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Nutritional evaluation of diets. Simulation model of digestion and passage of nutrients through the rumen–reticulum [1]

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Abstract

To evaluate the nutritional behaviour of simple and complex diets provided under different feeding regimes, a stochastic, dynamic and predictive simulation model was developed. Feed fractions, considered in the model were soluble non-structural carbohydrates (SNSC), insoluble non-structural carbohydrates (INSC), INSC degradation rate (kd_{INSC}), fractional passage rate (kp), neutral detergent fibre (NDF), NDF potentially digestible (PNDF), PNDF degradation rate (kd_{PNDF}), soluble crude protein (SCP), insoluble crude protein (ICP), ICP potentially degradable (PICP), and PICP degradation rate (kd_{PICP}). Animal characteristics considered in the model, were live weight and physiological status (lactation and/or pregnancy). Variables inherent to management practices were amounts and schedule of DM offered to the animals. The model was subjected to validation for a wide range of experimental conditions. Predictions of total DM and forage DM intakes (and therefore the estimate of the substitution of forage for concentrate) had an $R^2 = 0.95$ and 0.92, respectively. Prediction of NDF digestibility had an $R^2 = 0.61$ in a smaller range of experimental conditions. © 1997 Elsevier Science B.V.

Keywords: Simulation model; Rumen; Intake

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1. Introduction

In production systems, where feeding of animals is through grazing as the only source of nutrients or complemented with other feed sources such as conserved forages and/or concentrates, the feeding regime is discontinuous throughout the day. Interactions between the different feed and/or individual nutrients are functions of the nutritional characteristics of the feedstuff, the sequence and level of feeding, the animal potential and the environment (Chilibroste, 1992). These characteristics make such production systems, predominantly present in the southern hemisphere, different from those of the northern hemisphere, where the majority of the scientific information has originated. This means that many of the technologies developed to improve the efficiency of high production systems under confinement are not necessarily applicable to grazing systems. There is abundant work that has studied factors affecting voluntary intake in ruminant animals, mostly under confinement conditions (Conrad, 1966; Freer, 1981; Hodgson, 1982; Minson, 1982, 1990). In forage based animal production systems, a high correlation has been demonstrated between animal response and voluntary DM intake (Minson, 1990). Therefore, having the capacity to predict animal voluntary DM intake and the level of nutrient extraction from consumed feeds, has a strategic value in management practices for such systems as well as for the analysis of improvement alternatives.

In ruminant animals, the amount and type of nutrients available for absorption and metabolism differs profoundly from the profile of nutrients present in the feed consumed, and these differences primarily result from rumen microbial activity (Russell et al., 1992; Dijkstra, 1993). Maximal ruminal fermentation is characterized by high DM digestion together with an optimum level of microbial efficiency, goals that seem to depend on the quantity and ratio between the energy and protein supplied by the diet (Stokes et al., 1991b).

The reported mathematical and/or simulation models (Conrad et al., 1964; Forbes, 1977; Mertens and Ely, 1979; ARC, 1980; Mertens and Ely, 1982; Bywater, 1984; France et al., 1982; Kahn and Spedding, 1983; Jarrige et al., 1986; Baldwin et al., 1987; Fisher et al., 1987; Mertens, 1987; NRC, 1988; Ørskov et al., 1988b; Doyle et al., 1989; Hyer et al., 1991a,b; Seman et al., 1991; Aguilar and Cañas, 1992; Sniffen et al., 1992; Dijkstra, 1993), present great variability in the proposed objectives, although most of their titles directly reference DM intake (Chilibroste, 1993). The approach has been predominantly energetic, with few cases where energy and protein requirements are considered as a whole (ARC, 1980; NRC, 1988), and only the most recent studies take into account energy–protein interactions (Russell et al., 1992; Sniffen et al., 1992; Dijkstra, 1993). Previously mentioned models mostly work on the hypothesis of continuous supply of substrate. In general, these models evaluate one feed at a time (individual feed as well as complete diets) and little attention has been given to the construction of models with a combination of two or more feed ingredients fed separately, and the positive or negative associative effects derived from them.

The objective of the present study is to evaluate the nutritional behaviour of simple or complex diets under different nutritional regimes. To met this goal, a simulation model integrating and quantifying the dynamics of the simultaneous processes of digestion and

passage of the nutrients through the reticulo–rumen was developed. The hypothesis to be tested is that when the voluntary DM intake in ruminants is controlled by physical distension, the DM intake and ruminal digestion of the main nutrients can be predicted from quantification of the simultaneous processes of digestion and passage of nutrients through the rumen.

2. Methodology

A stochastic, dynamic (France and Thornley, 1984) and predictive simulation model was developed in the GW Basic language. The objective of the model is not to describe the process as it occurs naturally, dividing it in as many components as the available knowledge allows it, but to represent the function of the system, resulting in an acceptable predictive capacity for a wide range of production situations. A list of symbols and terms referred in the text are shown in Table 1.

2.1. Model structure

The general structure of the model and the feed fractions dynamics are presented in Figs. 1 and 2, respectively. The model allows the simultaneous use of up to five different feeds with a preferential intake of concentrates over forages and of these over silage. In the model's conception and construction, it was assumed that the animal has a potential maximum neutral detergent fibre (NDF) rumen capacity (MRC_{NDF}, Fig. 1)

Table 1
List of abbreviation used in the description of the model

Symbol	Description	Unit
NSC	Non-structural carbohydrates	% DM
SNSC	Water soluble non-structural carbohydrates	% DM
INSC	Water insoluble non-structural carbohydrates	% DM
NDF	Neutral detergent fibre	% DM
PNDF	Fraction of NDF potentiality digestible	% NDF
UNDF	Undegradable NDF	% NDF
CP	Crude protein	% DM
SCP	Water soluble crude protein	% CP
ICP	Water insoluble crude protein	% CP
PICP	Water insoluble crude protein potentiality digestible	% ICP
DCP	Degradable crude protein: SCP + (ICP * PICP)	% DM
UICP	Undegradable ICP	% ICP
kp	Potential fractional passage rate of insoluble fractions	%/h
kpe	Effective fractional passage rate of insoluble fractions	%/h
$kd_{(i)}$	Potential fractional degradation rate of fraction sub *i*	%/h
$kde_{(i)}$	Effective fractional degradation rate of fraction sub *i*	%/h
MRC_{NDF}	Maximal NDF rumen capacity	% of BW
ARC_{NDF}	Actual NDF rumen capacity	% of BW

BW = body weight.

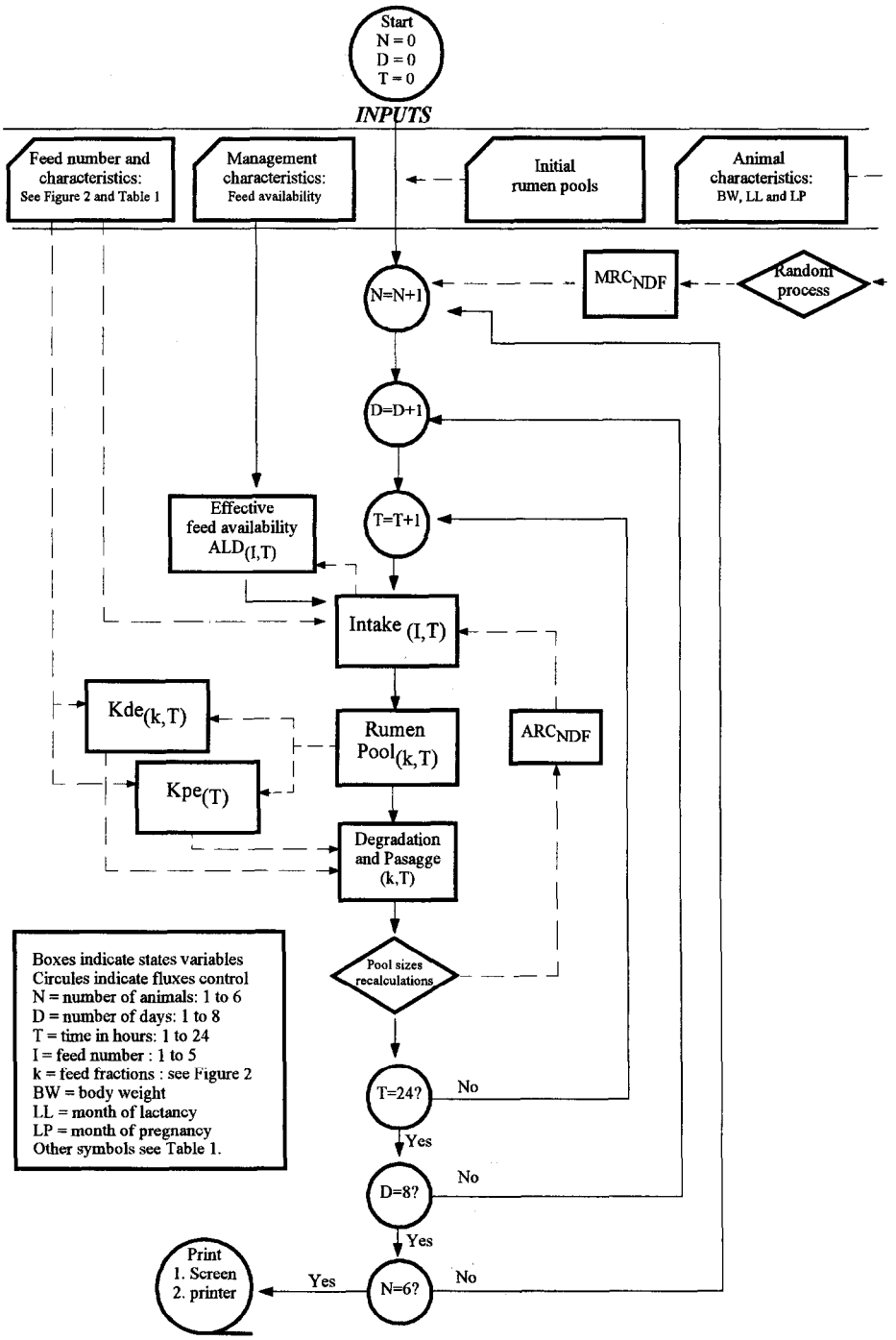

Fig. 1. Model structure and operation.

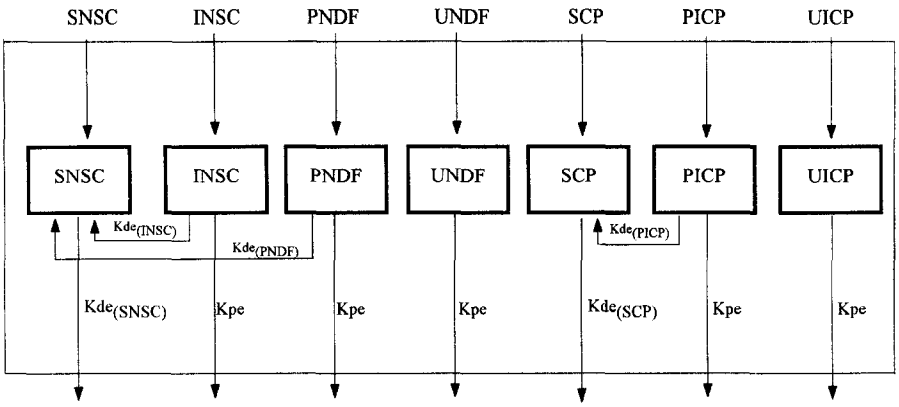

Fig. 2. Feed fractions ruminal dynamics.

which varies along its life cycles, and that the feeds have a given capacity to occupy space determined by its NDF content. Besides, feed disappearance from the rumen is given by two simultaneous and competitive processes: degradation and passage, both represented by a first order kinetics. Degradation occurs at a certain rate (kde_i, Fig. 1) varying with ruminal availability of non-structural carbohydrates (NSC) and potentially degradable protein (DCP) in each hour, thus considering the effect of the ruminal environment upon microbial activity. These parameters (availability of NSC and DCP) are functions of the type of feed consumed and the feeding regime. The effective rate of passage (*kpe*, Fig. 1) of the insoluble solid fractions is determined by the extension of NDF rumen fill. Hour was defined as the basic time unit in which the model operates. At each hourly model iteration, DM intake is calculated as the difference between MRC_{NDF} and the actual NDF rumen capacity (ARC_{NDF}) divided by the NDF content of the available feed (provided that $ARC_{NDF} \leq 80\%$ of MRC_{NDF}. The model iterates for 24 h a day for 8 consecutive days, giving results for the 8th day when an equilibrium has been reached.

2.2. Model components and exogenous variables

2.2.1. Feed inputs

The required feed inputs are SNSC, INSC, NDF, PNDF, CP, SCP, ICP, and PICP (Table 1). Carbohydrate characterization (structural and non-structural) for high production cows, has become important only in recent years. The interest for a better characterization of the different fractions is due to the fact that carbohydrates are the most important energy source for the rumen microflora and that fermentation differs largely depending upon the feed sources (Nocek and Tamminga, 1991). Non-structural carbohydrates are composed by the carbohydrates not recovered in the NDF fraction, including sugars, starch, fructans, galactans, pectines, β-glucans, etc. (Van Soest et al., 1991). This group of carbohydrates are active components of the plant metabolism and have a rapid and total fermentation potential within the rumen. Although important

advances have been achieved in the knowledge and quantification of the ruminal fermentation process in recent years, the exact quantities of carbohydrates and protein required at the ruminal level to maximize microbial performance is not yet known (Aldrich et al., 1993). While soluble feed components occupy little space in the rumen, fibre displaces considerable volume and NDF is the only chemical method isolating all the fibre components of the feed (cellulose, hemicellulose, and lignin) (Mertens, 1987). Van Soest et al. (1991), established that NDF is more closely related to the daily ruminating time, gastrointestinal tract filling and DM, than other fractions such as crude fibre and acid detergent fibre. Thus, space-occupying capacity of each feed was assigned in terms of their NDF content.

As for carbohydrates, N was differentiated between soluble fractions rapidly available for microorganisms, the potentially degradable insoluble fraction which has a slower availability and the indigestible fractions linked to the matrix of the cell wall which is not available for ruminal fermentation. The rumen indigestible fractions disappear only through passage (Fig. 2). The advantages of using this classification of N, over one applying only chemical and/or biochemical criteria, has been widely documented (Van Soest, 1982; Kristensen et al., 1982; Lindberg, 1985; NRC, 1985; Nocek and Russell, 1988; Ørskov, 1988c; Sniffen et al., 1992).

In the proposed model, degradation and passage of the different fractions was assumed to be described by as first order kinetics (Robinson et al., 1986). As inputs, the model requires potential degradation values for carbohydrates as well as for the N fractions. Although the effect of ruminal conditions on microbial activity and on degradation of insoluble fractions is well known (Hoover, 1986; Hoover and Stokes, 1991), it has usually not been incorporated in ruminal fermentation models. The models reported by Argyle and Baldwin (1988) referred by Dijkstra (1993), Russell et al. (1992) and Dijkstra (1993) are the first that consider the negative effect of low ruminal pH on NDF degradation. In the present model, the effective degradation rates (*kde*, Fig. 1) of INSC, PNDF and PICP are estimated each hour according to the ruminal availability of NSC and DCP at that moment. The potential degradation rate of NSC at high ruminal levels of NSC, is only affected by the availability of N given the high tolerance of amylolytic microorganisms to low pH levels (Hoover and Stokes, 1991). Reduction factors of the potential degradation rates used in the model are presented in Table 2. The reduction factors proposed accommodates the concept of differential capacity of cellulolitic and amylolytic microorganisms to take up N and the increased requirements for ruminal degradable protein, if the NSC availability rises (Ørskov, 1988c; Stokes et al., 1991a,b). The fixation of these levels is an arbitrary and preliminary approximation while more precise information is generated.

The dynamic nature of the digestion process indicates that the extension of digestion is a function of time feed remains in the gastrointestinal tract. In our model, it is assumed that each feed has its specific passage rate and this value must be provided assuming ad-libitum DM intake. The effective fractional passage rate (*kpe*, Fig. 1) of the different insoluble fractions is calculated at each model iteration as function of the actual NDF rumen capacity (ARC_{NDF}) expressed as fraction of MRC_{NDF}. For calculations, an arbitrary scale was defined (Table 2), using the values reported by Sniffen et al. (1992) as a reference.

Table 2
Calculation of effective fractional rates

Ruminal availability as % of rumen DM content		*Degradation rates*
NSC	DCP	Calculation of reduction factors
NSC ≤ 5	DCP ≻ 6	$Y_1 = Y_2 = Y_3 = 0.7$
	DCP ≤ 6	$Y_1 = Y_2 = Y_3 = 0.11 * DCP$
5 < NSC ≤ 8	DCP ≻ 8	$Y_1 = Y_2 = Y_3 = 0.75$
	DCP ≤ 8	$Y_1 = Y_2 = Y_3 = 0.0937 * DCP$
8 < NSC ≤ 10	DCP ≻ 10	$Y_1 = Y_2 = Y_3 = 0.85$
	DCP ≤ 10	$Y_1 = Y_2 = Y_3 = 0.085 * DCP$
10 < NSC ≤ 15	DCP ≻ 10	$Y_1 = Y_2 = Y_3 = 0.9$
	DCP ≤ 10	$Y_1 = Y_2 = Y_3 = 0.09 * DCP$
15 < NSC ≤ 35	DCP ≻ 12	$Y_1 = Y_2 = Y_3 = 1.0$
	DCP ≤ 12	$Y_1 = Y_2 = Y_3 = 0.083 * DCP$
35 < NSC ≤ 40	DCP ≻ 15	$Y_1 = 1.0$; $Y_2 = Y_3 = 0.9$
	DCP ≤ 15	$Y_1 = 0.083 * DCP$; $Y_2 = Y_3 = 0.075 * DCP$
40 < NSC ≤ 50	DCP ≻ 15	$Y_1 = 1.0$; $Y_2 = Y_3 = 0.7$
	DCP ≻ 12	$Y_1 = 0.066 * DCP$; $Y_2 = Y_3 = 0.07 * DCP$
	DCP ≤ 12	$Y_1 = 0.066 * DCP$; $Y_2 = Y_3 = 0.058 * DCP$
NSC > 50	DCP ≻ 15	$Y_1 = 1.0$; $Y_2 = 0.4$; $Y_3 = 0.5$
	DCP ≻ 12	$Y_1 = 0.066 * DCP$; $Y_2 = 0.4$; $Y_3 = 0.5$
	DCP ≤ 12	$Y_1 = 0.066 * DCP$; $Y_2 = 0.033 * DCP$; $Y_3 = 0.0416 * DCP$

Fill = $(ARC_{NDF}/MRC_{NDF}) * 100$	*Passage rates*
65 < Fill ≤ 85	$kpe = kp * 0.85$
45 < Fill ≤ 65	$kpe = kp * 0.65$
Fill ≤ 45	$kpe = kp * 0.55$

Y_1, Y_2 and Y_3 = reduction factors applied over kd_{PINSC}, kd_{PNDF} and kd_{PICP} respectively; other symbols see Table 1.

2.3. Animal input variables

Because the space-occupying capacity of feeds was expressed in terms of NDF content, the host capacity of the animal or ruminal volume, should be expressed in the same units. Since ruminal volume is a function of body weight (Van Soest, 1982), this variable is expressed in the model in terms of kg of NDF as percentage of the body weight. According to De Visser et al. (1992, 1993) and Bosch et al. (1992a) in which determination of rumen pool sizes were done, a value of 0.9% of body weight in terms of NDF (kg), was chosen as MRC_{NDF}. This value is corrected by animal physiological status (lactation and/or pregnancy), according to ARC (1980).

Taking in account the high individual variability that the animals present in terms of voluntary DM intake (Hartnell and Satter, 1979; Ørskov et al., 1988a), the MRC_{NDF} used during the simulation is estimated as a random variable according to Naylor et al. (1966) as follows:

$$x = \sigma_x * (12/K)^{1/2} * \left(\sum r_i - (K/2) \right) + u_x$$

where: x = normally distributed random variable; u_x and σ_x^2 = mean and variance, respectively, Σ sum from $i = 1$ to K and K = sum of 24 random numbers defined over the interval 0 to 1.

2.4. Management inherent variables

The schedules and amount of DM offered to the animals from each feed are inputs to the model. Additionally, restriction periods can be defined during the day, this means the hours in which the animal has no access to one or the other offered feeds thus, simulating enclosure, controlled grazing or milking time.

This model structure allows simulation of discontinuous feeding conditions and other situations in which feeds with different characteristics are offered at different times throughout the day.

2.5. Model state variables

2.5.1. Actual NDF rumen capacity

ARC_{NDF} (Fig. 1) is calculated each hour, and it is an indicator of the available space in the rumen for newly ingested feed. It is calculated as MRC_{NDF} minus the amount of NDF that remains in the rumen at each iteration.

2.6. Effective availability of feed

The amount of feed effectively available to the animal at a given hour (ALD(I, T), Fig. 1), is equal to the feed availability in the previous hour ($T-1$), minus the feed intake in the previous hour. The availability is equal to 0 during a restrictive period (animal has no access to the feed) and is equal to the amount of feed offer, during the hour when the feed is offered to the animals.

2.7. Pools

The model accounts for the state of seven pools (Fig. 2) where the contribution of each feed is kept. The pools are expressed in kg. The dynamics of the different fractions in the rumen is defined by Eqs. (1)–(7) as follows:

$$\boldsymbol{P}\mathrm{SNSC}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{SNSC}_{(I)} + (\boldsymbol{P}\mathrm{INSC} * kde_{(\mathrm{INSC},T)} + (\boldsymbol{P}\mathrm{PNDF}_{(I,T)} * kde_{(\mathrm{PNDF},T)}) \quad (1)$$

$$\boldsymbol{P}\mathrm{INSC}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{INSC}_{(I)} + \boldsymbol{P}\mathrm{INSC}_{(I,T-1)} - (\boldsymbol{P}\mathrm{INSC}_{(I,T)} * kde_{(\mathrm{INSC},T)}) - (\boldsymbol{P}\mathrm{INSC}_{(I,T)} * kpe_{(T)}) \quad (2)$$

$$\boldsymbol{P}\mathrm{PNDF}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{NDF}_{(I)} * \mathrm{PNDF}_{(I)} + \boldsymbol{P}\mathrm{PNDF}_{(I,T-1)} - (\boldsymbol{P}\mathrm{PNDF}_{(I,T)} * kde_{(\mathrm{PNDF},T)}) - (\boldsymbol{P}\mathrm{PNDF}_{(I,T)} * kpe_{(T)}) \quad (3)$$

$$\boldsymbol{P}\mathrm{UNDF}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{NDF}_{(I)} * (1 - \mathrm{PNDF}_{(I)}) + \boldsymbol{P}\mathrm{UNDF}_{(I,T-1)} - (\boldsymbol{P}\mathrm{UNDF}_{(I,T)} * kpe_{(T)}) \quad (4)$$

$$\boldsymbol{P}\mathrm{SCP}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{CP}_{(I)} * \mathrm{SCP}_{(I)} + \left(\boldsymbol{P}\mathrm{ICP} * kde_{(\mathrm{ICP},T)}\right) \quad (5)$$

$$\boldsymbol{P}\mathrm{PICP}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{CP}_{(I)} * \mathrm{ICP}_{(I)} * \mathrm{PICP}_{(I)} + \boldsymbol{P}\mathrm{PICP}_{(I,T-1)} - \left(\boldsymbol{P}\mathrm{PICP}_{(I,T)} * kde_{(\boldsymbol{P}\mathrm{ICP},T)}\right) - \left(\boldsymbol{P}\mathrm{PICP}_{(I,T)} * kpe_{(T)}\right) \quad (6)$$

$$\boldsymbol{P}\mathrm{UICP}_{(I,T)} = \mathrm{DMI}_{(I,T)} * \mathrm{CP}_{(I)} * \mathrm{ICP}_{(I)} * \left(1 - \mathrm{PICP}_{(I)}\right) + \boldsymbol{P}\mathrm{UICP}_{(I,T-1)} - \left(\boldsymbol{P}\mathrm{UICP}_{(I,T)} * kpe_{(T)}\right) \quad (7)$$

where: I = feed 1 to 5; T = hour 1 to 24; $\boldsymbol{P}$ state for pool; other symbols see Table 1.

3. Model evaluation

According to Black et al. (1993), validation is determined by the precision and level of certainty that a model achieves in its prediction under a wide range of simulation conditions. The wider the range of experimental and/or productive situations in which the model predicts accurately, the more reliable the concepts and parameters with those it was built and its predictions, will be. In this study, the simulation results were compared with results of controlled experiments by a T-test (Steel and Torrie, 1980) and a regression line between the observed and predicted results was built. A detailed description of the experiments used to validate the model is shown on Tables 3–5.

Table 3
Description of experiments used for validation

Ref.	Author	Animal breed	Weight (kg)	Treatments
1	Hartnell and Satter (1979)	Holstein	606	T1 = H + G (45:55) early lactation
			628	T2 = H + G (57:43) mean lactation
			656	T3 = H + G (67:33) late lactation
			700	T4 = H + G (82:17) dry period
2	Bosch et al. (1992a,b)	Holstein–Frisian	546	T1 = G1 + 1 kg conc., late lactation
			569	T2 = G1 + 7 kg conc., early lactation
			550	T3 = G2 + 1 kg conc., late lactation
			576	T4 = G2 + 7 kg conc., early lactation
			560	T5 = G3 + 1 kg conc., late lactation
			579	T6 = G3 + 7 kg conc., early lactation
3	Elizalde et al. (1992)	Holstein–A. Angus	615	T1 = Grazing oats; Period 1
				T2 = T1 + silage maize
				T3 = Grazing oats; Period 2
				T4 = T3 + silage maize
4	Fredrickson et al. (1993)	Hereford–A. Angus	194	T1 = Hay ad libitum
			194	T2 = T1 + 0.9 kg barley grain
			194	T3 = T1 + 0.85 kg corn grain
			194	T4 = T1 + 0.89 kg wheat grain

Ref. = reference; H + G = hay plus grain (forage: concentrate relationship); conc. = concentrate; G1, G2, G3 = early, mid and late silage harvested time respectively; T1, T2, ... = treatment number.

Table 4
Description of feeds used during validation: crude protein

Ref.	Feed name	DM %	CP %DM	SCP %CP	ICP %CP	PICP %ICP	Kd_{PICP} %/h
1	Hay	89.8	17.2	28.0	72.0	60.0	8.5
	Grain	90.1	18.3	30.0	70.0	75.0	8.0
2	Silage G1	59.4	21.3	58.0	42.0	93.0	12.0
	Silage G2	54.3	19.6	58.0	42.0	93.0	12.0
	Silage G3	60.8	20.9	58.0	42.0	93.3	12.0
	Concentrate	88.1	18.2	40.0	60.0	80.0	10.0
3	Oat Period 1	22.6	14.3	45.0	55.0	80.0	5.0
	Oat Period 2	22.8	12.0	30.0	71.0	71.0	5.0
	Silage M1	27.0	8.2	67.0	33.0	85.0	4.0
	Silage M2	27.6	8.5	60.0	40.0	85.0	4.0
4	Hay	s/d	8.9	25.0	75.0	75.0	10.0
	Barley	s/d	13.8	25.0	75.0	60.0	12.5
	Maize	s/d	13.4	15.0	85.0	76.0	3.5
	Wheat	s/d	13.3	30.0	70.0	75.0	8.0

M1, M2 = silage maize period one and two respectively; other symbols see Table 1 and Table 3.

In all the experiments used for validation, the information of the chemical composition of the feed corresponds to the one reported by the authors. The feed potential values for degradation parameters (digestion rate and extension) and passage rate, were estimated from different sources.

Table 5
Description of feeds used during validation: carbohydrates

Ref.	Feed name	SNSC %DM	INSC %DM	kd_{INSC} %/h	NDF %DM	PNDF %NDF	kd_{PNDF} %/h	kp %/h
1	Hay	10.0	15.0	30.0	49.4	70.0	4.0	3.5
	Grain	21.6	32.5	15.0	17.5	80.0	4.5	4.5
2	Silage G1	12.8	8.1	15.0	44.6	89.0	6.0	3.1
	Silage G2	10.8	5.6	15.0	54.7	82.0	6.0	3.7
	Silage G3	10.3	3.7	15.0	54.8	84.0	6.0	4.4
	Concentrate	26.2	17.5	15.0	28.6	85.0	6.0	4.0
3	Oat Period 1	10.0	16.0	25.0	38.2	78.0	6.0	3.5
	Oat Period 2	10.0	16.0	25.0	42.4	70.0	6.0	3.5
	Silage M1	10.0	10.0	25.0	47.8	50.0	4.0	3.0
	Silage M2	10.0	10.0	25.0	54.1	50.0	4.0	3.0
4	Hay	5.0	5.0	30.0	63.2	70.0	6.0	3.5
	Barley	38.9	21.4	24.2	17.3	90.0	14.5	4.0
	Maize	20.2	53.2	4.0	11.3	90.0	5.1	5.0
	Wheat	47.5	21.2	18.2	11.4	70.0	15.0	4.0

For symbols see Table 1 and Table 3.

(1) In the study of Hartnell and Satter (1979), the protein and structural carbohydrate degradation parameters were estimated from Nocek and Russell (1988) and Madsen and Hvelplund (1985), while the ruminal passage values were estimated from Sniffen et al. (1992).

(2) In the study of Fredrickson et al. (1993), the degradation and passage parameters of hay were taken from Sniffen et al. (1992) and the parameters for grains were estimated from the information reported by Tamminga et al. (1990).

(3) In the study of Bosch et al. (1992a,b), the degradation values of silage CP (rate and extension) were estimated from Sniffen et al. (1992), while the potential degradation and passage values of NDF and particulate fractions were taken from the study itself. The values assigned to the concentrate were built, based on the composition of the mixture and degradation values reported by Tamminga et al. (1990).

(4) In the study of Elizalde et al. (1992) passage rates values were taken from Sniffen et al. (1992), while the potential degradation values (CP and NDF) were taken from the ones reported in the study itself.

The comparison of results reported in the experiments with the ones obtained in the simulation, given the experimental conditions described in Tables 3–5, are shown in Table 6. In addition, Figs. 3 and 4, show the regression coefficients between the observed and model-predicted values, for total DM and forage intake, respectively. The

Table 6
Experimental and model results comparison. Total DM and forage intake

Ref.	Treatment	DM Total		DM Forage	
		Observed kg/day	Simulated kg/day	Observed kg/day	Simulated kg/day
1	T1	16.9	17.6 (0.87)		
	T2	19.8	19.1 (1.27)		
	T3	17.6	16.9 (1.02)		
	T4	10.8	11.2 (1.17)		
2	T1	12.8	16.1[a] (1.37)	11.8	15.1[a] (1.37)
	T2	17.0	19.9[a] (1.32)	9.7	13.0[a] (1.32)
	T3	12.0	11.9 (1.28)	11.0	10.9 (1.28)
	T4	17.0	16.7 (0.60)	9.7	10.0 (0.60)
	T5	15.6	5.0 (1.64)	14.0	14.6 (1.64)
	T6	19.0	18.2 (0.95)	11.2	12.0 (0.95)
3	T1	14.7	17.5[a] (0.61)		
	T2	12.8	12.9 (0.63)	6.9 (Oat)	7.7 (0.17)
				5.9 (S.M.)	5.2 (0.35)
	T3	13.6	14.5 (0.76)		
	T4	12.2	12.3 (0.32)	8.1 (Oat)	7.6 (0.17)
				4.1 (S.M.)	4.7 (0.17)
4	T1	3.3	3.2 (0.17)	3.3	3.2 (0.17)
	T2	4.2	3.9 (0.47)	3.3	3.0 (0.47)
	T3	4.2	3.8[a] (0.2)	3.4	3.0[a] (0.2)
	T4	4.1	3.9 (0.3)	3.2	3.1 (0.3)

[a] = ($P < 0.05$); S.M. = silage maize; values between brackets = standard deviation; other symbols see Table 3.

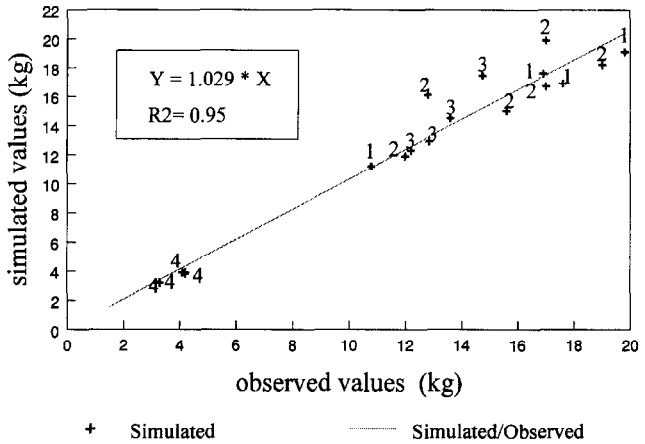

Fig. 3. Total dry matter intake.

values from the study of Elizalde et al. (1992), which appear on Fig. 4, correspond to oat and corn silage intake.

The correlation between the simulated and observed values ($R^2 = 0.95$ and $R^2 = 0.92$ for total DM and forage intake, respectively) was high. For total DM intake, 14 of the 18 treatments used in the validation (Table 6) were statistically similar while 4 differed ($P < 0.05$). Three of the latter 4 treatments, correspond to feeds with a lower NDF and higher CP and NSC content (Tables 4 and 5). It is possible that in these conditions the intake regulation was not determined by animal rumen fill, thus explaining the tendency of the model to overestimate the value of total DM and forage intake. Gasa et al. (1991), while working with Lolium perenne silage, with similar chemical composition to the G1 silage use by Bosch et al. (1992a) (Ref. 2, Tables 4 and 5), and with similar supplementation levels, determined that intake regulation with those materials was not

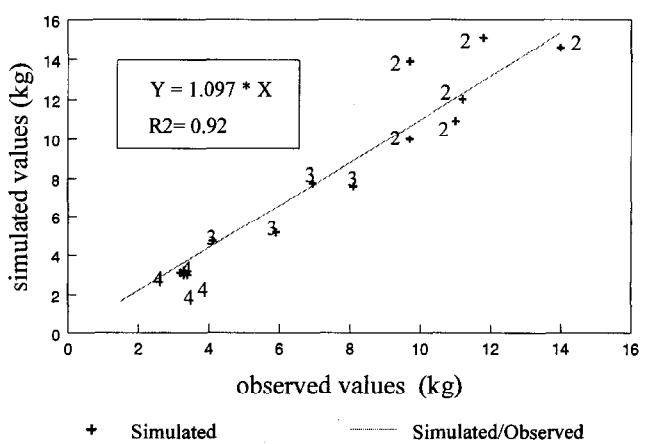

Fig. 4. Forage dry matter intake.

caused by fill. The lower NDF pools measured by Bosch et al. (1992a) for this silage (G1) at low or high levels of concentrate supplementation (4.7 and 5.4 kg NDF, respectively) compared with silage G2 (5.9 and 7.4 kg NDF) can be considered additional evidence in this respect. The particulate fractions passage rate values obtained in the experiments and estimated by the model were similar for Bosch et al. (1992b) (3.14 vs. 3.00%/h, respectively for T1) and higher in the case of Elizalde et al. (1992) (4.0 vs. 3.3%/h, respectively for T1).

For forage DM intake, in 11 of the 14 treatments, estimated values by the model and those observed in the experiment did not differ. This means that the model was useful in estimating the substitution of forage by concentrates.

Elizalde et al. (1992) completed estimates of ruminal CP and NDF digestibility. To compare the NDF ruminal degradability estimated by the model with the values of the Bosch et al. (1992a) experiment, the same quantitative procedure as that used by Elizalde et al. (1992) was used. Table 7 shows the comparison between ruminal digestibility of NDF and CP obtained by Elizalde et al. (1992) and of NDF estimated from the work of Bosch et al. (1992a,b), with the resulted degradation values from the simulation model. The regression of simulated values over observed values gave an $R^2 = 0.61$ and a $\beta 1 = 0.974$ not significantly different from 1 ($P < 0.05$). Comparison with Bosch et al. (1992a,b) shows that ruminal NDF digestibility estimated by the model and those estimated from the experimental information, were not different for silage G1 and G3 and significantly different for silage G2 (Table 7). This is not surprising because in the model, similar values were included for G2 and G3, due to the similarity of their chemical composition (Tables 4 and 5) and the potential degradation values of NDF (83.4 and 84% for G2 and G3, respectively). The degradability values resulting from the simulation (Table 7, Ref. 3) were not different when compared with experimental results for oat CP (T1 and T3), for oat and corn silage NDF, and were significantly higher for silage maize CP ruminal degradation in periods 1 and 2. Lack of agreement between the observed and simulated values for silage CP degradation can be associated as much as to

Table 7
Experimental and model results comparison. NDF and CP ruminal degradability

Ref.	Treatment Forage	Feed	Ruminal Degradability			
			CP		NDF	
			Observed (%)	Simulated (%)	Observed (%)	Simulated (%)
2	T1	G1			53.4	55.3 (3.1)
	T3	G2			33.6	49.6[a] (3.0)
	T5	G3			41.2	42.1 (2.9)
3	T1	Oat	79.1	83.6 (5.7)	45.9	44.2 (12.7)
	T2	Oat	75.3	79.6[a] (1.8)	44.0	39.6 (8.4)
	Period 1	Oat	80.6	85.2 (4.4)	51.6	45.2 (8.4)
	Period 2	Oat	72.8	77.9 (3.1)	36.6	38.6 (7.5)
	Period 1	S.M.	82.5	94.0[a] (2.8)	24.6	23.9 (3.8)
	Period 2	S.M.	77.1	88.9[a] (1.2)	25.9	22.8 (2.0)

[a] = ($P < 0.05$); S.M. = silage maize; other symbols see Table 3.

the methods used in the experiment for determination and estimation of degradation parameters (Kristensen et al., 1982; Lindberg, 1985; Madsen and Hvelplund, 1985) or in the utilization of chromium mordant NDF as a marker in the fractional passage rate estimation (Colucci et al., 1990; Bosch et al., 1992b), as in the assumptions made in the model building. The effective degradation rates estimated by the model during the calculating process, were 2.7 and 2.4%/h for periods 1 and 2, respectively, which were very similar to the ones estimated in the experiment (2.4%/h for both periods). Therefore, differences between the observed and predicted values, could have their origins in either, the differences in the assigned values to the potentially digestible fraction of the insoluble CP (85% was assumed in the model) or in the particulate fraction passage rate values or both.

Intermediate variables calculated by the model, such as ruminal degradation of individual fractions of each feed, variation in the pool size of different fractions throughout the day, and relationships between potential and effective rates of degradation and passage, cannot be statistically contrasted with experimental information.

This model identify as a major limitation the lack of reliable information about much of the ingredients commonly used in livestock feeding. Some efforts have been made to establish a data base which includes degradation characteristics (rate and extent of degradation) of structural, non-structural carbohydrates and N fractions. However, the lack of a standardized methodology has been the critical point for the development of this area (Nocek and Tamminga, 1991). During the past years, efforts have been made in Latin America to standardize the techniques used in feed characterization, making available the information generated in the different regions (RISPAL, 1990).

4. Conclusions

When the regulation of the animal's voluntary DM intake is controlled by rumen fill (physical regulation), processes that occur at the ruminal level are the most important in determining the efficiency by which the animal uses the feed consumed, and it is at this level, where the majority of the interactions between feed and its fractions are solved. It is possible to predict the voluntary DM intake and ruminal digestion of the major nutrients, from quantitative integration of the digestion process and rumen feed passage. Nutritionally important characteristics of the feed, are: (a) the ones linked to its capacity to occupy ruminal space; (b) the effective ruminal degradation rate for different feed fractions and (c) those related to the disappearance probability from the rumen towards the lower tract (e.g., hydration capacity, specific weight, etc.).

From the comparison of the experimental and simulated results (Tables 6 and 7; Figs. 3 and 4), it can be concluded that for a wide range of experimental conditions, the model showed a good accuracy level in the prediction of the total DM and forage intake ($R^2 = 0.95$ and $R^2 = 0.92$, respectively). The accuracy obtained was lower in the prediction of the NDF ruminal degradation ($R^2 = 0.61$) and moderate for CP degradation values.

Remarkable characteristics of this model are: (1) It takes into account the individual variability of animals in relation to the voluntary DM intake; (2) the degradation rates,

although they are entered as a feed attribute, do not remain constant, changing according to the ruminal availability of nitrogen and carbohydrates; (3) the passage rates are modified according the actual rumen filling; and (4) allows to predict the associative effects between different feeds.

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