Modelling of Herbage Intake and Milk Production by Grazing Dairy Cows

Rémy Delagarde
INRA, France

M. O'Donovan
Teagasc, Ireland

The XX International Grassland Congress took place in Ireland and the UK in June-July 2005. The main congress took place in Dublin from 26 June to 1 July and was followed by post congress satellite workshops in Aberystwyth, Belfast, Cork, Glasgow and Oxford. The meeting was hosted by the Irish Grassland Association and the British Grassland Society.
Proceedings Editor: D. A. McGilloway
Publisher: Wageningen Academic Publishers, The Netherlands

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R. Delagarde[1] and M. O'Donovan[2]
[1]*INRA, UMR Production du Lait, 35590 Saint-Gilles, France*
Email: Remy.Delagarde@rennes.inra.fr
[2]*TEAGASC, Moorepark Research Center, Fermoy, Co. Cork, Ireland*

Key-points

1. Models predicting intake and performance of grazing ruminants from animal, sward, grazing and supplements characteristics are rare, but they are now included in several decision support systems (DSS).
2. An evaluation of the performance and accuracy of published models are rarely undertaken by their authors, but this is proposed in this paper.
3. There is still a need for experimental research but also for the development of generic and dynamic models to predict intake and performance over a wide range of grazing conditions.

Keywords: grazing, model, evaluation, pasture intake, dairy cow

Introduction

In many parts of the world, grazed pasture is the main feed available for extensive and intensive ruminant production systems. A grazing system requires short-term and long-term management decisions for adequate herd feeding and pasture budgeting over the grazing season. However, feeding of grazing ruminants is difficult to manage in practice due to the inability of farmers to accurately estimate nutrient intake from grazed pasture. This can be achieved through an accurate prediction of pasture intake. Prediction of voluntary intake of ruminants fed indoors has been investigated over a long period, and many feeding system models have been developed (Ingvartsen, 1994; Forbes, 1995; Faverdin, 1995). Few models have been adapted to grazing, which take account of pasture availability (Pittroff & Kothmann, 2001). However, recent efforts have been made to develop and include such predictive models in decision support tools or simulators for the feeding of grazing cattle or for grazing management (Freer *et al*., 1997; Herrero *et al*., 2000; Delaby *et al*., 2001b; Cros *et al* ., 2003; Heard *et al*., 2004; Delagarde *et al*., 2004).

The purpose of this paper is to describe and list the main methods for predicting daily herbage intake and performance of grazing ruminants, especially dairy cows. The performance of the models under varying grazing and feeding managements are tested by simulations and the precision of the predictions of some models are statistically compared.

How to predict herbage intake at grazing

Factors affecting herbage intake are numerous, and can be divided into five classes: animal, sward, grazing management, supplementation and environmental factors. They were reviewed by Faverdin *et al*. (1995) for winter feeding and by Poppi *et al*. (1987), Dove (1996), McGilloway & Mayne (1996), Cherney & Mertens (1998), Peyraud & González-Rodríguez (2000) and Delagarde *et al*. (2001) for grazing. All these factors regulate DM intake through metabolic, digestive and behavioural limitations. The short-term control of feeding behaviour includes the motivation of the animal to eat and the prehensibility of the feed, determining the rate of nutrient intake. At a larger scale, the medium- or long-term regulation of intake includes the digestive and metabolic adaptations of the animal, as well as the management of body reserves and reproductive function (including gestation and lactation), especially for farm animals (Faverdin *et al*., 1995).

The general structure and complexity of existing models is be extremely variable according to the time scale of prediction, the biological function considered as determinant for intake prediction (metabolism, digestion, behaviour), the possible links with pre-existing feeding systems and the mathematical approach and databases selected for characterisation of the relationships. For simplicity, models predicting intake will be considered either as empirical or mechanistic.

Empirical models

Empirical models relate intake to several known factors that affect intake, generally by way of multiple regressions of compiled experimental data. Such an approach was developed for a long time for grazing dairy cows, but often considered a limited number of factors. The most complete multiple regressions consider animal characteristics (often milk yield and live weight), sward nutritive value (digestibility), grazing management (herbage allowance, herbage mass or sward height) and supplementary feeds (concentrate level) (Stockdale, 1985; Caird & Holmes, 1986; Peyraud *et al*., 1996; Stockdale, 2000; Maher *et al*., 2003; Stakelum & Dillon, 2004). Surprisingly, such empirical models predicting animal performance at grazing are scarce, compared to those predicting intake (Delaby *et al*., 2001a; Maher *et al*., 2003). A selection of multiple regressions predicting herbage intake and milk production by grazing dairy cows is presented in Table 1.

The main advantage of these empirical models is that intake and performance can be predicted rapidly from a single equation. However, they are limited by the size and range of the database used, the measured experimental factors, and the factors accounted for in the regression analysis. However, many interactions between factors cannot be predicted and the accuracy of the predictions is limited in extreme situations due to the simple mathematical approach of such models. Linear relationships in biological systems are unreliable across a widely differing range of situations.

Mechanistic models

Mechanistic models predict intake from a series of equations describing the main mechanisms regulating intake. They can be derived from many knowledge sources and sometimes only from theoretical concepts. As the mechanisms regulating intake are numerous and can be investigated at different time scales, the structure of these models is very variable. Some models are based on the short-term defoliation processes and on the dynamic estimates of bite mass, time per bite and grazing time according to the constraints of the sward canopy (Demment & Greenwood, 1988; Woodward, 1997; Smallegange & Brunsting, 2002; Baumont *et al*., 2004). Other models consider that animals graze successively different pools of homogeneous sward quality, the best quality pools being selected before the worse quality pools during the grazing-down process (Sibbald *et al*., 1979; Freer *et al*., 1997). Finally, others consider directly an integrated response of the animals to sward structure or pasture availability on a daily basis (Johnson & Parsons, 1985; Herrero *et al*., 2000; Delaby *et al*., 2001b; Cros *et al*., 2003; Heard *et al*., 2004; Delagarde *et al*., 2004). In many cases, intake at grazing is calculated relative to voluntary intake determined often from pre-existing winter-feeding models.

The advantages of a mechanistic approach are numerous. Generic models are potentially adaptable to many animal types, swards and management practices. The mathematical approach can be complex, integrating logarithmic or exponential relationships, with asymptotic limits of the predictions for extreme situations. Variations of intake can also be considered as relative to a non-limiting situation rather than absolute, enabling the simple simulation of interactions. Finally, the choice of algorithms or the succession of equations, with the development of some iterative calculations, leads to the increase of the model robustness and the prediction of many interactions between factors.

However, many so called mechanistic models should be considered to be both empirical and mechanistic. Many equations, parameters or assumptions in mechanistic models are based on expertise or on simple literature surveys and can be considered as empirical. Moreover, a truly mechanistic model should imply that all the relationships included in the model are from cause to effect relationships, which are rarely proven. As an example, milk yield can be seen as the result of nutrient intake (output) but genetic merit potential also influences the motivation to eat and the intake capacity of the dairy cow (input). Eating time is sometimes described as a determinant of herbage intake and is stated as a predictive variable in intake models, but it can also be the result of the balance between the motivation of the animal to eat (intake capacity) and sward state driving intake rate. In that case, eating time is a consequence and not a cause of herbage intake and cannot be used as an input in models predicting intake. Describing how the cow eats and digests will not necessarily help in the prediction of how much pasture will be consumed (Kyriazakis, 2003).

Several models for grazing dairy cows

The main characteristics, inputs and outputs of a selection of five published herbage intake models for grazing dairy cows are described in Table 2. Three of these models are simple considering the required inputs and algorithms (Sepatou, Pâtur'IN, Diet-Check). Two models can be considered more complex, with a higher number of required input variables, but also with greater applicability (GrazFeed, GrazeIn). All predict daily herbage intake and are included in decision support systems.

Sepatou is a biophysical dairy farm model developed in France to evaluate rotational grazing management strategies. The animal sub model predicting herbage intake is fully described by Cros *et al*. (2003). It is based on a simplified version of the French Feed Unit system (INRA, 1989), considering the intake capacity of the cows, driven by peak milk yield and stage of lactation, and the ingestibility or fill value of the feeds, as influenced by their digestibility. Fill value of either concentrates or forages offered as supplements are different but fixed. This voluntary intake model is then adapted to grazing, considering only a linear effect of herbage allowance on intake below 20 kg DM/day). Herbage allowance is calculated from herbage mass to ground level minus 0.8 t DM/ha, considering that this amount is not grazeable by cows. The specificity of this model is that the OM digestibility of the herbage selected is calculated for each defoliated stratum assuming a theoretical vertical distribution of herbage OM digestibility. The average OM digestibility is then integrated from the top of the sward to the post-grazing sward height, depending on herbage allowance. However, the average OM digestibility of the herbage selected remains difficult to calculate from the published equations and intake predictions seem insensitive to variations in OM digestibility, which is linked to herbage allowance variations.

Table 1 A selection of multiple regressions predicting herbage intake and milk yield of grazing dairy cows

Reference	Meijs & Hoekstra, 1984	Stockdale, 1985	Caird & Holmes, 1986	Caird & Holmes, 1986	Peyraud *et al.*, 1996	Peyraud *et al.*, 1996	Stockdale, 2000	Maher *et al.*, 2003	O'Donovan *et al.*, unpub	Delaby *et al.*, 2001a	Delaby *et al.*, 2003	Maher *et al.*, 2003	O'Donovan *et al.*, unpub
Grazing system	R	R	R	S	R	R	R	R	R	R	R	R	R
Predicted variable	HOMI	HDMI	TOMI	TOMI	HOMI	HOMI	HDMI	HOMI	HDMI	MY	MY	MY	MY
n	117	223	165	144	95	95	-	192	2839	197	550	192	2839
R^2	0.90	0.79	0.67	0.53	0.72	0.60	0.81	0.78	0.52	0.89	0.91	0.74	0.84
r.s.d	0.78	1.30	1.91	2.52	1.52	1.78	0.26	1.12	2.03	1.67	1.47	1.68	2.71
Intercept	-0.61	-7.817	0.32	8.23	-40.3	-2.5	2.34	3.85	-12.5	-1.9	-4.2	-0.835	-9.1
Animal													
LW		1.10	1.00	0.40	0.95	0.74		0.50	1.19				
FCMpre					0.26	0.26		0.14		0.69	0.63	0.66	
MY			0.18	0.21									
FCMmax									0.23				0.59
SL				0.069					0.035				-0.38
Sward and grazing													
Height basis (cm)	4	0	0	0	0	0	0	4	4	5	5	4	4
OM digestibility (0-1)	6			25				10				24	
A^{-1}					-114								
HM		1.1	-1.0		9.4				2.6				-0.9
HM^2					-0.82				-0.0005				
HA	0.98	0.27	0.54			0.33	0.28	0.23	0.17	0.2	0.68	0.30	0.14
HA^2	-0.0140	-0.0018	-0.0060			-0.0033	-0.0073		-0.0017		-0.0133		-0.0013
HA^{-1}													
RPMH				-0.29			0.42						
C supplementation													
C	1.48		1.64	-0.12					-0.48	1.04	0.95		0.76
C^2									-0.037				
C*HA	-0.039		-0.048										
C*RPMH				0.13									

R: Rotational ; S: Set-stocking ; TOMI or HOMI (HDMI): Total or herbage OM (DM) intake (kg); n number of data; R^2 coefficient of correlation; r.d.s. residual standard deviation; LW live weight (100 kg); FCMpre pre-experimental fat-corrected milk; MY milk yield (actual); FCMmax maximum fat-corrected milk at the peak of lactation; SL stage of lactation (weeks from calving); Height basis: for calculations of HM and HA; A daily offered area (m^2/cow/day); HM herbage mass (t DM/ha); HA herbage allowance (kg DM/cow/day), RMPH rising plate meter height (cm), C concentrate intake (kg DM)

Table 2 Main characteristics, input and output variables for five predictive herbage intake models for grazing dairy cows (• factor taken into account, (•) factor partly taken into account, - factor not taken into account).

Model	GrazFeed	Pâtur'IN	Sepatou	DietCheck	GrazeIn
Country	Australia	France	France	Australia	E.U.
Reference	Freer *et al* . 1997	Delaby *et al* . 2001b	Cros *et al* . 2003	Heard *et al* . 2004	Delagarde *et al.* 2004
Type of animals	all ruminants	dairy cows	dairy cows	dairy cows	dairy cows
Type of swards	many	PRG-WC	PRG-WC[a]	several	many
Grazing system	R+S[b]	R	R	R	R+S
Animal					
Peak milk yield	•	•	•	-	•
Live weight	•	•	-	•	•
Body condition score	•	-	-	-	•
Age	•	-	-	-	•
Days in milk	•	•	•	-	•
Stage of gestation	•	-	-	-	•
Sward					
Species	•	-	-	•	•
OM digestibility (offered)	•	-	•	-	•
OM digestibility (selected)	•	-	•	-	-
Crude protein	•	-	-	-	•
Vertical structure	•	-	(•)	-	-
Morphology	•	-	-	-	-
Grazing					
Herbage allowance	•	•	•	•	•
Herbage mass	•	•	(•)	•	•
Daily access time	-	-	(•)	-	•
Supplementation					
Concentrate amount	•	•	•	•	•
Concentrate nature	•	-	-	-	•
Forage amount	•	•	•	-	•
Forage nature	•	-	-	-	•
Interactions					
Animal × Grazing	•	•	-	-	•
Animal × Supplem	•	•	-	-	•
Grazing × Supplem	•	•	•	•	•
Animal × Grazing × Supplem		•	•	-	- •
Outputs of the model					
Herbage intake	•	•	•	•	•
Milk yield	•	-	-	-	•
Weight gain	•	-	-	-	-

[a] PRG-WC perennial ryegrass-white clover; [b] R: rotational, S: set-stocking; Supplem.: supplementation

Pâtur'IN is a tactical decision support tool developed in France to help grazing management of dairy herds (Delaby *et al*., 2001b). The intake sub model is based on a simplified version of the French Feed Unit system (INRA, 1989), estimating intake capacity of the herd from the average peak milk yield, stage of lactation and live weight of the cows. The fill value of grazed herbage, concentrates and forages offered as supplements are fixed. The relative herbage intake at grazing is calculated as a proportion of voluntary intake considering grazing conditions, mainly sward depletion. This model is designed, in particular, to estimate the day-to-day variation in herbage intake under rotational grazing with several days residency time in each paddock. Each day within a paddock, the increasing negative effect of sward structure on herbage intake is taken into account from an exponential function based on the ratio between the sward depth still available for grazing expressed as a proportion of the initial sward depth available for grazing. The sward depth available for grazing is calculated as the difference between the pre-grazing sward height and a minimum post-grazing sward height, defined as a proportion of the pre-grazing sward height. Under strip grazing, the sward height depletion effect on intake is calculated hourly with the same exponential function. Moreover, low or high pre-grazing herbage masses negatively affect herbage intake.

Diet-Check is a simple tactical DSS developed in Australia to help dairy farmers to estimate nutrient intake by strip-grazing dairy cows. The herbage intake model is fully described by Heard *et al*. (2004). Daily herbage intake (per 100 kg LW) is firstly calculated for unsupplemented cows from herbage allowance (per 100 kg LW), pasture height and sward species. The effect of herbage allowance to ground level is considered with an exponential function, and pasture height with a positive and linear effect on intake. For cows receiving concentrates, the substitution rate is a linear function of herbage intake (of unsupplemented cows), supplement intake, season and sward species. The relationships were developed from a large Australian database. In the decision support tool, the prediction of herbage intake enables the calculation of energy and protein balance, as well as the marginal milk response to supplements from the herbage intake of unsupplemented cows (given their body condition score and the season).

GrazFeed is a commercially available sofware package providing estimates of animal intake and production at grazing, and is part of the decision support tool GrazPlan developed in Australia. The details of the herbage intake model are fully described by Freer *et al*. (1997). It is designed for any ruminant and sward type. The potential herbage intake is firstly calculated from body size, peak milk production and stage of lactation. The relative herbage intake at grazing is thereafter calculated taking into account the effect of green and dead herbage masses for either strip-grazing or continuous grazing, and the herbage allowance effect under strip grazing. The specificity of this model is that herbage mass is arbitrarily divided into six pools of fixed digestibility. During the grazing process, animals select successively these pools from the highest to the lowest digestibility. Under strip-grazing, these calculations are made five times a day, to account for the high rate of sward depletion. However, the herbage allowance effect on intake is not easily simulated from the published equations. Rotational grazing with several days of residency time in a paddock also seems difficult to simulate. For supplemented animals, the model considers that the amount of the supplement offered will not be automatically consumed. The amount of supplement really consumed is calculated through an estimate of the motivation of the animal to eat the supplement. This motivation is a function of the relative digestibility of the supplement compared to the digestibility of the grazed pasture pool. Finally, the substitution rate between supplements and grazed pasture varies with a number of factors, including the availability of ruminal degradable protein and lactation stage. This model also estimates milk production and live weight change.

GrazeIn is a model for predicting herbage intake and milk yield of grazing dairy cows, developed as part of the European Grazemore decision support tool (Mayne *et al*., 2004). The animal sub model is briefly described by Delagarde *et al*. (2004) and a full description of the model will be published soon. The model first calculates the voluntary herbage intake according to the principles of the French Fill Unit system (INRA, 1989), including the intake capacity of the cows and the offered feeds ingestibility. Intake capacity is a function of peak milk yield, live weight, condition score, age, stage of lactation and of gestation. Herbage fill value depends mainly on the main sward species, OM digestibility and crude protein content. Concentrate fill value is a function of substitution rate, depending on energy balance of the cows. In a second step, the model estimates the relative intake at grazing taking into account the effects of herbage allowance and herbage mass under strip- or rotational grazing, sward surface height under set-stocking, and daily access time to pasture whatever the grazing system. Exponential equations were developed from a literature review. The specificity of this model is based on the assumption that herbage mass has no effect on intake when swards are compared at similar herbage allowance above 2 cm. Moreover, iterative calculations enable the estimation of all the interactions between animal, sward, grazing conditions and supplement characteristics. This model is designed for dairy cows only, but is easily adaptable for other ruminants. The model also predicts the herd milk production for each grazed paddock.

Predicting grazing conditions and supplementary feeding effects on intake

The influences of animal characteristics and sward nutritive value on intake are not specific to grazing situations, and they will not be investigated. In order to make possible the comparison between predictions, characteristics of the dairy herd (multiparous cows, peak milk yield of 40 kg/cow per day, DIM of 150 days, LW of 600 kg), sward grazed (pure vegetative perennial ryegrass, herbage mass of 4.2 t DM/ha to ground level, i.e. 2.0 t DM/ha above 4 cm, OM digestibility of 0.80, CP of 180 g/kg DM) and season (spring) were fixed in all simulations. Some simulations were not possible to run from the published description of the models but were obtained from direct use of the DSS in which the models are included (GrazFeed version 4.1.5.) or with the help of the authors (Pâtur'IN).

Herbage allowance

The allowance-intake relationship for rotationally grazing dairy cows has been widely researched with linear, curvilinear and more recently exponential relationships developed. A selection of seven published curvilinear or exponential relationships between herbage allowance to ground level and herbage intake of grazing dairy cows are presented in Figure 1.

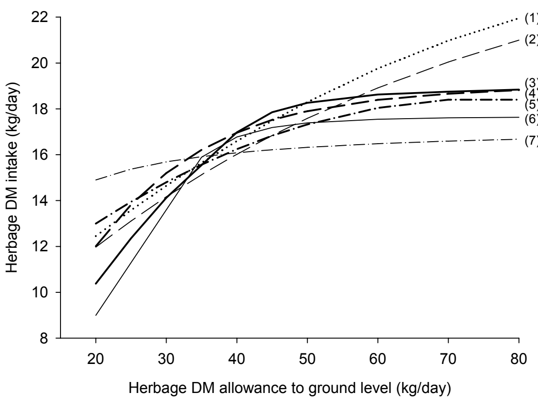

Figure 1 Simulated effect of herbage allowance on herbage intake by grazing dairy cows. The conditions of the simulations are described in the text. Models : (1) Stockdale (2000), (2) Diet-Check (Heard *et al*., 2004), (3) GrazFeed (Freer *et al* ., 1997), (4) GrazeIn (Delagarde *et al*., 2004), (5) Stockdale (1985), (6) Pâtur'IN (Delaby *et al*., 2001b), (7) Peyraud *et al*. (1996)

The average increase in herbage intake is close to 0.20, 0.15 and 0.11 kg DM per kg DM increase in herbage allowance in the ranges 20 to 30, 30 to 40 and 40 to 50 kg DM herbage allowance, respectively. Intake predictions are quite similar between models for medium herbage allowances but predicted intake differences are greatest at low (< 30 kg DM/day) and high (> 50 kg DM/day) herbage allowances. The range in herbage intake predictions between models is close to 6, 1, 4 and 6 kg DM/day for herbage allowances of 20, 40, 60 and 80 kg DM/day, respectively. These discrepancies for extreme herbage allowances may arise from the dataset used to calibrate equations but also from the mathematical approach, which often determines the curvature of the relationship and the robustness of the predictions for atypical situations.

Pre-grazing herbage mass or sward height

In this section, pre-grazing herbage mass and sward height will be considered as similar descriptors of sward state, i.e. a linear relationship between mass and height. In rotational grazing systems, the effect of pre-grazing sward height on herbage intake has not been researched to the same extent as the effect of herbage allowance. Recent reviews or data compilations suggest that intake is less sensitive to sward height than to herbage allowance (Delagarde *et al*., 2001; Heard *et al*., 2004). In published multiple regressions, the effect of sward height or herbage mass on intake is linear or quadratic, with a large range in slopes (Table 1). Delagarde *et al*. (2001) highlighted that the slope of the relationship between herbage mass and herbage intake largely depends on the height at which herbage mass and then herbage allowance are considered. In the more complex models, the effect of sward height is often taken into account indirectly (see above models description). The simulated effect of sward height on intake for four recent models is shown in Figure 2. Sward heights of 8, 12, 16, 20 cm are approximately equivalent to 1, 2, 3 and 4 t DM/ha above 4 cm, and 3.0, 4.2, 5.3 and 6.4 t DM/ha to ground level, respectively. Globally, all models predict a positive effect of sward height on intake at similar herbage allowance to ground level, but with very different slopes and interactions with herbage allowance. GrazFeed and GrazeIn predict a curvilinear effect of sward height on intake, with a slightly higher effect at high herbage allowance for GrazFeed and a higher effect at low allowance for GrazeIn. Diet-Check predicts a strong and linear effect of sward height on intake, whatever the herbage allowance. Pâtur'IN predicts an intake reduction for low sward height whatever herbage allowance but also for high sward height at high herbage allowance. These discrepancies of approach and of results between models highlights that the effect of pre-grazing sward height or herbage mass on intake for rotationally grazed dairy cows is not yet clearly established and requires further investigations. Under set-stocking management, the curvilinear relationship between sward surface height and herbage intake is widely known (Penning *et al*., 1991; Rook *et al*., 1994) and taken into account in GrazFeed and GrazeIn.

Sward structure

For a given herbage mass, sward structure may be defined by the bulk density (ratio between mass and height), by the vertical distribution of the herbage mass over different strata, and by the morphological composition of the sward, i.e. proportion of leaves, stem, pseudostem and dead material. The influence of these factors on daily herbage intake by grazing ruminants were scarcely studied, and generally are not taken into account in existing models. However, models already taking into account the effects of herbage allowance, herbage mass, sward species, herbage digestibility and CP content probably indirectly account for several aspects of sward structure. GrazFeed is the model integrating most of the sward structure variables. However, simulation with the GrazFeed software shows that herbage intake prediction is not sensitive to sward bulk density *per se* at similar herbage mass, with a decrease of 0.1 to 0.2 kg DM of herbage intake from 250 to 330 kg DM/ha/cm of the above ground bulk density. Herbage intake prediction is more sensitive to dead material proportion in the sward, decreasing by 1.0 kg DM from 10 to 20% of dead material, at similar herbage OM digestibility.

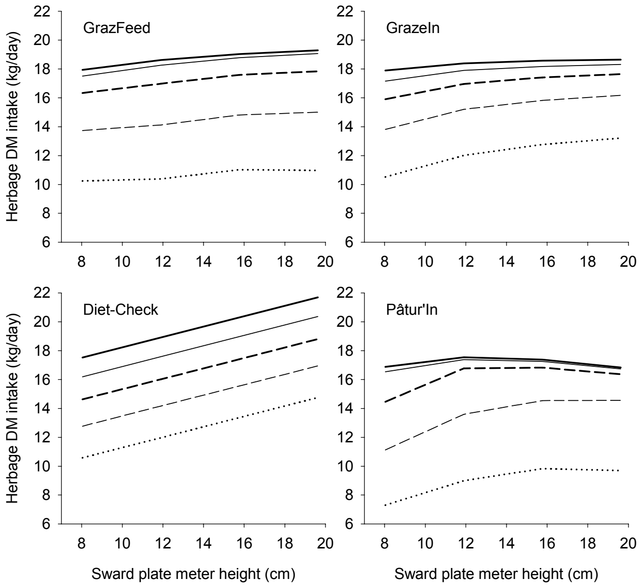

Figure 2 Simulated effect of pre-grazing sward height, measured with a plate meter, on herbage intake by grazing dairy cows according to different herbage allowances measured to ground level. The conditions of the simulations are described in the text. Models : GrazFeed (Freer *et al*., 1997), GrazeIn (Delagarde *et al*., 2004), Diet-Check (Heard *et al*., 2004), Pâtur'IN (Delaby *et al*., 2001b). Herbage allowance: ····· 20, – – 30, ▬ ▬ 40, —— 50 and ▬▬ 60 kg DM/cow/day.

Daily access time to pasture

In most of the models, herbage intake is predicted only for full daily access to pasture, i.e. approximately 18 to 20 h per day for lactating cows milked twice daily. However, in autumn, winter and early spring, cows have frequently limited access to pasture, for instance between milking times. Buckmaster *et al*. (1997) first tried to take into account the daily access time available for grazing with a simple two linear-phase equation, considering that access time to pasture is not limiting for intake up to 8 h per day (Figure 3). More recently, Delagarde *et al*. (2004) built an exponential relationship between intake and access time from a literature review (Figure 3). The relationship is modulated by the sward height, which determines the potential intake rate by the grazing cows when daily access time is limiting. Compared to the herbage intake of unsupplemented dairy cows with full daily access time to pasture, the herbage intake predicted by GrazeIn is approximately 0.94, 0.90, 0.84 and 0.67 for daily access times of 12, 8, 6 and 4 hours, respectively. The decrease of herbage intake with decreasing access time to pasture is low above 8 hours of daily access because cows generally graze close to 8 hours daily and because they are able to confine their grazing activities during this period of access. Better prediction of herbage intake by ruminants with limited access time to pasture requires extra experimental research, particularly considering the possible interactions with other grazing or supplementary feeding conditions.

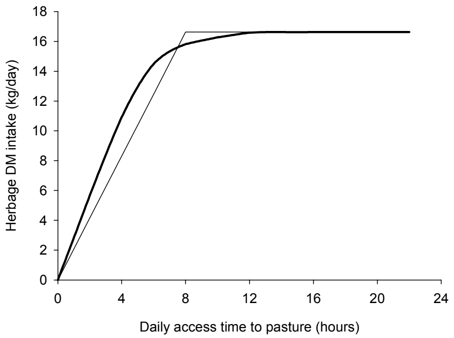

Figure 3 Simulated effect of daily access time to pasture on herbage intake by grazing dairy cows. The conditions of the simulations are described in the text. Models : ▬▬ GrazeIn (Delagarde *et al*., 2004), —— Buckmaster *et al*. (1997)

Concentrate supplementation

For dairy cows fed indoors, the marginal substitution rate between roughages and concentrates depends on animal requirements, roughage quality, concentrate quality and finally the energy balance of the animal (Faverdin *et al*., 1991). At grazing, the same concepts can be applied. Rate of substitution increases with increasing pasture availability, from 0 for high grazing pressure to 0.6-0.8 for low grazing pressure (Stockdale, 2000; Peyraud & Delaby, 2001). The challenge for an accurate prediction of substitution rate at grazing is to account for all of the possible interactions between animal, sward, grazing conditions and supplement characteristics. An empirical approach cannot achieve this. Responses of strip-grazing dairy cows to concentrate intake level in four models are shown in Figure 4. All models show similar trends, and predict increasing substitution rate and decreasing marginal milk response for increasing herbage allowance and concentrate intake level. However, the absolute values of substitution rate and marginal milk response to concentrate are quite different between models. European models predict lower substitution rate and higher milk response than Australian models. This difference can originate partly from different cow production potentials as illustrated in the study of Horan *et al*. (2005). In this study a low milk production response to concentrate and high substitution rate was observed with a New Zealand cow strain, while a Holstein Friesian of high milk production potential exhibited a low substitution rate and a high response to concentrate.

Forage supplementation

As forage (hay, haylage or silage) supplementation at grazing is not as extensively researched as concentrate supplementation, there are no multiple regression equations predicting intake for grazing dairy cows supplemented with forages. Substitution rate between grazed pasture and forage supplements was reviewed by Phillips (1988). All the models presented in Table 2 predict the substitution rate for forage-supplemented dairy cows, with interactions between forage supplements and pasture availability. Substitution rates are higher for forage than for concentrate supplementation due to higher forage fill value.

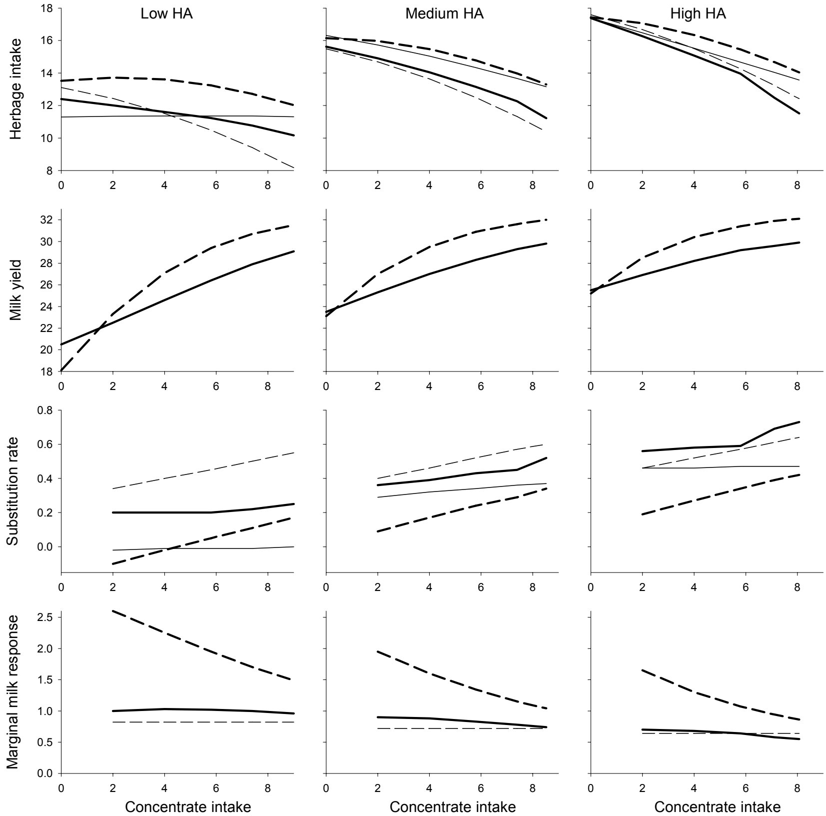

Figure 4 Simulated effect of concentrate supplementation level (kg DM/day) on herbage intake (kg DM/day), milk yield (kg/day), substitution rate (DM basis) and marginal milk response to concentrate (kg milk/kg DM concentrate) by grazing dairy cows. The conditions of the simulations are described in the text. Simulations are done for low, medium and high herbage allowance (HA: 25, 37 and 50 kg DM/day to ground level, respectively). Models: – – Diet-Check (Heard *et al*., 2004), ▬ ▬ GrazeIn (Delagarde *et al*., 2004); —— Pâtur'IN (Delaby *et al*., 2001b); ▬▬ GrazFeed (Freer *et al*., 1997)

Comparison of the accuracy of a number of models

The authors of respective models rarely carry out an evaluation of the accuracy of model predictions. In this section, a global and statistical comparison of the accuracy of some multiple regression equations and models is investigated. Experimental databases coming from TEAGASC (Ireland) and from INRA (France) were used to compare model predictions and actual values of herbage intake by grazing dairy cows. Individual herbage intake was measured from n-alkanes at TEAGASC and from faecal output and herbage digestibility estimates at

INRA. The individual cow characteristics and herbage intake were averaged per grazing herd and per paddock before running the different models. The dataset from TEAGASC includes a total of 20 experiments from 1988 to 2000, representing 190 grazing herds with an average of 15 cows per herd. The dataset from INRA includes 11 experiments from 1988 to 2000, representing 114 grazing herds with an average of 6 cows per herd (Table 3). The accuracy of predictions is investigated through the calculation of the mean prediction error (MPE) and the proportions of the mean square prediction error explained by the mean bias, the line bias and random error (Rook *et al*., 1990). A relative MPE of 0.15, expressed as a proportion of the mean actual value, means that the model predicts herbage intake with an error of 15%.

Models compared

Five multiple regressions and four herbage intake models taking into account at least some animal characteristics and grazing conditions were selected for this comparison (Table 4). Unfortunately, it was not possible to run a number of models from the published information, for example GrazFeed (Freer *et al*., 1997). A constant substitution rate of 0.4 was added in the multiple regressions of Stockdale (1985) and Peyraud *et al*. (1996) in order to predict intake for supplemented cows. For the Sepatou model (Cros *et al*., 2003), the OM digestibility of the herbage offered (above 4 or 5 cm) was used as an input because the estimation of the OM digestibility of the selected herbage cannot be easily estimated. Herbage mass and herbage allowance were measured above 4 cm at TEAGASC and above 5 cm and/or to ground level at INRA. As many regressions and models are calibrated to ground level, herbage mass and thus herbage allowance was calculated to ground level before simulations.

Table 3 Description of the database of 304 experimental herds of grazing dairy cows (190 from TEAGASC and 114 from INRA) used to compare the precision of the prediction of herbage intake between different multiple regressions and models

Variable	Mean (n = 304)	s.d.	Max	Min	TEAGASC (n = 190)	INRA (n = 114)
Actual Intake (kg DM)						
Herbage	15.9	2.09	22.0	9.9	15.6	16.2
Concentrate	0.9	1.23	5.4	0.0	0.9	0.8
Total	16.7	2.28	23.4	10.4	16.6	17.0
Actual milk yield (kg)	21.7	5.51	41.8	8.9	22.4	20.6
Peak milk yield (kg)	33.7	5.73	46.7	21.0	31.1	38.1
Stage of lactation (weeks)	24.2	7.80	39.9	3.8	21.3	29.0
Live weight (kg)	565	39.9	677	487	549	592
Herbage OM digestibility	0.80	0.035	0.87	0.72	0.82	0.78
Herbage CP (g/kg DM)	184	36.9	277	86	200	156
Herbage mass (t DM/ha)						
above 4 cm	2.5	0.85	5.7	0.6	2.3	2.8
to ground level[a]	4.9	1.14	9.1	3.1	4.4	5.8
Area (m²/cow)	93	38.8	246	21	111	64
Allowance (kg DM/cow)						
above 4 cm	21.3	8.58	61.2	6.6	24.5	15.8
to ground level[a]	43.2	14.91	105.4	16.5	48.6	34.4

[a] measured or estimated

Results

The mean bias between actual and predicted herbage intake ranged from –1.3 to 1.1 kg DM between models considering the 304 experimental herds (Table 4). The overall under- or over-estimation of herbage intake according to the model was generally consistent between the two datasets. The average mean prediction error ranged from 1.44 to 3.82 kg DM between models. The overall precision of the prediction of herbage intake averaged 0.15 and ranged from 0.10 to 0.25 according to the model. This range is similar to that found by Keady *et al.* (2004) evaluating five intake models for dairy cows fed on grass silages (0.10 to 0.20). Rook *et al.* (1990) also reported similar precision for intake models in beef cattle fed on grass silages, ranging from 0.08 to 0.26.

Table 4 Statistical comparison of the accuracy of different multiple regressions and models predicting herbage intake of grazing dairy cows. The TEAGASC, INRA and GLOBAL (TEAGASC+INRA) databases include 190, 114 and 304 experimental herds, respectively

Database	Regression or model	Mean predicted HI	Mean bias (P-A)	R^2	MSPE	Proportion of MSPE: bias %	line %	random %	MPE: kg DM	relative
TEAGASC	(1)	16.3	0.6	0.31	3.40	12	2	86	1.84	0.12
	(2)	16.3	0.7	0.01	19.77	2	77	21	4.45	0.29
	(3)	15.3	-0.4	0.39	3.95	4	32	64	1.99	0.13
	(4)	16.9	1.2	0.23	6.76	23	30	47	2.60	0.17
	(5)	15.4	-0.2	0.68	1.38	3	0	97	1.18	0.08
	(6)	17.0	1.4	0.17	5.46	37	0	63	2.34	0.15
	(7)	15.2	-0.5	0.30	3.13	7	0	93	1.77	0.12
	(8)	16.2	0.5	0.23	5.23	5	33	62	2.29	0.15
	(9)	15.8	0.2	0.48	2.21	1	1	98	1.49	0.10
INRA	(1)	16.5	0.3	0.22	4.58	2	24	74	2.14	0.14
	(2)	15.7	-0.5	0.17	5.86	4	34	62	2.42	0.15
	(3)	14.9	-1.3	0.25	5.51	31	9	60	2.35	0.15
	(4)	17.2	1.0	0.19	9.27	10	52	38	3.04	0.19
	(5)	16.3	0.1	0.28	3.22	0	3	97	1.79	0.12
	(6)	16.9	0.6	0.14	4.16	9	1	90	2.04	0.13
	(7)	13.6	-2.6	0.32	10.54	65	7	28	3.25	0.20
	(8)	16.3	0.1	0.21	6.95	0	50	50	2.64	0.17
	(9)	15.5	-0.8	0.39	3.38	18	3	79	1.84	0.12
GLOBAL	(1)	16.4	0.5	0.26	3.84	7	10	83	1.96	0.13
	(2)	16.1	0.2	0.03	14.56	0	71	29	3.82	0.25
	(3)	15.1	-0.7	0.32	4.53	12	23	65	2.13	0.14
	(4)	17.0	1.1	0.21	7.70	17	39	44	2.78	0.18
	(5)	15.7	-0.1	0.53	2.07	1	1	98	1.44	0.10
	(6)	17.0	1.1	0.14	4.97	25	0	75	2.23	0.15
	(7)	14.6	-1.3	0.18	5.91	27	13	60	2.43	0.16
	(8)	16.2	0.4	0.22	5.87	2	42	58	2.43	0.16
	(9)	15.7	-0.2	0.41	2.65	1	2	97	1.63	0.11

Multiple regressions : (1) Stockdale, 1985; (2) Caird & Holmes, 1986; (3) Peyraud *et al*., 1996; (4) Stockdale, 2000; (5) O'Donovan *et al* ., unpublished
Models: (6) Sepatou (Cros *et al*., 2003); (7) Pâtur'IN (Delaby *et al*., 2001b); (8) Diet-Check (Heard *et al*., 2004); (9) GrazeIn (Delagarde *et al*., 2004)

The lowest precision of intake prediction (0.29) was observed with the multiple regression of Caird & Holmes (1986) in the TEAGASC dataset. The highest precision of intake prediction (0.08) was observed with the multiple regression of O'Donovan *et al*. (unpublished, presented in Table 1) in the TEAGASC dataset, but the same data were used to develop the multiple regression (at the cow level) and to test it (at the herd level). However it also predicted herbage intake well in the INRA dataset. The large size of the TEAGASC database probably explains its high level of accuracy (Table 1). Among models, GrazeIn predictions seem the most precise in both datasets (MPE of 10 and 12%), because more factors are taken into account and because more interactions are estimated compared to the other models or regressions. The simple models are less precise (MPE from 12 to 20%) but can be used more easily.

For each model, the study of the correlations between the herbage intake bias (predicted minus actual) and the main input variables showed that the most significant correlations ($R^2 > 0.30$) were found with herbage allowance. The correlation was negative for the model of Caird & Holmes (1986) and positive for the models of Stockdale (2000) and Heard *et al*. (2004). The quadratic intake/allowance relationship of Caird & Holmes (1986) model clearly under-estimated herbage intake for high herbage allowances. The low curvature of the intake/allowance relationship of the models of Stockdale (2000) and Heard *et al*. (2004) possibly over-estimates intake for high herbage allowances (Figure 1). In the global database, considering only grazing herds offered less than 60 kg DM/cow above ground level (n=272), the accuracy of the three above models was significantly increased (MPE of 0.18, 0.16 and 0.14 for Caird & Holmes (1986), Stockdale (2000) and Heard *et al*. (2004), respectively).

Conclusions

This review has shown that models predicting intake and performance of grazing dairy cows are scarce, particularly regarding models with a mechanistic approach. The different ways of considering grazing conditions and pasture availability leads to large variations of intake predictions for atypical situations. However, the selected multiple regressions or models showed precision comparable to winter feeding models when comparing predicted values to a large set of independent actual values (mean prediction error range 10 to 20%). From a practical point of view, future models should have higher applicability, predicting both intake and performance over a large range of feeding and grazing management practices, and preferably from easy-to-obtain input variables. Moreover, much effort should be made to evaluate these models, testing prediction, robustness and accuracy. Today, even the more complex models are static, intake and performance being predicted from the description of the actual conditions. The challenge for future models is also to predict the dynamic pattern of intake during the gestation-lactation cycle, considering the carry-over effects of previous feeding strategies on subsequent intake and performance. Obviously, the development of such models should not be considered without the development of decision support tools enabling the effective use of such models.

Acknowledgements

Dr. Janna Heard is gratefully acknowledged for the clarifications on the Diet-Check program. Many thanks are due to Dr. Luc Delaby for the provision of equations to evaluate the herbage intake model of Pâtur'IN and to Dr. Gearoid Stakelum for the compilation of the TEAGASC experimental database.

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