii) relations between herbage mass and intake. The model relies on a combination of the first approach to deal with periods of mixed feeding, and the third when grazing animals are fed only on grass, to take into account the effect of herbage allowance and herbage digestibility and their time-course on herbage intake [17].

2.2.3. Interaction between sward and animal states

The plant and animal submodels have to be designed in an integrated way such that the strong interaction between the two components of the grazing system can be dealt with. Indeed, a grazing event affects the dynamics of herbage digestibility through the amount and composition of the residual herbage on a pasture. Conversely, the herbage mass offered, its digestibility and its vertical distribution of composition influence the cows' intake and milk yield. This aspect is one of the original ones possessed by the SEPATOU model; it is actually a required feature in order to enable simulation of grazing management strategies that control the paddock rotation on the basis, for instance, of the daily milk production curve. The herbage digestibility plays therefore a key role in the plant-animal interaction.

The classical digestibility prediction models [14, 18, 47, 52] are inadequate because they are based only on age or accumulated temperature and therefore cannot take into account two key management-dependent aspects, the nitrogen supply and intensity of grazing [19]. Indeed, low N input reduces herbage digestibility by up to 5 g $(100\ g)^{-1}$ [13, 30, 55]. Moreover, the digestibility of the offered herbage depends on the sward mass after defoliation [36]. In order to evaluate management strategies, we need to explore the effects of different N supplies or grazing policies on residual sward height or the interval between two grazing episodes. On the basis of a preliminary work [76] and more recent findings [22, 28, 30], the decrease in herbage digestibility over time is the result of leaf aging as well as of changes in leaf anatomy and chemical composition with the leaf insertion level [47, 76]. The greater the sheath and leaf elongation rates, the faster the decrease in leaf digestibility is [28]. For this reason, an approach based on herbage mass [23] is used to predict the digestibility.

In order to represent the effect of herbage quality on the cows' intake the model must account for the gradient of digestibility vertically in the sward [39]. Furthermore, in order to cope with different grazing pressures, the model must reproduce the dynamics of the digestibility following any kind of defoliation from lenient to severe. The decrease in herbage digestibility is the result of acid detergent-soluble fiber and neutral detergent-soluble fiber that decrease from the top to the base of each lamina [28, 39]. Experimental data have shown that this decrease is slower for the top few centimeters in the sward, and therefore the digestibility falls toward the base of the sward [36]. Although the phenomenon of digestibility variation down the sward profile is well known, no grazing models seem to incorporate this aspect, which therefore contributes to the originality of our model.

3. MODEL OF THE BIOPHYSICAL SYSTEM

The biophysical model is composed of three sub-systems (soil, plant, animal). Its state variables are evaluated at the beginning of each day. The model is defined through the relationships between these components and the processes governing their dynamics through the effect of actions (nitrogen supply, time and area of grazed field allocation to grazing animals, feeding with silage) or external factors (weather). Figure 1 gives a partial and simplified overview of the considered relationship. The model components presented in this section either come from the agronomic literature or have been especially adapted from published or as yet unpublished research work. The values of the parameters

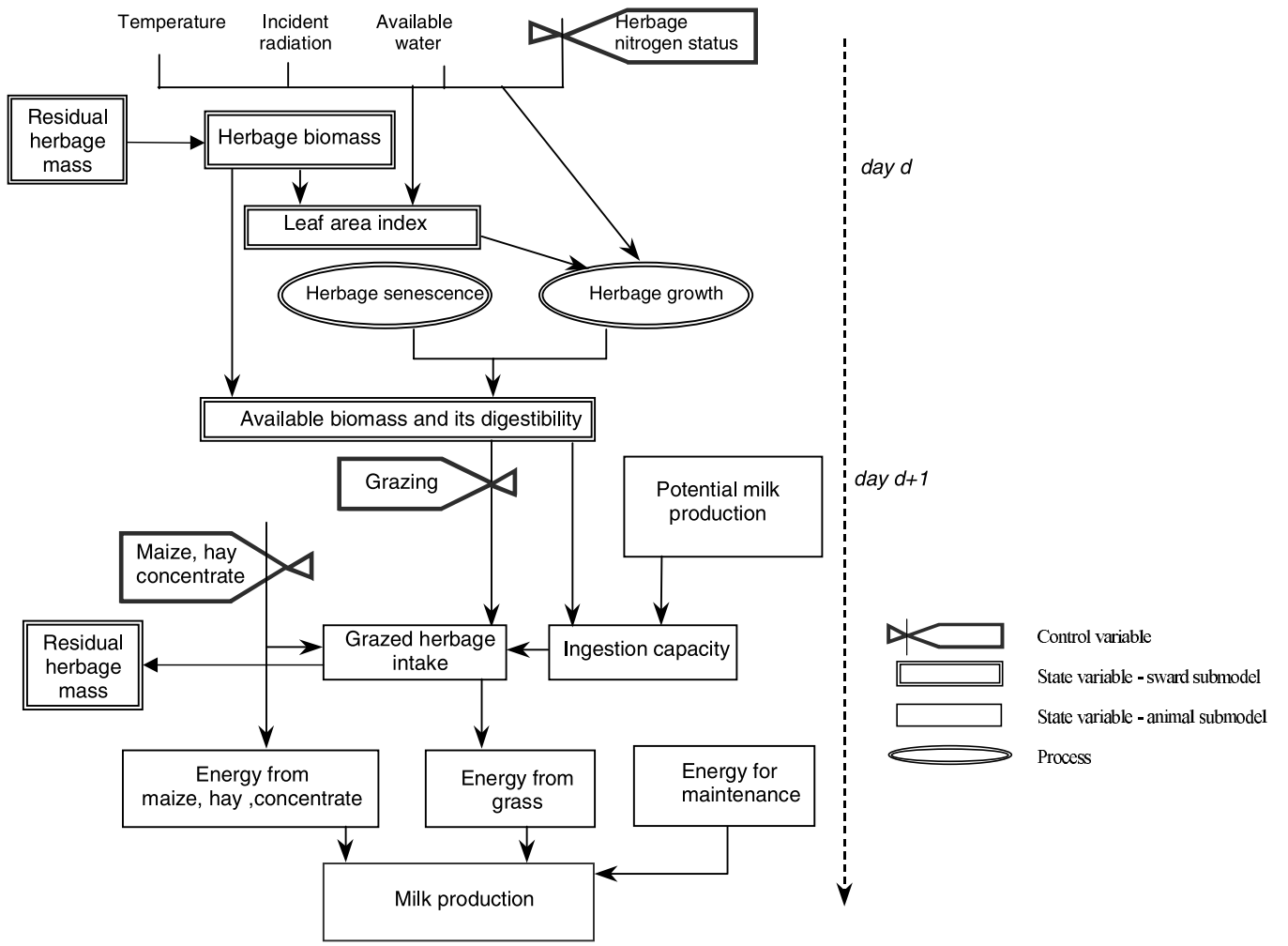


Figure 1. Partial and simplified overview of the model.

involved in these equations are taken from the same sources and have been revised when needed on several occasions during the validation process (see Sect. 4).

3.1. Soil submodel

This elementary submodel computes the water balance on which grass growth depends. The soil water status, some soil characteristics (texture, etc.) and rainfall are assumed to be accessible for the decision model. The variables used in this submodel are indicated in Table I.

3.1.1. Available water

The amount of water available (*AW*) for grass growth depends on the balance between rainfall and actual evapo-transpiration (*AET*) or on the soil water capacity (*SWC*) when it is lower than the balance:

$$AW(d) = min(Rain(d-1) + AW(d-1) - AET(d-1), \mathrm{SWC}). \quad (1)$$

Table I. Soil submodel variables (*X(d)*: state of the variable *X* on the day *d*).

Variable	Description	Unit	Domain
AET(d)	Actual evapo-transpiration	mm	0–
AW(d)	Available water	mm	0–250
PET(d)	Potential evapo-transpiration	mm	0–
Rain(d)	Rainfall	mm	0–
SWC	Soil water capacity	mm	0–200
WI(d)	Water index		0–1

3.1.2. Actual evapo-transpiration and water deficit index

Actual evapo-transpiration *AET(d)* depends on the available water *AW(d)* and the potential evapo-transpiration *PET(d)* which is given as a weather input:

$$AET(d) = min\,(PET(d), AW(d)). \quad (2)$$

The water deficit index *WI(d)* is defined as the ratio between *AET(d – 1)* and *PET(d – 1)*, [21].

3.2. Submodel of sward under grazing

The sward state is described by 4 variables: a driving one, the herbage nitrogen index *NI(d)*, two state variables used for the animal submodel (herbage dry matter *DM(d)* and average digestibility *D(d)*) and an intermediate one for the growth submodel (leaf area index *LAI(d)*). All the plant variables and parameters are given in Table II. Specific parameters for certain grass species are given in Table III. The model must compute the time-course of each of the state variables and how the different processes are affected by the farmer's actions.

3.2.1. Sward nitrogen index and its time-course over a grazing season

In the plant submodel the sward nitrogen status is used as an input variable (from a lookup table) that integrates the effects of nitrogen fertilization and soil characteristics which act on soil nitrogen transformations. It is expressed as an index *NI*(*d*), defined as the ratio of the sward N content (% in DM) to the critical N content that allows the maximal herbage growth rate multiplied by 100 [45, 46]. We assume that N is supplied three times over a grazing season, at specific dates defined in the management strategy. This is typical practice in French dairying. Sward nitrogen index profiles throughout the grazing season are therefore defined in relation to these times and amounts of N supply (for example 100, 80, 60). The value *NI*(*d*) for a date *d* between two dates d_i and d_j is computed by linear interpolation between $NI(d_i)$ and $NI(d_j)$. Such a database of herbage nitrogen indices on farm and regional scales can be provided by advisory services.

3.2.2. Leaf lifespan

Leaf lifespan is a key variable for modeling LAI and net herbage accumulation [44]. Indeed, to simulate the LAI, one has to consider the moment when the lamina begins to senesce (LLSmin: appearance of yellow spots), whereas to simulate the dead leaf mass one has to consider the moment when senescence is ending (LLSmax: the leaf being completely yellow). The leaf lifespan, which is therefore the total of two time periods (green life and senescent life), is a relatively constant characteristic of a given grass species when expressed in degree-days (accumulated average daily temperatures over a given period; 0 °C basis) [24]. In the model the two parts of a leaf lifespan are expressed by the degree-day parameters LLSmin and LLSmax, respectively. In assessing leaf senescence status one has to count only the effective degree-days, i.e. degrees above a temperature threshold are ignored [60]. This threshold is estimated to be a maximum daily temperature of 25 °C according to the literature [60], roughly corresponding to a daily mean of 18 °C. Values of the leaf lifespan are given for different grass species in Table III.

3.2.3. Leaf area index

The model requires a knowledge of the value of the LAI at the start of simulation (February 1st) and immediately after each defoliation day (cutting or grazing). Following [20], the initial value of the LAI at the end of winter is:

$$LAI(d) = \text{K_sward} \times 1.9 \times [0.01 \times DM(d)]^{0.73} \quad (3)$$

where K_sward (see Tab. III) is a parameter that is specific to a grass species and that characterizes the vertical structure of the canopy.

Immediately after a defoliation day, the LAI is a function of: the grass species (K_sward), the standing herbage mass before defoliation (*DM(d–1)*) and the herbage mass after defoliation (*DM(d)*). In fact, the greater the herbage mass before cutting or grazing, the higher is the lamina insertion level on the sheath [22] and the lower the residual LAI. Following [20], the LAI state immediately after a defoliation day is computed as:

$$LAI(d) = \text{K_sward} \times 1.9 \times [0.01 \times DM(d)]^{0.73} \frac{DM\,(d)}{DM\,(d-1)} \cdot \quad (4)$$

The net daily LAI increase is the result of new leaf growth and leaf senescence:

$$LAI(d) - LAI(d-1) = LAIr(d-1) - LAIs(d-1). \quad (5)$$

The increase in LAI (*LAIr*) depends on the sward N status [3], the water availability (*WI*) and the average daily temperature (*T*). A quadratic relationship between the LAI and temperature [43] is used. Moreover, as for the leaf lifespan, the same upper threshold of 18 °C for average daily temperature applies here. In other words, *LAIr* is computed as:

$$LAIr(d-1) = 11 \times 10^{-6} \times [min(T(d), 18)]^2 \times [NI\,(d-1) - 20] \times WI(d-1). \quad (6)$$

The LAI decrease due to leaf senescence (*LAIs*) [24] is a fraction of the residual leaf area index taken at a reference day that is either the end of the last defoliation event (*dayCG(d)*) if the time interval in degree-days between the current time and the end of that defoliation event is less than the leaf green life period (LLSmin) or else the date that corresponds to one leaf lifespan interval after the last defoliation. In other words, the LAI of reference assumed in the computation of the LAI loss is either the LAI at the end of the defoliation event if this time is reached before the end of the green life period; otherwise it is the LAI at a green life duration after the defoliation time. The fraction of daily LAI loss is the ratio of the daily average temperature (below 18 °C) to the temperature sum that corresponds to the green life period (LLSmin). To summarize, the daily LAI decrease is given by:

$$LAIs(d-1) = LAI(dayLAIleft(d)) \frac{min(T\,(d),\,18)}{\text{LLSmin}} \quad (7)$$

where *dayLAIleft(d)* is equal to *dayCG(d)* if $\sum_{k\,=\,dayCG(d)}^{d} min(T(k),\,18) < \text{LLSmin}$ or the earliest day d° such that $\sum_{k\,=\,dayCG(d)}^{d^\circ} min(T(k),\,18) \geq \text{LLSmin}$ otherwise.

Table II. Variables (italics) and parameters of the plant submodel (*X(d)*: state of *X* on day *d*).

Variable	Description	Unit	Domain
A	Area of a plot	ha	0.5–20
ad	Physiological factor involved in RUE computation		
al	Seasonal factor involved in RUE computation		
b	Temperature factor involved in RUE computation		
Au(d)	Useful area of a plot	ha	0–20
D(d)	Average herbage digestibility	g·(100 g)$^{-1}$	40–100
Dτ(d)	Decrease of herbage digestibility due to temperature	g·(100 g)$^{-1}$	40–100
Dcg(d)	Average herbage digestibility after a defoliation	g·(100 g)$^{-1}$	40–100
Dlayer(q)	Herbage digestibility per layer as fraction of mass	g·(100 g)$^{-1}$	40–100
Dmax	Maximum leaf digestibility	g·(100 g)$^{-1}$	
DM(d)	Standing herbage dry matter	g·m^{-2}	0–1500
DMi(d)	Herbage intake	g·m^{-2}	0–
DMr(d)	Herbage growth	g·m^{-2}	0–50
DMs(d)	Herbage senescence	g·m^{-2}	0–50
K_sward	Constant reflecting the vertical structure of canopy		
LAI(d)	Leaf area index		0–15
LAIr(d)	Increase of leaf area index due to growth		0–15
LAIs(d)	Decrease of leaf area index due to senescence		0–15
LLSmax	Leaf lifespan w.r.t end of senescence	degree days	
LLSmin	Leaf lifespan w.r.t end of green life	degree days	
Ncows	Number of cows in the mob		5–300
Ndungs(d)	Number of dungs per cow		
NI(d)	Herbage nitrogen index		0–100
PAR(d)	Intercepted photosynthetic radiation	MJ·m^{-2}	
RG(d)	Incident radiation	MJ·m^{-2}	
RUE(d)	Radiation use efficiency	g·MJ^{-2}	
T(d)	Average daily temperature	°C	
WI(d)	Water index		0–1
dayBG(d)	The first day in the last grazing episode		
dayCG(d)	The last day of the last defoliation (cut or grazing)		
dayDMleft(d)	The day whose DM is taken as reference to compute the daily decrease of DM		
dayLAIleft(d)	The day whose LAI is taken as reference to compute the daily decrease of LAI		
εi (d)	Intercepted radiation efficiency		
$q_i^h(d)$	Grazed herbage intake per day and per cow	kg	
$q_o^h(d)$	Offered herbage per cow	kg	0–2000

Table III. Specific species parameters.

Species	Leaf lifespan for beginning (LLSmin) and complete (LLSmax) senescence in °C·days	Maximum leaf digestibility: *Dmax* in g·(100 g)$^{-1}$	Constant reflecting the vertical structure of the canopy: K_sward *
Cocksfoot	600–800 [24]	90 [15, 25]	1
Perennial rye grass	500–700 [11, 44]	95 [15]	1.2
Tall fescue	700–900 [15, 24, 44]	85 [15, 25]	1.1

* Coefficient to assess the effect of grazing intensity on sheath length (Duru, unpublished).

3.2.4. Herbage dynamics without grazing

The net herbage accumulation rate between defoliation events is computed per unit of area (m^2) as the difference between growth (*DMr*) and senescence (*DMs*):

$$DM(d) = DM(d-1) + DMr(d-1) - DMs(d-1). \quad (8)$$

Growth is modeled as a function of intercepted photosynthetic radiation (*PAR*) and radiation use efficiency (*RUE*):

$$DMr(d) = RUE(d) \times PAR(d). \quad (9)$$

According to [31, 51], the intercepted photosynthetic radiation depends on the incident radiation (*RG*) and the intercepted radiation efficiency (εi) that itself varies exponentially with the LAI. Formally

$$PAR(d) = 0.48 \times \varepsilon i(d) \times RG(d) \quad (10)$$

$$\varepsilon i(d) = 0.95 \times \left(1 - e^{-\mu \times LAI(d)}\right) \quad (11)$$

where μ varies according to the sun's angle; μ equals 0.57 before the 1st May and 0.52 for the subsequent days [73].

The maximum of RUE values observed for grass swards are around 2.2 g·(MJ)$^{-1}$ [3, 26] when nitrogen does not limit growth. When there are nitrogen and water deficiencies, we assume that the decrease in RUE is proportional to these indices (following [3, 26] for N, and [21] for water). Furthermore, RUE depends on the physiological stage and on temperatures, which are taken into account through *ad, al* and *b* which are physiological, seasonal and temperature factors, respectively, in the following equation:

$$RUE(d) = ad(d) \times al(d) \times b(d) \times 2.2 \times NI(d) \times WI(d). \quad (12)$$

In spring, during the reproductive stage, the RUE tends to be greater than in summer. As regards the sward structure, the sheath/lamina length ratio is proportionally greater in spring, leading to a higher photosynthetic rate [62]. The effect of the sward structure increases progressively over the stem elongation period, resulting in up to 65% more photosynthesis [62]. For the period before stem elongation we empirically set *ad(d)* to 1.1, then 1 for vegetative regrowths.

Although the photosynthetic efficiency is rather constant over the grazing season, the RUE decreases because the fraction of assimilate allocated to the shoot component declines from spring to autumn. Using data from Lemaire [46], the following equation expresses the seasonal factor:

$$al(d) = -(0.6 / 180) \times d + 2.5 + 32 \times (0.6 / 180). \quad (13)$$

To take into account the effect of temperature on RUE, we use data from Woledge and Dennis [78], who have studied the effect of low and high temperatures on photosynthesis for a range of incident radiation. The *b* coefficient is computed from their data according to the following equation:

$$b(d) = 0.037 + 0.09 \times min(T(d), 18) - 0.0022 \times [min(T(d), 18)]^2. \quad (14)$$

In the senescence process the leaf weight decreases due to respiration and carbohydrate and protein remobilization [75]. The remobilization through leaf senescence varies according to the sward N status and previous grazing events. It could be as high as 20% of the maximum leaf weight [61] and has been estimated at 15% from our set of data (Duru, unpublished data), i.e. $\alpha = 0.15$. Similarly to the LAI decrease due to senescence, the leaf senescence flux (*DMs*) depends on the residual herbage mass (*DM*) [53], the average daily temperature and the leaf lifespan (LLSmax). Taking into account the remobilization rate, the leaf senescence flux becomes:

$$DMs(d-1) = (1-\alpha) \times DM(dayDMleft(d)) \frac{min(T(d), 18)}{\text{LLSmin}} \quad (15)$$

where *dayDMleft(d)* is equal to *dayCG(d)* if

$$\sum_{k = dayCG(d)}^{d} min(T(k), 18) < \text{LLSmax}$$

or the earliest day d° such that

$$\sum_{k = dayCG(d)}^{d^\circ} min(T(k), 18) \geq \text{LLSmin}$$

otherwise.

3.2.5. Herbage dynamics and herbage availability in the course of grazing

This subsection describes the model of standing herbage dynamics in the course of grazing. Due to the role of cows in this process the model requires herbage mass both per unit of area (*DM*) and per cow (expressed by variables starting with *q*) to be considered.

On a given paddock, we define a grazing episode as the interval of time (in whole days) between the day the herd is moved into the paddock and the day it is moved out. During a grazing episode the herbage dynamics model must take into account the effect of herbage intake per unit of area (*DMi*) and the decrease in grazable area due to cow pats:

$$DM(d) = DM(d-1) + DMr(d-1) - DMs(d-1) - DMi(d-1). \quad (16)$$

The dry matter loss due to senescence is taken as

$$DMs(d) = DMs(dayBG(d)-1) \quad (17)$$

where *dayBG(d)* is the first day of the grazing episode. In other words, the loss due to senescence during a grazing episode is assumed to be negligible, compared with loss due to defoliation and fouling.

DMi depends on the herbage intake per cow ($q_i^h(d)$) and the stocking rate, which is the number of cows (Ncows) divided by the usable grazing area of a paddock (*Au*).

$$DMi(d) = \frac{q_i^h(d) \times \text{Ncows} \times 0.1}{Au(d)}. \quad (18)$$

The model of the herbage intake process, which determines ($q_i^h(d)$) is described in Subsection 3.3.1.

The usable area (*Au*) for grazing is less than the area of a paddock (A) due to cow pats. It decreases throughout the growing season. It is assumed (Peyraud, pers. com.) that a cow defecates on average 10 or 20 times per day depending on whether grazing is diurnal only or both diurnal and nocturnal. The area of a cow pat is estimated at 0.07 m^2, which corresponds to a diameter of 0.3 m. The usable area is given by:

$$Au(d) = \text{A} - \text{Ncows} \times Ndungs(d-1) \times 0.07 \times 10^{-4}. \quad (19)$$

To estimate the amount of offered herbage per cow, we assume that only part of the above-ground biomass is available for cutting and grazing. It is assumed that the lower sward layer that corresponds to 80 g·m^{-2} is physically ungrazable by cattle [57].

$$q_o^h(d) = \frac{10 \times [DM(d) - 80] \times Au(d)}{\text{Ncows}}. \quad (20)$$

Furthermore, it is assumed that for the day *d* immediately after a cut, $DM(d) = 125$ g·m^{-2}.

3.2.6. Digestibility of the offered herbage

The digestibility[2] of the offered herbage varies from the top to the bottom of the sward. The average digestibility depends firstly on the digestibility of the new leaf mass produced since the last defoliation event and of the residual herbage mass that is still available and, secondly, on their respective proportions in terms of mass.

The digestibility of the new leaves produced depends on grass species, temperature, sward N status and the rate of herbage accumulation. The highest possible value (*Dmax*), also called the potential value, is given in Table III for some grass species growing in optimal conditions (high N herbage status, low temperature). The digestibility decreases with increasing temperature. The decrease in rate has been estimated experimentally at -0.6 g·(100 g)$^{-1}$ per degree Celsius [12, 77]. Some field experiments with grazed swards [20] confirmed this value. For the sake of simplicity, the temperature effect is assumed to vary linearly from day 30 till day 210. The daily decrease in herbage digestibility due to temperature ($D\tau(d-1)$) is empirically approximated by:

$$D\tau(d-1) = 0.0588 \times d - 0.5280 \text{ for } 30 < d < 210. \quad (21)$$

The extra reduction in herbage digestibility due to low N status is modeled by a multiplicative factor that is equal to 1 when *NI* is equal to 100, 0.9 if *NI* is equal to 0 and varies linearly in-between. The herbage digestibility declines through growth in function of the herbage accumulation rate after a defoliation event. Typically an average growth rate of 10 g·m^{-2} per day leads to a decrease in herbage digestibility of 0.4 g·(100 g)$^{-1}$ per day, which is consistent with estimates based on age [15].

Formally, after a defoliation finishing at *dayCG(d)*, the average digestibility of the new leaves produced is equal to *Dcg(d)* given by:

$$Dcg(d) = [Dmax - D\tau(d-1)] \times [0.9 + 0.001 \times NI(d-1)] - 0.04 \times \sum_{k=dayCG(d)+1}^{d-1} DMr(k). \quad (22)$$

Given the average digestibility of the new leaves produced (*Dcg(d)*) the average digestibility of the offered herbage (*D(d)*) is approximated by the following equation:

$$D(d) = \frac{Dcg(d) \times DMR(d) + D(dayCG(d)+1) \times DMS(d)}{DMR(d) + DMS(d)} \quad (23)$$

where *DMR(d)* is the accumulated mass of new leaves produced since the last defoliation and *DMS(d)* is the residual mass that is still available at day *d*. More formally

$$DMR(d) = \sum_{k=dayCG(d)+1}^{d-1} DMr(k) \text{ and} \quad (24)$$

$$DMS(d) = DM(dayCG(d)+1) - \sum_{k=dayCG(d)+1}^{d-1} DMs(k). \quad (25)$$

By computing *DMS(d)* from the above formula it is assumed that the variation in digestibility in the residual mass is negligible.

The modeling of decrease in herbage digestibility from the top to the base of the sward relies on literature data [28, 36, 39, Duru unpublished]. Based on these data, the upper third of the herbage mass has a digestibility 6.5 g·(100 g)$^{-1}$ higher than the average value, and for the remaining part the digestibility

[2] Unless otherwise specified digestibility refers to in vitro digestibility [2].

decreases linearly down to 13 g·(100 g)$^{-1}$ lower than the average value. The variation in digestibility down through the sward is modeled through the function *Dlayer*(q) that maps a fraction q of the offered herbage mass to the actual level of digestibility such that *D(d)* is the average value of this function between 0 and q_o^h *(dayCG(d))* where *dayCG(d)* is the last day of the last defoliation (cut or grazing) and q_o^h *(dayCG(d))* is the amount of herbage offered per cow. In other words, we have:

$$D(q) = \frac{1}{q_o^h(d)} \int_0^{q_o^h(d)} Dlayer(q)dq \,. \quad (26)$$

Consistent with the above mentioned data, *Dlayer(q)* is defined by:

$$Dlayer(q) = \frac{29.25}{q_o^h(dayCG(d))} \times q + D(dayCG(d)) - 13$$

$$if\ q < 2/3 \cdot q_o^h\ (dayCG(d)), \quad (27)$$

$$Dlayer(q) = D(dayCG(d)) + 6.5 \quad \text{otherwise.} \quad (28)$$

3.3. Animal submodel

The animal submodel computes: (i) the daily herbage intake, knowing the amount of feed given indoors, and (ii) the potential and actual milk produced per cow.

The cows are characterized by the average cow weight (fixed at 600 kg presently), the calving date and the potential milk yield [37]. The herd is characterized by the number of cows. The last three parameters are under the user's control. The set of variables and parameters is given in Table IV.

3.3.1. Daily feed intake

The daily intake of a cow is restricted by its feeding capacity and the fill of each type of feed consumed.

When there is no grazed herbage in the daily diet we assume that the cow is offered a given amount of hay and a given amount of concentrates and is provided with maize silage ad libitum. The silage maize intake ($q_i^m(d)$) is determined by:

$$q_i^m(d) = BD_i^m(d) / BD^m \quad (29)$$

where BD^m is the fill of silage maize, which is normally fixed at BD^m = 1.0 UE·kg^{-1} [15] (UE is a French unit of fill) and $BD_i^m(d)$ is the fill of the consumed maize silage. $BD_i^m(d)$ is computed as follows:

$$BD_i^m(d) = BDmax(d) - BD_i^c(d) - BD_i^a(d) \quad (30)$$

where the different terms are defined below.

The maximum feeding capacity of the cow (*BDmax(d)*) depends [37] on the maximum daily milk yield per cow ($y_p(d)$) that is defined in the next subsection:

$$BDmax(d) = 22 - 8.25 \times e^{-0.02 \times y_p(d)} \,. \quad (31)$$

The fill of a given feed in the daily diet ($BD_i^c(d)$ and $BD_i^a(d)$ for concentrates and hay, respectively) is the product of its fill (BD^c and BD^a for concentrates and hay, respectively) by the amount intake ($q_i^c(d)$ and $q_i^a(d)$ for concentrates and hay, respectively). That is

$$BD_i^c(d) = BD^c \times q_i^c(d); \quad (32)$$

$$BD_i^a(d) = BD^a \times q_i^a(d). \quad (33)$$

It is assumed that $BD^a = BD^m$ and the fill of concentrates is given by:

$$BD^c = 0.6 \times BD^m \text{ or } 0.6 \times BD^a \quad (34)$$

where the value 0.6 is an average coefficient for the substitution of concentrate for other feeds, whatever the other kind of feed used (maize silage, hay or herbage) [35].

When the daily diet includes grazed herbage, the herbage intake ($q_i^h(d)$) depends on grazing management options (quantity of offered herbage per cow, grazing duration per daily cycle), sward characteristic (digestibility), indoor feeding (roughage, concentrates) and cow characteristics (weight, stage of lactation) [42, 49, 56, 83].

Grazed herbage intake is limited by and is a function of the amount $q_o^h(d)$ of offered herbage per cow (herbage allowance) because the larger the amount offered, the easier the access to this feeding resource by the cows [58]. In the case of 24-hour grazing, if the amount of herbage offered is more than 20 kg of dry matter per cow, the herbage intake only depends on the maximum herbage intake of the cow ($qmax_i^h(d)$). Otherwise, the decrease can be approximated by a linear function such that there is a diminution of about 0.3 kg per kilo of offered herbage below 20 kg [49]. Formally:

$$q_i^h(d) = qmax_i^h(d) \quad \text{if} \quad q_o^h(j) \geq 20 \text{ kg}, \quad (35)$$

$$q_i^h(d) = qmax_i^h(d) - 0.3\,(20 - q_o^h(d)) \quad \text{otherwise.} \quad (36)$$

In the case of diurnal grazing, and when no feed is given indoors, we assume that only 80% of the above can be eaten, due to too short a grazing time (Peyraud, pers. com.).

The maximum amount of herbage intake per cow ($qmax_i^h(d)$) is the amount of herbage that can be consumed by a cow once it has eaten the feed provided indoors, assuming there is no shortage in herbage allowance. This quantity depends on the cow's feeding capacity, expressed by *BDmax(d),* and the fill of the grazed herbage, which is a function of the variation in digestibility down through the sward (*Dlayer*). More formally, $qmax_i^h(d)$ is the solution of:

$$\int_{q_o^h(d) - qmax_i^h(d)}^{q_o^h(d)} [1.2117 - 0.0033 \times Dlayer(d)]dq = BDmax_i^h(d) \quad (37)$$

where 1.2117 – 0.0033 × *Dlayer(q)* is the fill of grazed herbage in relation to its digestibility (Peyraud, pers. com.).

When the offered herbage is too little, i.e. does not allow the maximum herbage intake to be reached, the previous equation

Table IV. Variables (italics) and parameters of the animal submodel. UFL is a French energy unit [29] and UE is the French unit of fill.

Variable	Description	Unit	Domain
$BD_i^c\ (d)$	Fill of a given amount of concentrates intake	UE	
$BD_i^a\ (d)$	Fill of a given amount of hay intake	UE	
$BD_i^m\ (d)$	Fill of a given amount of maize silage intake	UE	
BD^a	Fill of hay per kg	UE·kg^{-1}	
BD^c	Fill of concentrate per kg	UE·kg^{-1}	
BD^m	Fill of maize silage per kg	UE·kg^{-1}	
$BDmax\ (d)$	Maximum feeding capacity of a cow	UE	
$BDmax_i^h\ (d)$	Maximum fill available for grazed herbage intake	UE	
$Dlayer(q)$	Herbage digestibility per layer as fraction of mass	g·(100 g)$^{-1}$	
$D_i(d)$	Average in vitro digestibility of grass intake	g·(100 g)$^{-1}$	
$Dvv(d)$	Average in vivo digestibility of grass intake	g·(100 g)$^{-1}$	
$E_i\ (d)$	Energy intake per cow	UFL	
$E_i^c(d)$	Energy from the concentrates intake	UFL	
$E_i^a\ (d)$	Energy from the hay intake	UFL	
$E_i^h\ (d)$	Energy from the grazed herbage intake	UFL	
$E_i^m\ (d)$	Energy from maize silage intake	UFL	
$Emaintenance(d)$	Energy needed for maintenance	UFL	
$Eproduction(d)$	Energy needed for milk production	UFL	
$EV_i^h\ (d)$	Energetic value of grazed herbage	UFL·kg^{-1}	
EV^a	Energetic value of hay	UFL·kg^{-1}	
EV^c	Energetic value of concentrates	UFL·kg^{-1}	
EV^m	Energetic value of maize silage	UFL·kg^{-1}	
$Ncalving(d)$	Number of days spend from the calving day	day	
$q_i^c(d)$	Amount of concentrates intake	kg	
$q_i^a\ (d)$	Amount of hay intake	kg	
$q_i^m\ (d)$	Amount of maize intake	kg	
$q_i^h\ (d)$	Amount of grazed herbage intake	kg	
$q_o^h\ (d)$	Amount of offered herbage per cow	kg	0–2000
$q_i^m\ (d)$	Maize silage intake per cow	kg	
$qmax_i^h(d)$	Maximum amount of herbage intake	kg	
$ymax_p$	Highest potential milk yield per cow in the lactation period (genetic characteristic)	kg	
$y_p\ (d)$	Daily potential milk yield	kg	
$y_r\ (d)$	Actual daily milk yield per cow	kg	

has no solution and the maximum herbage intake is then equal to the offered herbage:

$$qmax_i^h(d) = q_o^h(d). \quad (38)$$

In the case of a mixed diet, the maximum feed fill for grazed herbage ($BDmax_i^h(d)$) is given by:

$$BDmax_i^h(d) = BDmax(d) - BD_i^c(d) - BD_i^a(d) - BD_i^m(d). \quad (39)$$

3.3.2. Milk yield

The potential milk production per cow per day ($y_p(d)$) is maximal (i.e reaches $ymax_p$) 40 days after the beginning of lactation and then decreases steadily by 0.35% per day according to [79]. As the study is restricted to autumn calving and the February to July grazing period we need only consider the potential milk production after these 40 days:

$$y_p(d) = ymax_p \times (1 - 0.0035)^{(Ncalving(d) - 40)} \quad \text{for } 40 < Ncalving(d) < 300. \quad (40)$$

The milk produced per cow per day ($y_r(d)$) is determined by the amount of energy devoted to milk production ($Eproduction(d)$) and is limited by the potential daily milk yield ($y_p(d)$). This relation is expressed formally by the following equation:

$$y_r(d) = \min\left(\frac{Eproduction(d)}{0.44}, y_p(d)\right) \quad (41)$$

where the factor 0.44 is the amount of energy (in UFL which is a French energy unit) needed to produce 1 kg of milk [15].

The energy available for milk production is the difference between the energy coming from intake and the energy needed for maintenance ($Emaintenance(d)$).

$$Eproduction(d) = E_i(d) - Emaintenance(d). \quad (42)$$

The energy needed for maintenance is fixed at 6 or 5 UFL per day according to whether it is a grazing day or a day during which the cows are exclusively fed indoors [15].

The total available energy per cow ($E_i(d)$) is the sum of the energy supplied by the different feeds eaten (c: concentrates, a: hay, m: maize silage, h: grazed herbage):

$$E_i(d) = E_i^c(d) + E_i^a(d) + E_i^m(d) + E_i^h(d). \quad (43)$$

For each feed, the energy supplied is the product of its energetic value and the amount eaten, as expressed by the following formulae:

$$E_i^c(d) = EV^c \times q_i^c(d) \quad (44)$$

$$E_i^a(d) = EV^a \times q_i^a(d) \quad (45)$$

$$E_i^m(d) = EV^m \times q_i^m(d) \quad (46)$$

$$E_i^h(d) = EV_i^h(d) \times q_i^h(d). \quad (47)$$

We assume that the energetic value is fixed for concentrates and maize silage. More specifically, after [15]:

$$EV^c = 1.1 \text{ UFL}\cdot\text{kg}^{-1} \quad (48)$$

$$EV^m = 0.9 \text{ UF}\cdot\text{kg}^{-1}. \quad (49)$$

For hay, we assume that the energetic value may take one of two values depending on the quality of the hay:

$EV^a = 0.8$ for hay of good quality; or 0.6 otherwise.

For grazed herbage, the energetic value is computed from the in vivo herbage intake digestibility ($Dvv(d)$) in the following manner (Peyraud, pers. com.):

$$EV_i^h(d) = 0.0108 \times Dvv(d) + 0.208. \quad (50)$$

The in vivo digestibility $Dvv(d)$ is obtained from the in vitro digestibility of herbage intake ($D_i(d)$) by the following relation (Peyraud, pers. com.):

$$Dvv(d) = 1.39 \times D_i(d) - 26.0. \quad (51)$$

Finally, the in vitro digestibility is computed similarly to the average digestibility of the offered herbage by:

$$D_i(d) = \frac{1}{q_i^h(d)} \int_{q_o^h(d) - q_i^h(d)}^{q_o^h(d)} Dlayer(d)\,dq. \quad (52)$$

4. VALIDATION OF THE MODEL

This section discusses briefly how the biophysical system has been validated. Detailed results of the validation of the whole SEPATOU simulation system are reported in [9] and in a forthcoming paper.

4.1. The validation context

The biophysical model presented in this paper is one of the two main components of the SEPATOU system. SEPATOU also incorporates a decision model that reproduces the implementation of a management strategy. Within the SEPATOU simulator, the biophysical model inputs are decision settings produced periodically by the decision model and the daily climatic data. The outputs are the values of the state variables over the simulation period. Classically, validation of such a biophysical model involves experiments comparing model behavior against actual measurements. Obviously, this approach is feasible only in cases of models involving a relatively small number of variables and parameters. Validation becomes increasingly difficult for the present model which is expected to provide realistic estimates of different dynamic aspects varying on a daily scale over several months. The extent of variation of most input variables (weather and management) is large and precludes any systematic exploration. Consequently, as noted by [6], it is impossible for this kind of simulation model to be validated over its entire domain of application [63]. Moreover, records from the observation of the natural system (dairy enterprise and weather) are scarce and incomplete with respect to the set of aspects listed above and the time frame of interest.

Although these data might be used to perform standard statistical validations of some parts of the model there is no assurance that the assembled model will necessarily behave acceptably well [80]. Some errors may be introduced through linking model components at a higher level. The various parts of the model may be unequally checked and some interactions may not be predictable.

Hence, the only possible approach is a subjective one [6] in which scientists and grazing management experts are provided with simulations of cases familiar to them and asked if the model behavior is consistent and reasonably accurate [65]. The validation consists then of checking that the results of the simulation are in agreement with those expected by the knowledgeable people involved in the validation process. Furthermore, validation has to form part of the development of the whole simulation system; the results of evaluation provide feedback to make corrective changes to the biophysical model. Ultimately, validation must provide "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [64].

The validity of the model is defined in terms of its ability to reproduce faithfully and accurately the biophysical system behavior induced by a particular management strategy and its consistency and sensitivity to different weather patterns. Strategies are evaluated with respect to user-defined criteria that are valued as a function of output results provided by the model. Typically, the criteria are concerned with the dynamics and timing of key events or the magnitude or trend of relevant quantities. More specifically, the kinds of outputs that might be used in evaluation include:

- time series of daily values of model variables (dry matter amount, digestibility, herbage intake, milk production, etc.);
- date and duration of operations on each field (grazing, cutting, fertilization);
- actual daily diet per cow and proportion of each type of feed;
- times series of daily values of user-defined variables, that is, variables defined as functions of model variables for inspection purposes or for synthesizing decision-relevant indicators (height of grass derived from dry matter amount, net grass growth, etc.);
- calendar of key events, that is, the date of occurrence of decision-relevant situations (for example, the turnout date may be defined as the date when the amount of herbage available represents more than 5 days of consumption per cow, the date of the start of night-and-day grazing may be defined as the date when grass growth attains a specific threshold value);
- histograms of variable values simulated for different climatic scenarios.

The analysis of outputs obtained with particular farm configuration and management options needs to be made using the weather pattern assumed for the simulation. Some illustrations of the kind of information used in the validation process are shown in the next subsection.

4.2. A qualitative and corrective validation process

The validation rested on the expertise available in Brittany and, to a lesser extent, in the south-western part of France. In Brittany typical strategies have been defined beforehand by extension service specialists of grazing aspects in feeding cows [70]. In each region, several strategies compatible with the model framework have been considered. These strategies were synthesized from typical observed management practices and are therefore realistic, which is an essential feature of test cases to ensure pertinence of experts' judgement. Moreover, small variations in the strategies, and therefore in decision inputs, have also been explored in order to verify underlying relationships and evaluate the sensitivity of the model. The validation process may lead to some modifications of the parameter values or of the structure of the model including, if necessary, the introduction of new variables and new equations.

The validation experiments focused on the exploration of the model response to the application of a given strategy in a particular weather scenario and in a set of weather scenarios. Different aspects are scrutinized in each case. For the detailed examination of outputs obtained with a given weather scenario, the experts judged whether the simulated behavior was consistent and accurate enough. They went through the daily changes in model or user-defined variables. For instance, they checked that the model reproduced properly the average daily herbage intake, its overall decreasing trend over the grazing season and the phenomenon of decrease in the ingested amount of herbage during a grazing episode on each field (see Fig. 2). They also verified that the triggering conditions of decisions and actions were indeed fulfilled. They also looked at time-related aspects including variations in some quantities over a period of several days (e.g. weekly herbage growth) or the duration of grazing activities (number of days of grazing per field, taking into account the stocking rate). Finally, they checked the soundness of the calendars of key events and activities, and of synthetic results such as the percentage of herbage in the intake of the cows over the considered period. Cases exhibiting poor fits with the experts' expectations revealed the cause of incorrect behavior. The problem could be fixed sometimes by modifying some parameters and other times by introducing some structural changes to the model. We occasionally noticed that some relations statistically validated for short periods were not adequate. For example, in the growth submodel, the radiation use efficiency (RUE) did not originally depend on daily temperature. The use of a database containing weekly dry matter yield after defoliation at the beginning of February only allowed the average RUE over the following weeks to be computed. This was validated using an independent set of data (Duru, unpublished). But such a model was not satisfactory in the case of early turnout to pasture. The dependence on daily temperature had to be taken into account in order to simulate consistent turnout dates defined as a function of herbage availability. After modification of the model, the experts declared that the results were realistic for the strategies considered [9].

Concerning the outputs obtained with a range of weather scenarios, the goal was to check the correctness of response of

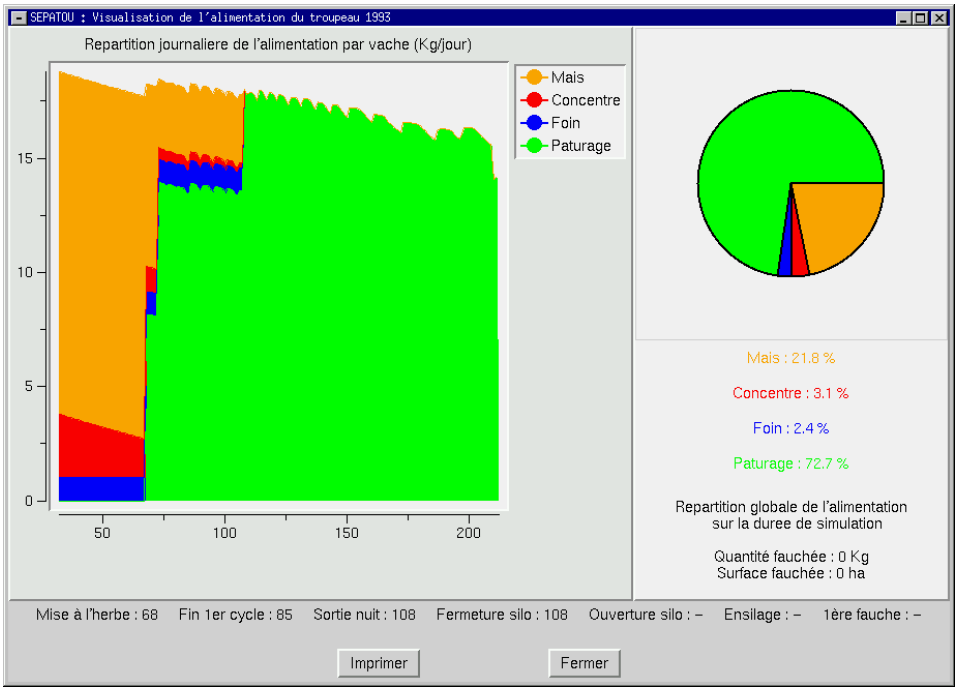


Figure 2. Display window of the daily diet composition (kg per cow on Y-axis) over the studied period (from day 25 to day 210 on X-axis) on the left part and the aggregated diet composition for the whole period on the right part; (maize silage: mais, hay: foin, concentrates: concentrés and grazed herbage: pâturage).

the model to variation in weather conditions throughout the period of interest. The experts looked at various histograms and statistical information such as minimum, maximum and mean values. For instance, the simulated net herbage accumulation was compared with field assessments of herbage mass [9]. The values used as reference result from an evaluation of herbage height for around 100 plots in commercial dairy farms, taking into account an average herbage fill which is assumed to be constant throughout the grazing season and independent of management aspects. The soil water capacity and management options such as herbage nitrogen status, residual sward mass and interval between grazing episodes were determined on the basis of empirical knowledge extracted by averaging data coming from the monitored plots. The simulated results (see Fig. 3) are fairly close to those derived from sward measurements. The trends are the same in the two cases. However, the simulated values are almost always greater than assessed values, and the between-year variation is greater with simulated values. The incompleteness of the field data precludes a rigorous comparison and illustrates why validation cannot be done in the classical manner.

In the management strategies, key events are defined with respect to available herbage mass per cow over the entire grazing area. For 4 out of 6 cases, there is a very close fit between the targeted periods and the simulated median dates, and for the two other cases the simulated median dates do not match exactly with the targeted periods but yet are still compatible. The agreements on these key event occurrences is a clear indication of the soundness of the model because a wrong model would have generated diverging behaviors, especially late in the grazing season. Other aspects of particular interest included, for instance, key dates (turnout, end of first grazing cycle; see Tab. V) and the proportion of each kind of feed in the cows' diet over the entire period of interest. This type of analysis did not reveal much, however, about any malfunctioning or lack of accuracy of the model. This may be due to scarcity of expertise about the between-year behavior of the biophysical system.

Throughout this process we have noticed the importance of the user interface of the software implementing the model. Time series plots and graphical displays of calendars of activities and dietary composition over time form the basis for evaluation of consistency of the simulated results and sensitivity of the model. Essentially, operational validation is determined subjectively by a visual assessment. When unexpected behavior is noticed, a deeper analysis is performed by thoroughly inspecting some variables and questioning some causal relationships in the model or their underlying assumptions.

Finally, the conducted tests have resulted in successive improvements that now yield qualitatively realistic simulations of milk production, grazing and feeding calendars for a set of grazing strategies [9]. The analysis of the resulting time series of the main quantitative variables (e.g. dry matter and milk yield) suggests that major prediction flaws are unlikely and that the model is conceptually valid. It is in accord with the available data and with experts' judgment or beliefs. The model yields justifiable results that are appropriate to the purpose of evaluating strategies.

The authors realize that much more could be done on the validation issue which would require a great deal more work.

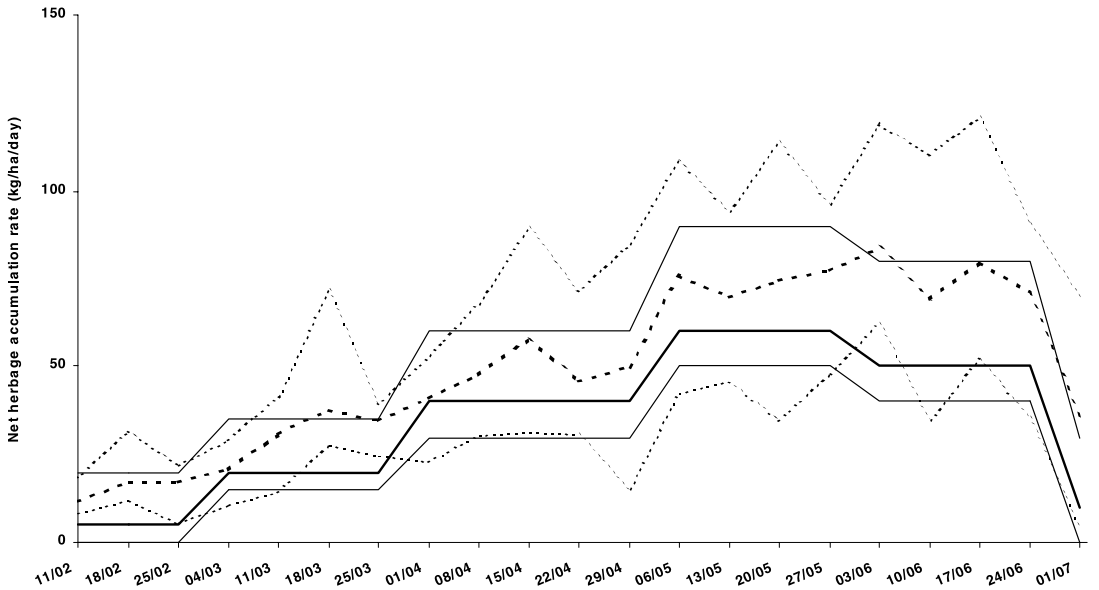


Figure 3. Net herbage accumulation on a weekly scale: comparison of simulated (broken lines) with assessed values for six years (full lines), after [70]. Thick lines are drawn for average weekly values over the six years; upper and lower full or broken lines are, respectively, maximal and minimal weekly values observed over the six years.

Table V. Dates of key events for three grazing strategies [from 69]: comparison of simulated occurrences (median, minimum and maximum over 17 years) with targeted periods.

Grazing strategy	Key events	Target dates	Simulated dates and intervals
"70 full grazing days"	Turn out date	beginning of March	02/03 (01/03–16/03)
	Closure of silage silo date	end of April	29/04 (05/04–22/04)
"100 full grazing days"	Turn out date	middle of February	26/02 (08/02–13/03)
	Closure of silage silo date	middle of April	14/04 (18/03–12/05)
"150 full grazing days"	Turn out date	beginning of February	22/02 (15/02–11/03)
	Closure of silage silo date	beginning of April	04/04 (25/03–15/04)

In particular, it would be good to consider other test cases, other regions of application and to involve other experts. More exploration is needed to gain a better appreciation of the robustness of the model with respect to geographical sites of application and management styles. The sensitivity of the model would also require further investigation.

5. GENERAL DISCUSSION AND CONCLUSION

The presented biophysical model, which is incorporated in the SEPATOU system, has been put to work in a range of situations that served as test and validation cases and led to the improvement of different aspects. The behavior of the model, as assessed by grazing management experts, has reached a stage of acceptable maturity in terms of global consistency and faithfulness to reality. Clearly, the model already provides a framework for discussing management strategies and operational options and pinpoints opportunities for alternative forms of management. The essential contribution made through the development of this model lies in its ability to simulate the behavior of a dairy farm system throughout a season in response to realistic management practices and various weather patterns. Given the practical objective of the model and the breadth and complexity of the modeling needs, this development represents an engineering [7] as well as scientific undertaking. The model is a suitable tool to help gain insight into the functioning of the whole biophysical feeding system of a dairy farm and on production risks. Once trusted and accepted, the model will be able to be used as a basic tool to justify particular decisions.

The model could be refined in several ways. Modeling the sward structure to account for the sheath and lamina composition could be done easily and might improve the intake module if necessary. More importantly, but more difficult, would be the incorporation of a nitrogen cycle submodel which could use parameters easily recorded on typical production systems, when no database is available at a regional level. At present, SEPATOU has only a region-specific submodel based on a rough relation between qualitative nitrogen fertilizer input and the resulting herbage nitrogen index. Some extensions of the model might also be considered. Handling the whole year's cycle of production would require only a slight enhancement of the growth process

submodel [43]. Also, it would not be too costly in principle to go from a pure grass cover to grass-legume mixtures to simulate deferred grazing management over the summer period. A more ambitious project would be to adapt or broaden the model so as to cope with different grazing management problems involving, for instance, ruminant livestock other than dairy cows or mixed grazing in which different herds would graze successively on the same fields.

A distinctive feature of the project is that the biophysical model was designed to interact with a decision model. The comprehensiveness, and the temporal and spatial scope of the model, together with its intended use, led us to make key assumptions about the underlying simplification and theorization of reality. Clearly, the degree of abstraction and coarseness of inner processes are an impediment to the pertinence, usability and acceptance of the model. Choosing field and sward rather than plant or organs of plant as the basic unit of the model is a crucial design step. The model, by virtue of being organized at this level of detail, can integrate simple soil, herbage and animal modules that simplify validation and contribute to overall soundness. The information required to describe typical farm configurations considered in simulation studies is commonly accessible to extension agents familiar with specific sites. From an agronomic point of view this modeling effort embodies a shift of emphasis from a physiology-focused approach to a management-oriented approach. This project suggests that dealing with the complex interactions between management operations and their delayed effects is still a challenging task in agronomic research. The main lesson when developing a management-oriented model is not to rely too much on approaches based on a straightforward assembly of existing detailed research models, but to start by identifying the requirements imposed by the purpose of the model.

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REFERENCES

[1] Aubry C., Papy F., Capillon A., Modelling Decision-Making Processes for annual Crop Management, Agric. Syst. 56 (1998) 45–65.

[2] Aufrère J., Étude de la prévision de la digestibilité des fourrages par une méthode enzymatique, Ann. Zootech. 31 (1982) 111–130.

[3] Bélanger G., Gastal F., Lemaire G., Growth of a tall fescue sward fertilized with different rates of nitrogen, Crop Sci. 32 (1992) 1371–1376.

[4] Brisson N., STICS: a generic model for the simulation of crops and their water and nitrogen balances. 1. Theory and parameterization applied to wheat and corn, Agronomie 18 (1998) 311–346.

[5] Coléno F.C., Le pâturage des troupeaux laitiers en question : contribution d'une analyse des décisions des éleveurs, Fourrages 157 (1999) 63–76.

[6] Coquillard P., Hill D.R.C., Modélisation et simulation d'écosystèmes, Masson, Paris, 1997.

[7] Cox P.G., Some issues in the design of agricultural Decision Support Systems, Agric. Syst. 52 (1996) 355–381.

[8] Cros M.J., Duru M., Garcia F., Martin-Clouaire R., SEPATOU: a Decision Support System for Management of Rotational Grazing in a Dairy Production System, Proceedings of 2nd European Conference on Information Technology in Agriculture, in: Schiefer G., Helbig R., Rickert U. (Eds.), published by Universität Bonn, Germany, 1999, pp. 549–557.

[9] Eros M.J., Duru M., Peyre D., SEPATOU: simulation de conduite de pâturage – exemple des "menus" bretons, Fourrages 166 (2001) 165–188.

[10] Cros M.-J., Duru M., Garcia F., Martin-Clouaire R., Simulating rotational grazing management, Environ. Int. 27 (2001) 139–145.

[11] Davies A., The regrowth of grass swards, in: Jones M.B., Lazenby A. (Eds.), The Grass Crops, Chapman et Hall; London, New York, 1988, pp. 85–117.

[12] Deinum B., Dirven J.G., The effect of temperature on the digestibility of grasses. An analysis, Forage Res. 3 (1970) 1–17.

[13] Demarquilly C., Influence de la fertilisation azotée sur la valeur alimentaire des fourrages verts, Ann. Zootech. 19 (1970) 423–437.

[14] Demarquilly C., The feeding value of forages, in: Proceeding of the XVI International Grassland Congress, 4–11 October 1989, Nice, France, 1989, pp. 1817–1823.

[15] Demarquilly C., Andrieu J., Sauvant D., Tableaux de la valeur nutritive des aliments, in: Alimentation des ruminants, Versailles INRA Publications, 1978, pp. 519–562.

[16] Donnelly J.R., Moore A.D., Decision support: delivering the benefits of grazing systems research in: Buchanan-Smith J.G., Bailey L.D., McCaughey P. (Eds.), Proceedings of the XVIII Int. Grassland Congr., 1997, pp. 469–478.

[17] Dove H., Constraints to modelling the diet selection and intake in the grazing ruminant, Aust. J. Agric. Res. 47 (1996) 257–275.

[18] Doyle C.J., Baars J.A., Bywater A.C., A simulation model of bull beef production under rotational grazing in the Waikato region in New Zealand, Agric. Syst. 31 (1989) 247–278.

[19] Ducrocq H., Croissance des prairies de graminées selon la fertilisation azotée, l'intensité et la fréquence de défoliation, Ph.D. Thesis, INA-PG Paris, France, 1996.

[20] Ducrocq H., Duru M., Effet de la conduite d'un pâturage tournant sur la digestibilité de l'herbe offerte, Fourrages 145 (1996) 91–104.

[21] Duru M., Langlet A., Croissance de repousse de luzerne et dactyle. II. Modélisation, Agrochimica 39 (1987) 111–121.

[22] Duru M., Ducrocq H., Growth and senescence of the successive leaves on a Cocksfoot tiller. Effect of nitrogen and cutting regime, Ann. Bot. 85 (2000) 645–653.

[23] Duru M., Ducrocq H., A model of in vitro Lamina digestibility of vegetative cocksfoot (*Dactylis glomerata* L.), Swards influenced by nitrogen supply, defoliation and growing season, Crop Sci. 42 (2001) 214–223.

[24] Duru M., Justes E., Langlet A., Tirilly V., Comparaison des dynamiques d'apparition et de mortalité des organes de fétuques élevée, dactyle et luzerne (feuilles, talles et tiges), Agronomie 13 (1993) 237–252.

[25] Duru M., Calvière I., Tirilly V., Évolution de la digestibilité in vitro du dactyle et de la fétuque élevée au printemps, Fourrages 141 (1995) 63–74.

[26] Duru M., Ducrocq H., Tirilly V., Modeling growth of cocksfoot (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* shreb.) at the end of spring in relation to herbage nitrogen status, J. Plant Nutr. 18 (1995) 2033–2047.

[27] Duru M., Lemaire G., Cruz P., The nitrogen requirements of grasslands, in: Lemaire G. (Ed.), Diagnosis of the nitrogen status in crops, Springer Verlag, New-York, 1997, pp. 59–72.

[28] Duru M., Feuillerac E., Ducrocq H., In vitro digestibility response of cocksfoot (*Dactylis glomerata* L.) to growth and defoliation: a simple model, J. Agric. Sci. 133 (1999) 379–388.

[29] Duru M., Ducrocq H., Bossuet L., Decision rules based on herbage volume to manage a rotational grazing system in spring. Case of dairy cows and ewes, J. Range Manage. 53 (2000) 395–402.

[30] Duru M., Lemaire G., Gibon A., Balent G., Sol, fertilisation et qualité des fourrages, in: Thévenet G., Riou P. (Eds.), Qualité des sols et qualité des productions agricoles Comité pour la fertilisation raisonnée, Blois, 1997, pp. 145–154.

[31] Gosse G., Varlet-Grancher C., Bonhomme R., Chartier M., Allirand J., Lemaire G., Production maximale de matière sèche et rayonnement solaire intercepté par un couvert végétal, Agronomie 6 (1986) 47–56.

[32] Gustavsson A.M., Angus J.F., Torssell B.W.R., An integrated model for growth and nutritional value of timothy, Agric. Syst. 47 (1995) 73–92.

[33] Hémidy L., Maxime F., Soler L.G., Instrumentation et pilotage stratégique dans l'entreprise agricole, Cah. Econ. Sociol. Rural. 28 (1993) 91–118.

[34] Herrero O.M., Dent J.B., Fawcett R.H., The plant-animal interface in models of grazing systems, in: Peart R.M.N, Curey R.B. (Eds.), Agricultural system modeling and simulation, Marcel Dekker, New York, 1997, pp. 495–542.

[35] Hoden A., Muller A., Journet M., Faverdin P., Pâturage pour vaches laitières. 2. Simplification des systèmes de pâturage et des niveaux de complémentation en zone normande, Bull. Theix 66 (1986) 16–66.

[36] Hoogendoorn C.J., Holmes C.W., Chu A.C.P., Some effects of herbage composition, as influenced by previous grazing management, on milk production by cows grazing on raygrass/ white clover pastures. 2. Milk production in late spring/summer; effects of grazing intensity during the preceding spring period, Grass Forage Sci. 47 (1992) 316–325.

[37] Jarrige R., Introduction, Alimentation des ruminants, INRA, Paris, 1978, pp. 11–21.

[38] Jarvis S.C., Nitrogen management and sustainability, in: Cherney J.H., Cherney D.J.D. (Eds.), Grass for dairy cattle, CABI Publishing, Wallingford, Oxon, UK 1998, pp. 161–192.

[39] Johnston J.E., Singh A., Clark E.A., Sward height in grazing management: vertical profiles, in: Forage quality, Proc 17th Int. Grassland Congr. Palmerston North, 1993, pp. 890–891.

[40] Kerr D.V., Cowan R.T., Chaseling J., DAIRYPRO – a knowledge-based decision support system for strategic planning on sub-tropical dairy farms: 1. System Description, Agric. Syst. 59 (1999) 245–255.

[41] Kristensen T., Sorensen J.T., Clausen S., Simulated effect on dairy cow and herd production of different grazing intensities, Agric. Syst. 55 (1997) 123–138.

[42] Leaver J.D., Milk production from grazed temperate grassland, J. Dairy Resour. 52 (1985) 313–344.

[43] Lemaire G., Cinétique de la croissance d'un peuplement de fétuque élevée (*Festuca arundinacea*) pendant l'hiver et le printemps. Effet des facteurs climatiques, Ph.D. Thesis, University of Caen, 1985.

[44] Lemaire G., Productivité des peuplements prairiaux : caractérisation et diagnostic, Fourrages 127 (1991) 259–272.

[45] Lemaire G., Salette J., Relation entre dynamique de croissance et dynamique de prélèvement d'azote pour un peuplement de graminées fourragères. 1. Étude de l'effet du milieu, Agronomie 4 (1984) 423–430.

[46] Lemaire G., Gastal F., N uptake and distribution in plant canopies, in: Lemaire G. (Ed.), Diagnosis of the nitrogen status in the crops, Springer Verlag, Berlin, 1997, pp. 3–44.

[47] Marten G.C., Factors influency feeding value and effective utilization of forages for animal production, in: Proc. XV Int. Grassland Congr., Kyoto, Japon, 1985, pp. 89–97.

[48] Maurice I., Gastal F., Durand J.L., Generation of form and associated mass deposition during leaf development in grasses: a kinetic approach for non steady growth, Ann. Bot. 80 (1997) 673–683.

[49] Mayne C.S., Peyraud J.L., Recent advances in grassland utilization under grazing and conservation, in: Parente G., Frame J., Orsi S. (Eds.), The Grassland and land use systems, Proceeding of the XVI Meeting of EGF, Grado, 1996, pp. 347–362.

[50] Mohtar R.H., Buchmaster D.R., Fales S.L., A grazing simulation model: GRASIM a model development, Trans. Am. Soc. Agric. Eng. 40 (1997) 1483–1500.

[51] Monteith J.L., Solar radiation and productivity in tropical ecosystems, J. Appl. Ecol. 9 (1972) 747–766.

[52] Moore A.D., Donnelly J.R., Freer M., GRAZPLAN: decision support systems for australian grazing enterprises. 3. Pasture growth and soil moisture submodels, and the GrassGro DSS, Agric. Syst. 55 (1997) 535–582.

[53] Parsons A.J., Johnson I.R., Harvey A., Use of a model to optimize the interaction between frequency and severity of intermittent defoliation ant to provide a fundamental comparison of the continuous and intermittent defoliation grass, Grass Forage Sci. 43 (1988) 49–60.

[54] Parsons A.J., Schwinning S., Carrère P., Plant growth functions and possible spatial and temporal scaling errors in models of herbivory, Grass Forage Sci. 56 (2001) 21–34.

[55] Peyraud J.L., Astigarraga L., Review of the effect of nitrogen fertilization on the chemical composition, intake, digestion and nutritive value of fresh herbage: consequences on animal nutrition and N balance, Anim. Feed. Sci. Technol. 72 (1998) 235–259.

[56] Peyraud J.L., Comeron E., Wade M., Lemaire G., The effect of daily herbage allowance, herbage mass and animal factors upon herbage intake by grazing dairy cows, Ann. Zootech. 45 (1996) 201–217.

[57] Pfimlin A., Europe laitière : diversité, spécificités et complémentarités, Fourrages 143 (1995) 5–20.

[58] Prache S., Peyraud JL., Préhensibilité de l'herbe pâturée, Prod. Anim. 10 (1997) 377–390.

[59] Rickert K.G., Stuth J.W., McKeon G.M., Modelling pasture and animal production, in: Mannetje L., Jones R.M. (Eds.), Field and laboratory methods for grassland and animal production research, CABI Publishing, Wallingford, Oxon, UK, 2000, pp. 29–66.

[60] Robson M.J., The effect of temperature on the growth of S170 tall fescue. 2. Independant variation of day and night temperature, J. Appl. Ecol. 10 (1973) 93–105.

[61] Robson M.J., Deacon M.J., Nitrogen deficiency in small closed communities of S24 Rye grass. II. Changes in the weight and chemical composition of single leaves during their growth and death, Ann. Bot. 42 (1978) 1199–1213.

[62] Robson M.J., Ryle G.J.A., Woledge J., The grass plant-its form and function, in: Jones M.B., Lazenby A. (Eds.), The Grass Crops, Chapman et Hall; London, New York, 1988, pp. 25–84.

[63] Rykiel E.J., Testing ecological models: The meaning of validation, Ecol. Model. 90 (1996) 229–244.

[64] Sargent R.G., Validation and Verification of Simulation Models, Proceedings of the 1999 Winter Simulation Conference, Squaw Peak, Phoenix, AZ, USA, 1999, pp. 39–48.

[65] Society for Computer Simulation – Technical Committee on Model Credibility, Terminology for Model Credibility, Simulation 32 (1979) 103–107.

[66] Sébillotte M., Soler L.-G., Les processus de décision des agriculteurs, in: Brossier J., Vissac B., le Moigne J.L. (Eds.), Modélisation Systémique et Système Agraire. Décision et Organisation, Versailles, INRA, 1990, pp. 93–118.

[67] Sheehy J.E., Johnson I.R., Physiological models of grass growth, in: Jones M.B., Lazenby A. (Eds.), The Grass Crop. Chapman and Hall, New York, 1988, pp. 243–276.

[68] Simon J.C., Vertès F., Decau M.L., Le Corre L., Les flux d'azote au pâturage. I. Bilans à l'exploitation et lessivage du nitrate sous prairies, Fourrages 151 (1997) 249–262.

[69] Sinclair T.R., Muchow R.C., Radiation use efficiency, Adv. Agron. 65 (1999) 151–214.

[70] Thébault M., Dequin A., Follet D., Grasset M., Roger P., Cinq menus pour vaches laitières au pâturage. Dossier Établissement Départemental de l'Élevage d'Ile et Vilaine, 1998.

[71] Thornley J.H.M., Modelling grassland ecosystems, in Proceedings of the XIX International Grassland Congress, in: Mattos W.R.S., da Silva S.C. (Eds.), Sao Paulo, Brazil, 2001, pp. 1029–1035.

[72] Topp C.F.E., Doyle C.J., Simulating the impact of global warming on milk and forage production in Scotland. 2. The effect on milk yields and grazing management of dairy herds, Agric. Syst. 52 (1996) 243–270.

[73] Varlet-Grancher C., Gosse G., Chartier M., Sinoquet H., Bonhomme R., Allirand J.M., Mise au point : rayonnement solaire

absorbé ou intercepté par un couvert végétal, Agronomie 9 (1989) 419–439.

[74] Wilkins R., Vidrish T., Grassland for 2000 and beyond, in: Soegaard et al. (Eds.), Grassland farming. Grassland in Europe, Vol. 5, Organizing Committee of the 18th Meeting of the European Grassland Federation, Aälborg, 2000, pp. 9–18.

[75] Wilman D., Acuna P.G.H., Michaud J.P., Concentrations of N, P, K, Ca, Mg and Na in perennial ryegrass and white clover leaves of different ages, Grass Forage Sci. 49 (1994) 422–428.

[76] Wilson J.R., Variation of leaf characteristics with level of insertion on a grass tiller. I. Development rate, chemical composition and dry matter digestibility, Aust. J. Agric. Res. 27 (1976) 343–354.

[77] Wilson J.R., Minson D.J., Prospects for improving the digestibility and intake of tropical grasses, Trop. Grassl. 14 (1980) 253–257.

[78] Woledge J., Dennis W.D., The effect of temperature on photosynthesis of ryegrass and white clover leaves, Ann. Bot. 50 (1982) 25–35.

[79] Wood P.D.P., Factors affecting the shape of the lactation curve in cattle, Anim. Prod. 11 (1969) 307–316.

[80] Woodward S.J.R., Validating a model that predicts daily growth and feed quality of New Zealand dairy pastures. Modeling the Dynamics of Natural, Agricultural, Tourism and Socio-economic Systems, in: Oxley L., Scrimgeour F., Jakeman A. Hamilton (Eds.), New Zealand, 6th-9th/12/99: Modelling & Simulation Sty of Australia and New Zealand Inc. 3 (1999) 777–782.

[81] Woodward S.J.R., Wake G.C., McCall D.G., Optimal grazing of a multi-paddock system using a discrete time model, Agric. Syst. 48 (1995) 119–139.

[82] Wu L., McGechan M.B., Simulation of biomass, carbon and nitrogen accumulation in grass to link with a soil nitrogen dynamics, Grass Forage Sci. 53 (1998) 233–249.

[83] Zoby J.L.F., Holmes C.W., The influence of size of animal and stocking rate on the herbage intake and grazing behaviour of cattle, J. Agric. Sci. 100 (1983) 139–148.

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