Prediction of the digestibility of the diet of horses: evaluation of faecal indices

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Abstract

Data from *in vivo* digestibility trials with four to six horses fed twenty-seven forage-based diets are used to calculate prediction equations for the digestibility of dry and organic matter, based on the crude ash (CA), crude protein (CP) and crude fibre (CF) contents of diets and faeces. The most precise prediction of dry-matter digestibility (r.s.d. = 0·032, R^2 = 0·80) was derived from a multiple regression including faecal (CP, CF) and dietary parameters (CF). Among faecal parameters, CP was the best single predictor of both digestibility (r.s.d. = 0·040, r^2 = 0·63) and dietary CP content (r.s.d. = 0·028, r^2 = 0·59). For biological reasons we propose a non-linear model that allows prediction of dry- and organic-matter digestibility from faecal CP content with reasonable precision (r.s.d. = 0·038, 0·036, r^2 = 0·65, 0·74, respectively). This will be adequate for many studies, especially for free-living animals in rangelands.

Introduction

The assessment of the quality of the diet of grazing animals is difficult: various methods have been used for equids, depending on the type of diet and the precision required (Table 1). Where pastures are homogeneous and selective behaviour is limited, representative samples of the diet may be collected and used to predict digestibility from indoor *in vivo* trials (Chenost and Martin-Rosset, 1985), from the chemical composition of dietary samples (Vander Noot and Trout, 1971; Martin-Rosset *et al.*, 1984), from *in vitro* measurements (Applegate and Hershberger, 1969; Uden and Van Soest, 1984; Miraglia and Tisserand, 1985; Chenost, 1986; Miraglia *et al.*, 1988) or from ruminant values (Hintz, 1969; Martin-Rosset *et al.*, 1984). Methods based on external markers (Haenlein *et al.*, 1966) or on dietary tracers, such as insoluble ash (Orton *et al.*, 1985), neutral-detergent fibre (Rittenhouse *et al.*, 1982) or chromogens (Kaseda *et al.*, 1983), have also been used in horses, but these did not provide reliable estimates of digestibility (e.g. Sutton *et al.*, 1977).

Most of these methods are based on dietary parameters which are therefore not available in rangelands, where complex diets and selective feeding generally prevent accurate and precise sampling of all the major items of diets. The use of faecal indices is particularly suitable in these circumstances because this technique does not require diet sampling or handling the animals, and it involves only routine chemical determinations. Although it is controversial (Hobbs, 1987; Leslie and Starkey, 1987), this useful technique has been applied in several studies of wildlife and free-ranging domestic herbivores (Caughley and Sinclair, 1996), including horses (Duncan, 1992).

The review by Holecheck *et al.* (1982) showed that, as with ruminants, various faecal variables, including crude protein content, are correlated with diet digestibility in horses (Chenost, 1986). Predictive equations of practical use are, however, not yet available. We review here methods of predicting the digestibility and crude protein content of the diet of horses from variables (crude protein, crude fibre) of the diet and faeces.

Material and methods

Measurements were carried out on four to six adult geldings (≈ 500 kg), in individual stalls. These were fed twenty-seven different forages: twelve green forages of different species and maturities (natural grassland, rye-grass and lucerne) and fifteen hays (fourteen from natural grassland and one lucerne). All forages were offered *ad libitum* except green lucerne, which was offered at 95% of voluntary intake.

Digestibility trials were conducted according to the

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Table 1 Published studies of dry-matter (DMD) and organic-matter digestibility(OMD) in horses.

Diets	Equations	R^2 or r^2	r.s.d.	Authors
4 Hays	DMD = 1·96 − 0·001CPd − 0·004CFd	0·81	–	Vander Noot and Trout (1971)
	DMD = 0·32 + 0·002CPd	0·77	–	
	DMD = 1·55 − 0·003CFd	0·81	–	
72 Hays	OMD = 0·78 − 0·001CFd	0·17	0·06	Martin-Rosset *et al.* (1984)
28 Grass hays	OMD = 0·88 − 0·001CFd	0·51	0·04	
25 Forb hays	OMD = 0·90 − 0·001CFd	0·44	0·04	
10 Forages	OMD = f(CPd)	0·63	0·04	Chenost and Martin-Rosset (1985)
	OMD = f(CFd)	0·50	0·04	
	OMD = f(CPd, CFd)	0·64	0·04	
10 Dry forages	DMD = f(IVDA)	0·92	–	Miraglia and Tisserand (1985)
	OMD = f(IVDA)	0·89	–	
9 Green forages	DMD = 0·43 − 0·27IVDT + 0·75IVDT^2	0·69	0·04	Chenost (1986)
7 Green forages	DMD = f(IVDA)	0·94	0·01	
13 Forages	DMD = f(IVDT)	0·90	–	Miraglia *et al.* (1988)
	OMD = f(IVDT)	0·88	–	
25 Diets (review)	DMD = 0·43 + 0·001CPd	0·38	–	Duncan (1992)
29 Diets	OMD = 0·001 + 0·867OMDc	0·60	–	Hintz (1969)
	OMD = −0·017 + 0·9105OMDs	0·60	–	
4 Hays	DMD = −0·23 + 1·27DMDc	0·31	–	Vander Noot and Trout (1971)
18 Grass diets	OMD = −0·15 + 1·1544OMDs	0·96	0·02	Martin-Rosset *et al.* (1984)
15 Forb diets	OMD = −0·10 + 1·262OMDs	0·71	0·03	
25 Diets (review)	CPd = −3·2 + 1·09CPf	0·88	–	Duncan and Gleize (1985 and unpublished)
	DMD = 0·43 + 0·001CPf	–	–	
10 Forages	OMD = f(CPf)	0·73	0·03	Chenost (1986)
	OMD = f(CFf)	0·36	0·04	
	OMD = f(WSMf)	0·38	0·05	

OMDs, OMDc, digestibility of organic matter for sheep and cattle (decimal fraction); DMDc, digestibility of dry matter for cattle(decimal fraction); IVDT, IVDA, *in vitro* digestibility according to Tilley and Terry (1963) or Aufrere (1982) (decimal fraction); CPd, CFd, dietary crude protein and crude fibre contents (g kg^{-1} DM); CPf, CFf, faecal crude protein and crude fibre contents (g kg^{-1} DM); WSMf, faecal water-soluble matter (g kg^{-1} DM); r.s.d., residual standard deviation.

method described by Martin-Rosset *et al.* (1984). Each experimental period included 2 weeks of adaptation to the diet and 6 d of total faecal collections. The horses were fitted with rubber sheets to prevent mixing of urine and faeces. Dietary and faecal samples were oven-dried at 80°C for 48 h for dry-matter determinations. Ground-dried samples were analysed for ash, crude protein (CP) (Kjeldahl nitrogen × 6·25) and crude fibre (CF) content using standard methods (Giger and Pochet, 1987). Individual values were pooled to characterize each diet by its average digestibility and chemical composition. Van Soest fibre determinations (Van Soest, 1982) were not made as crude fibre is the official measure for forage fibrousness in France; furthermore, it is highly correlated with Van Soest fibre determinations (Giger and Pochet, 1987).

The relationship between diet digestibility and faecal composition was determined using linear and non-linear fits, with analysis of variance (SAS Institute, 1988). Independent variables were dietary parameters; crude ash (CAd), crude protein (CPd), crude fibre (CFd); and faecal parameters (CPf and CFf). These were expressed both on a dry-matter (CAd_d, CPd_d and CFd_d) and on an organic-matter basis (CAd_o, CPd_o and CFd_o), to predict both dry-matter (DMD) and organic-matter (OMD) digestibility.

As digestibility cannot increase indefinitely, non-linear relationships with faecal indicators were expected. The factors affecting faecal excretion of nitrogen by horses have not been studied extensively in relation to the digestibility of forages (Meyer, 1983), but they may be the same as those in ruminants. The relationship between digestibility and faecal crude protein in cattle was well described by a reciprocal function (Boval *et al.*, 1996). In the absence of the information necessary to develop a specific model for horses, we fitted a reciprocal function to our data.

Results

Characteristics of the diets

The chemical composition of the diets corresponded to the range of values reported for forages usually fed to domestic horses (Table 2a). The crude protein and crude fibre content of the hays varied from 69 to 214 g

Table 2 Chemical composition and *in vivo* digestibility of the samples: (a) of the whole samples (n = 27); (b) of the green forage samples (n = 12); (c) of the hay samples (n = 15).

	Chemical composition ($g\ kg^{-1}$ DM) and digestibility (decimal fraction)			Chemical composition ($g\ kg^{-1}$ OM)		
	Mean	s.d.	Range of values	Mean	s.d.	Range of values
(a) *Feed*						
Organic matter	898·4	23·4	844–933	–	–	–
Crude protein	156·2	42·0	69–291	167·2	53·1	75–344
Crude fibre	296·6	67·6	155–415	310·6	50·9	184–412
Dry-matter digestibility	0·58	0·06	0·44–0·71	–	–	–
Organic-matter digestibility	0·60	0·07	0·46–0·76	–	–	–
Faeces						
Organic matter	858·7	49·0	707–928	–	–	–
Crude protein	119·6	30·6	58–187	134·6	47·5	64–264
Crude fibre	344·8	90·8	142–498	370·9	68·9	201–537
(b) *Feed*						
Organic matter	887·0	27·0	844–911	–	–	–
Crude protein	167·0	47·5	117–291	189·5	59·3	127–344
Crude fibre	250·9	40·1	155–305	282·2	39·9	184–336
Dry-matter digestibility	0·61	0·06	0·51–0·71	–	–	–
Organic-matter digestibility	0·64	0·05	0·58–0·76	–	–	–
Faeces						
Organic matter	821·5	48·1	707–885	–	–	–
Crude protein	131·3	24·5	109–177	162·2	40·1	124–264
Crude fibre	288·7	58·8	142–357	349·2	59·1	201–422
(c) *Feed*						
Organic matter	907·5	15·8	885–933	–	-	–
Crude protein	147·4	36·3	69–214	149·4	41·4	75–229
Crude fibre	333·2	63·3	235–415	333·2	48·2	258–412
Dry-matter digestibility	0·56	0·06	0·44–0·64	–	–	–
Organic-matter digestibility	0·56	0·06	0·46–0·64	–	–	–
Faeces						
Organic matter	888·4	22·6	849–928	–	–	–
Crude protein	109·5	30·9	58–173	112·6	42·0	64–204
Crude fibre	389·7	88·0	247–498	388·2	73·2	291–537

Table 3 Correlation matrix of dietary and faecal parameters with significance.

	DMD	CPd_d	CFd_d	CPf_d
CPd_d	+0·72***			
CFd_d	−0·70***	−0·65***		
CPf_d	+0·75***	+0·77***	−0·77***	
CFf_d	−0·45*	−0·53**	+0·85***	−0·76***
	OMD	**CPd_o**	**CFd_o**	**CPf_o**
CPd_o	+0·76***			
CFd_o	−0·82***	−0·84***		
CPf_o	+0·80***	+0·86***	−0·85***	
CFf_o	−0·44*	−0·59***	+0·70***	−0·71***

*$P < 0·05$, **$P < 0·01$, ***$P < 0·001$.
CP, CF, DMD and OMD for crude protein, crude fibre, dry-matter digestibility and organic-matter digestibility respectively; 'd' and 'f' refer to dietary and faecal samples, and '$_o$' and '$_d$' subscripts referring to parameters expressed on an organic or a dry-matter basis.

kg^{-1} DM and from 235 to 415 g kg^{-1} DM respectively (Table 2c); the crude protein and crude fibre content of green forages varied between 117 and 291 g kg^{-1} DM and 155 and 305 g kg^{-1} DM respectively (Table 2b).

Prediction of digestibility

Because there was no effect of forage type (hay or green forage) on any of the prediction equations, the whole data set was used (n = 27). Both dietary and faecal variables were significantly related to digestibility (Table 3), and there was strong collinearity among the predictive variables (e.g. r = 0·86 between CPf and CPd expressed on organic-matter basis). The best single predictors of digestibility were faecal crude protein (r.s.d., 0·040–0·044) and dietary crude fibre (r.s.d., 0·040–0·044) contents, Table 4. The best estimates were derived by including both faecal and dietary variables, and the lowest residual standard deviation was 0·032 when CPf, CFd and CFf were used as predictors of DMD or OMD. Omission of dietary crude protein content did

Table 4 Predictions of digestibility (Y) from faecal and dietary chemical composition (X_n), using a linear regression (n = 27): $Y = a_0 + a_1X_1 + a_2X_2 + ... + a_nX_n$.

(a) Dry-matter digestibility (Y) on dry-matter basis (X_n).

Predictors (g kg^{-1} DM)				Parameters of the regressions						
X_1	X_2	X_3	X_4	a_0	a_1	a_2	a_3	a_4	r.s.d.	r^2 or R_2
CPf_d				0·401	0·0015				0·041	0·575
CPd_d				0·417	0·0011				0·043	0·525
CFd_d				0·769	−0·0006				0·044	0·495
CPd_d	CFd_d			0·584	0·0007	−0·0004			0·039	0·620
CPf_d	CPd_d			0·388	0·001	0·0005			0·039	0·618
CPf_d	CFf_d			0·281	0·0019	0·0002			0·040	0·610
CPf_d	CFd_d	CFf_d		0·442	0·0014	−0·0007	0·0005		0·032	0·758
CFd_d	CPd_d	CFf_d		0·589	−0·0007	0·0006	0·0003		0·036	0·685
CPf_d	CFd_d	CPd_d	CFf_d	0·437	0·0012	−0·0007	0·0002	0·0005	0·032	0·765

(b) Dry-matter digestibility (Y) on organic-matter basis (X_n).

Predictors (g kg^{-1} OM)				Parameters of the regressions						
X_1	X_2	X_3	X_4	a_0	a_1	a_2	a_3	a_4	r.s.d.	r^2 or R_2
CFd_o				0·852	−0·001				0·044	0·530
CPf_o				0·439	0·001				0·044	0·518
CPd_o				0·454	0·0008				0·045	0·491
CFf_o				0·702	−0·0003				0·059	0·129
CPf_o	CFf_o			0·107	0·0018	0·0006			0·037	0·676
CFd_o	CFf_o			0·836	−0·0011	0·0003			0·042	0·580
CPf_o	CFd_o			0·663	0·0005	−0·0005			0·043	0·572
CPf_o	CFd_o	CFf_o		0·348	0·0013	−0·0006	0·0006		0·034	0·750
CPf_o	CPd_o	CFf_o		0·120	0·0016	0·0002	0·0006		0·038	0·682
CPf_o	CFd_o	CPd_o	CFf_o	0·354	0·0014	−0·0006	−0·0001	0·0006	0·035	0·751

Table 4 (continued)
(c) Organic-matter digestibility (Y) on dry-matter basis (X_n).

Predictors (g kg⁻¹ DM)				Parameters of the regressions						
X_1	X_2	X_3	X_4	a_0	a_1	a_2	a_3	a_4	r.s.d.	r^2 or R_2
CPf_d				0·390	0·0017				0·042	0·627
CFd_d				0·824	−0·0008				0·043	0·596
CPd_d				0·417	0·0012				0·047	0·528
CPf_d	CFd_d			0·586	0·0011	−0·0004			0·029	0·688
CFd_d	CPd_d			0·653	−0·0005	0·0006			0·039	0·685
CPf_d	CPd_d			0·379	0·0013	0·0004			0·041	0·655
CPf_d	CFd_d	CFf_d		0·516	0·0014	−0·0008	0·0004		0·034	0·768
CFd_d	CPd_d	CFf_d		0·656	−0·0008	0·0006	0·0002		0·038	0·713
CPf_d	CFd_d	CPd_d	CFf_d	0·511	0·0012	−0·0007	0·0002	0·0004	0·035	0·773

(d) Organic-matter digestibility (Y) on organic-matter basis (X_n).

Predictors (g kg⁻¹ OM)				Parameters of the regressions						
X_1	X_2	X_3	X_4	a_0	a_1	a_2	a_3	a_4	r.s.d.	r^2 or R_2
CFd_o				0·914	−0·001				0·040	0·644
CPf_o				0·433	0·0012				0·040	0·634
CPd_o				0·462	0·0008				0·046	0·520
CFf_o				0·768	−0·0004				0·059	0·234
CPf_o	CFf_o			0·178	0·0018	0·0004			0·037	0·719
CPf_o	CFd_o			0·689	0·0006	−0·0006			0·038	0·698
CFd_o	CPd_o			0·806	−0·0008	0·0002			0·040	0·659
CPf_o	CFd_o	CFf_o		0·441	0·0012	−0·0006	0·0005		0·032	0·797
CPf_o	CPd_o	CFf_o		0·181	0·0018	0·00002	0·0004		0·038	0·719
CPf_o	CFd_o	CPd_o	CFf_o	0·459	0·0015	−0·0007	−0·0003	0·0005	0·032	0·808

not significantly affect the precision of the prediction based on these three variables (R^2, 0·76 for the two equations; r.s.d., 0·0321 vs. 0·0319).

Faecal crude protein content, which is easy to measure, was retained because it had a highly significant linear relation with digestibility. The reciprocal function provided a slightly (but non-significantly) better fit than a linear one (Table 5 and Figure 1). The elimination of extreme values did not change the estimates of the regression parameters significantly, and the inclusion of CFd or CFf did not lead to a significant increase in accuracy. Two sets of prediction equations are provided in Table 5, as parameters expressed on a dry-matter basis are easier to measure, but prediction on the basis of organic-matter digestibility is more accurate because it is not affected by contamination by soil.

Table 5 Comparison of the prediction equations based on linear and reciprocal models (n = 27). The reciprocal models were better (r^2 values higher, r.s.d. values lower), but not significantly so.

Faecal crude protein content	Digestibility (decimal fraction)		
	DMD or OMD†	r^2	r.s.d.
g kg⁻¹ DM			
Linear model	0·401 + 0·002CPf	0·57	0·041
Reciprocal model	0·734 − 17·872/CPf	0·65	0·038
g kg⁻¹ OM			
Linear model	0·433 + 0·001CPf	0·63	0·040
Reciprocal model	0·786 − 19·793/CPf	0·74	0·036

†As appropriate.

Prediction of the chemical composition of the diet

Dietary crude protein and crude fibre contents were both significantly correlated with faecal variables (Table 3). The single most accurate predictor of dietary crude protein content was a linear fit with faecal crude protein (on a dry-matter basis, $CPd_d = 1{\cdot}08CPf_d + 27{\cdot}03$; $r^2 = 0{\cdot}59$; and on an organic-matter basis: $Cpd_o = 0{\cdot}958CPf_o +$

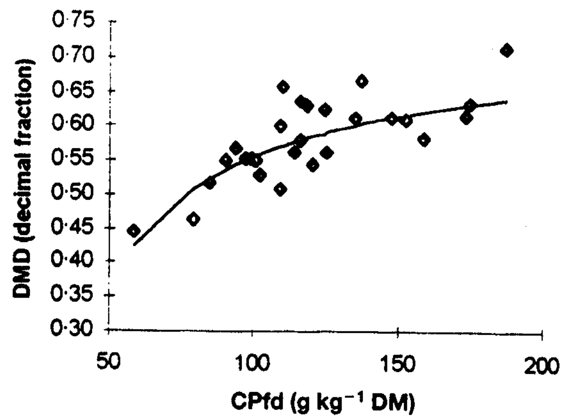

Figure 1 The relationship between faecal crude protein content expressed on a dry-matter basis (CPfd) and dry-matter digestibility in horses. DMD = 0·734 − 17·872/CPfd, n = 27, r^2 = 0·65, r.s.d. = 0·04. ——, model; ♦, DMD.

38·29; r^2 = 0·73). The elimination of the two extreme values did not modify significantly the estimation of dietary CP content ($CPd_d = 0{\cdot}739CPf_d + 66{\cdot}09$; $r^2 = 0{\cdot}44$; $CPd_o = 0{\cdot}724CPf_o + 68{\cdot}09$; $r^2 = 0{\cdot}58$).

Discussion

In this data set, the best single predictor of the digestibility and crude protein content of the diet of horses was faecal crude protein, in agreement for both parameters with previous findings for ruminants (Holloway *et al.*, 1981) and for horses (Chenost, 1986). However, faecal crude protein content alone does not have a high predictive value (r.s.d. = 0·036–0·038 according to the prediction equations) compared with results obtained with the same predictor for ruminants (Le Du and Penning, 1982). Greater precision (r.s.d. below 0·020) was achieved for cattle by increasing the number of regression parameters, or by taking animal and dietary factors into account. Because digestibility is primarily related to dietary undigestible fractions, predictions are significantly improved by including dietary crude fibre and faecal indigestible matter.

An advantage of faecal crude protein content is its ease of measurement. Dietary variables, in particular crude fibre content, led to a precision very similar to faecal crude protein content in linear models (Table 4), but these are not usually suitable for use in patchy rangelands where selective feeding behaviour and low herbage availability make it difficult to sample accurately all the major plant species in the diets. Among faecal variables, crude protein content was a better predictor than crude fibre content (r.s.d. 0·044 vs. 0·059).

Faecal crude protein content was related to digestibility in a nearly linear manner, but a reciprocal function was preferred because there are biological reasons for expecting digestibility to reach a plateau at high values of CPf (see above, Material and methods). This model led to a slightly better fit (Table 5), and it appears to be more robust than the linear one, which did not provide accurate estimates for high-quality pastures because it underestimates digestibility when CPf > 200 g kg^{-1} DM. The reciprocal model predicts a maximum OM digestibility of about 780 g kg^{-1} DM. For ruminants the theoretical maximum apparent OM digestibility is about 840 g kg^{-1} DM (see Van Vuuren *et al.*, 1992; Peyraud *et al.*, 1997). This agrees with previous findings on horses (Chenost and Martin-Rosset, 1985) and is consistent with the fact that the ruminant digestive system is more efficient than the hind-gut fermentation of equids.

The low predictive value of crude fibre in this study is consistent with previous findings (e.g. Chenost, 1985, 1986); however our data set contained a limited range of fibre values (142–498 g kg^{-1} DM) and it is possible that across a wider range fibre could be more important, as in cattle, when fibre is included in some prediction equations (see Comeron and Peyraud, 1993). Faecal parameters correlated with fibre content (specific gravity, water-soluble matter...), which are less expensive to measure, may also improve the predictions (see Chenost, 1986).

Predictions based on crude protein are sometimes biased by variations in the ratio of dietary to non-dietary (microbial, endogenous and metabolic) faecal nitrogen losses and by non-protein nitrogen in forages. Variations in plant species, growth cycles and part of plant (leaf, stem) may partly account for the high residual standard deviations found here (Chenost, 1985). Martin-Rosset *et al.* (1984) have suggested that different equations should be used for legume- and grass-dominated pastures. This would require a larger sample size than was available in the present work. Nitrogen recycling is also a possible cause of bias among horses fed low-protein diets for they may recycle up to 50% of the urea absorbed by the intestine (Prior *et al.*, 1974), with an efficiency of 25% (Hintz and Schryver, 1972). These equations should therefore be used with caution on rangelands, especially when the diets are rich in browse species, and on nitrogen-deficient pastures when CPd is less than 70 g kg^{-1} DM. A more detailed understanding of the nitrogen digestion of equids is clearly required to improve predictions of the nutritional value of their diets based on faecal parameters.

Despite these limitations, faecal indices can be useful on rangelands when accurate diet sampling and digestibility trials are not feasible. They are particularly suitable for the evaluation of seasonal changes on a single pasture and of differences between populations of animals when their diets are not too dissimilar (Leslie and Starkey, 1987). Our regressions may be useful in such circumstances as rangelands of low production, areas of non-uniform patchy vegetation, or with untractable grazing animals, when forage sampling and *in vivo* digestibility trials are not feasible.

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