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Prediction of fecal crude protein excretion of goats

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Abstract

A database of 622 treatment mean observations of the dietary concentration of CP and apparently digestible CP (DCP) from 146 publications was used to estimate true digestibility of CP and metabolic fecal CP (MFCP) in goats. A regression of DCP against CP with the entire database yielded the equation: DCP $= 0.8566 \times$ CP (%DM) $- 2.697$ ($r^2 = 0.851$, root mean square error $= 1.58$). There were some observations with lower than predicted DCP, some of which were with diets containing browse. Therefore, observations with residuals <1.58 were deleted, resulting in the equation: DCP $= 0.8831 \times$ CP (%DM) $- 2.67$ ($r^2 = 0.952$, root mean square error $= 0.86$; $n = 562$); estimates of MFCP and true CP digestibility were considered the Y intercept and slope, respectively. To address variables of the entire database with less than expected DCP, the database was split into a subset to develop equations (60% of observations), with inclusion of additional variables such as DM intake and dietary concentrations of forage and browse, and one to evaluate. However, multiple regression equations did not greatly improve prediction, with lower than predicted DCP appearing a consequence of depressed true CP digestibility rather than increased MFCP. In conclusion, for goats consuming diets without browse, 0.88 and 2.67% DM appear appropriate estimates of true CP digestibility and MFCP, respectively, similar to values for other ruminant species.

Keywords: Goats; Crude protein; Digestibility

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1. Introduction

Fecal crude protein (CP) excretion is the sum of endogenous or metabolic CP (MFCP) and undigested dietary CP. In addition to MFCP from sources such as enzymes and sloughed epithelial cells, microbial cells synthesized in the hindgut make a contribution (NRC, 2000). Apparently digestible CP (DCP) intake, the difference between total CP intake and fecal CP, is often not known, in which case an estimate can be made based on characteristics of the diet. With most diets and most animals, there is a consistent and close

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relationship between concentrations of dietary CP and DCP, as shown by the “Lucas test” of nutritive entities (Van Soest, 1994). With low CP intake, this may be in part because of N recycling, which appears more extensive in goats versus cattle and sheep (Silanikove, 2000). The Lucas test involves regressing the concentration of an apparently digestible dietary constituent on the total concentration of that constituent. If the slope can be regarded as being between 0 and 1, the intercept is 0 or less and the equation fits the data well, then the slope is an estimate of the true digestibility of the nutrient and the intercept is an estimate of endogenous loss (i.e., excretion at 0 intake) expressed as a percentage of DM intake (DMI).

In studies with cattle and sheep, the Lucas test applied to CP has shown a consistent true digestibility of CP of 0.88–0.90 and a MFCP of 2.5–3% of DMI across a wide range of animals and diets (Swanson, 1982; NRC, 1984; Reed, 1995; Preston, 2000; Hove et al., 2001). However, true digestibility of CP and MFCP in goats have not been extensively studied. Such knowledge is necessary to determine CP requirements of goats based on a factorial method (e.g., NRC, 1984) or for assessing metabolizable protein needs. Therefore, objectives of this study were to develop equations for goats to estimate DCP from dietary CP concentration, to obtain predictions of MFCP and true digestibility of CP. In addition, other characteristics of the diet that might improve accuracy of estimating DCP, such as DMI and dietary concentrations of forage (Fpct) and browse (Bpct), were considered.

2. Materials and methods

2.1. Database description

The database analyzed in this study included publications (references) reporting both CP and CP digestibility (CPD), except for omission of studies with consumption of milk or milk replacer. There were 622 treatment mean observations from 146 publications, representing 3543 goats at various physiological states, except for preweaning kids, and more than 30 goat breeds. Table 1 lists the breed, country in which the experiment was conducted, mean BW, number of goats represented, number of treatments and dietary forage percentage for each reference or source. Means, S.D. and ranges of selected variables are in Table 2. Comparable data for diets containing browse are in Table 3. Although it might have been desirable to include condensed tannin concentrations in models for diets containing browse, only a few studies reported tannin values and there was little consistency among studies in method of tannin quantification.

2.2. Lucas tests

Regressions of DCP on CP were conducted using PROC REG of SAS (1990). Treatment means were used as input variables in the models, without including the effect of study or weighting for numbers of individual observations behind each mean. Estimates of MFCP and true CP digestibility were considered to be the Y intercept and slope, respectively.

In addition to the entire database, there were also three subsets used for Lucas test regressions. The root mean square error (RMSE) from the regression with the entire database (DCP $=$ 1.58% of DM; Fig. 1) was used to identify observations that might be removed to improve prediction accuracy. The criterion for removing an observation was the residual (DCP, % of DM) from the overall regression relative to the values of 1.58 (one RMSE) or 3.16 (two RMSE). The three database subsets were:

Subset 1: observations were deleted if residuals were $\leq$1.58 or $>$1.58.

Subset 2: observations were deleted if residuals were $\leq$1.58.

Subset 3: observations were deleted if residuals were $\leq$3.16.

A subset in which only the more positive regressions were omitted was not constructed, because there were only three observations with residuals $>$3.16 and the maximum residual was 4.07. Most observations with large deviations were associated with negative residuals (Fig. 1). Deleted observations were examined, although commonalities were not detected. For example, some were with browse-containing diets but many were not.

2.3. Multiple regression equations to enhance prediction of DCP

Because there were some observations in the entire database with DCP not predicted well by the Lucas

Table 1
Summary of references used to predict fecal crude protein excretion in goats

Biotype	Breed	Country[a]	BW[b] (kg)	Goats[c]	Treatments[d]	Forage (%)	Source
Dairy	Alpine	USA	23.7	20	4	50.0	Qi et al. (1994a)
	Alpine	USA	38.5	7	1	69.6	Randy et al. (1984)
	Alpine	USA	15.2	10	2	57.2	Beede et al. (1986)
	Alpine	USA	23.8	32	4	50.0	Qi et al. (1993)
	Alpine	USA	64.0	20	4	59.1	Santini et al. (1992)
	Alpine	USA	48.0	15	3	100.0	Kouakou et al. (1998)
	Alpine	USA	48.6	18	3	43.4	Lu et al. (1990)
	Alpine	USA		18	3	33.0	Barnes and Brown (1990)
	Alpine	USA	46.1	58	4	43.9	Lu (1993)
	Alpine	USA		12	3	100.0	Park et al. (1989)
	Alpine	Italy	51.9	28	2	50.0	Andrighetto and Bailoni (1994)
	Alpine	Honduras	68.0	6	1	100.0	Rodriguez et al. (1992)
	Alpine	France	52.0	70	14	61.4	Archimede et al. (1995)
	Alpine	France	35.0	9	3	100.0	Masson et al. (1986)
	Alpine	France	52.3	6	2	97.1	Baracos et al. (1991)
	Alpine	France	66.0	32	4	60.0	Schmidely et al. (1999)
	Alpine	France	46.9	55	5	13.0	Brun-Bellut et al. (1990)
	Alpine	France	62.7	108	9	70.0	Schmidely et al. (2002)
	Saanen	USA		28	7	100.0	Baumgardt et al. (1964)
	Saanen	USA	26.5	16	3	100.0	Gelaye et al. (1990)
	Saanen	USA	47.9	15	3	40.0	Gelaye and Amoah (1991)
	Saanen	USA	68.9	10	2	59.6	Hong et al. (1988)
	Saanen	Italy		27	3	56.0	Badamana et al. (1990)
	Saanen	Germany	59.9	16	3	36.0	Rodehutscord et al. (2000)
	Saanen	UK		18	3	56.0	Badamana and Sutton (1992)
	Saanen	Swiss		24	2	100.0	Kessler (1985)
	Saanen	Israel	35.4	12	3	100.0	Silanikove (1999)
	Saanen	Japan	44.1	9	3	91.5	Khan et al. (1998)
	Nubian	USA	17.5	18	3	33.0	Richards et al. (1994a)
	Nubian	USA	18.9	24	3	70.0	Richards et al. (1994b)
	Toggenburg	Canada	24.9	18	6	100.0	Jones et al. (1972)
	Toggenburg	Kenya	28.9	5	1	100.0	Brown et al. (1988)
	Damascus	Cyprus	67.8	40	10	75.1	Antoniou and Hadjpanayiotou (1985)
	Damascus	Cyprus	28.3	156	8	6.2	Economides et al. (1990)
	Damascus	Cyprus		4	2	40.5	Hadjipanayiotou (1984)
	Damascus	Cyprus	62.2	64	19	24.4	Hadjipanayiotou (1988a,b)
	Damascus	Cyprus	73.3	39	2	29.5	Hadjipanayiotou (1995)
	Damascus	Cyprus	32.0	10	2	12.9	Hadjipanayiotou (1988a,b)
	Granadina	Spain	28.2	32	4	79.0	Prieto et al. (1990)
	Granadina	Spain	38.6	70	6	39.7	Aguilera et al. (1990)
	Granadina	Spain	31.5	10	2	100.0	Ceron et al. (1996)
	Granadina	Spain	49.4	10	2	46.5	Sanz Sampelayo et al. (1998)
	Alpine × Beetal	India	50.9	8	2	85.4	Kurar and Singh (1982)
	Alpine × Beetal	India	32.8	16	4	62.5	Rai and Mudgal (1988)
	Saanen × feral	New Zealand	13.3	15	2	100.0	Alam et al. (1983)
	Granadina × Murciano	Spain	40.1	16	4	85.6	Madrid et al. (1997)
	Granadina × Murciano	Spain	32.0	15	5	100.0	Madrid et al. (1996)
	Damascus × Baladi	Saudi Arabia	18.0	12	2	36.4	Abdel-Rahman and El Kaschab (1996)
	Anglo-Nubian × native goat	Viet Nam		25	5	100.0	van Hao and Ledin (2001)

Table 1 (*Continued*)

Biotype	Breed	Country[a]	BW[b] (kg)	Goats[c]	Treatments[d]	Forage (%)	Source
	Alpine, Nubian	USA	31.6	24	6	46.9	Sahlu et al. (1993)
	Toggenburg, Saanen	USA	27.0	27	3	53.2	Brown and Johnson (1985)
	Toggenburg, Saanen	USA	21.2	28	4	48.2	Beede et al. (1985)
	Alpine, Saanen	France	50.9	45	14	44.9	Brun-Bellut (1997)
	Swedish Landrace	Sweden	48.9	80	10	39.2	Ciszuk and Lindberg (1988)
	Norwegian	Norway	38.5	129	10	64.8	Havrevoll et al. (1995)
	Jamnapari	India		4	1	100.0	Sharma and Murdia (1974)
	Jamnapari	India	33.4	24	4	60.0	Srivastave and Sharma (1998)
	Jamnapari	India	37.6	8	2	100.0	Majumdar (1960)
	Egyptian Nubian	Egypt	30.5	48	4	38.8	El-Gallad et al. (1988)
Meat	Boer	USA	25.3	36	4	71.5	Luginbuhl et al. (2000)
	Boer	South Africa	57.0	25	5		Cronjé (1992)
Indigenous	West African goat	Nigeria		12	3	100.0	Ifut (1989)
	West African goat	Ghana	9.7	12	3	100.0	Larbi et al. (1991)
	East African goat	Zambia		12	1	100.0	Gihad (1976)
	West African goat	Nigeria	15.7	24	6	36.4	Aregheore (1995)
	West African goat	Nigeria	8.6	20	5	100.0	Adejumo and Ademosun (1991)
	West African goat	Nigeria	25.3	32	4	65.8	Ogundola (1990)
	West African goat	Nigeria	12.9	24	3	35.8	Akinsoyinu and Ologhobo (1989)
	West African goat	Nigeria	16.5	16	4	27.3	Onwuka and Akinsoyinu (1989)
	West African goat	Nigeria	28.3	20	5	25.8	Osuagwuh and Akinsoyinu (1990)
	West African goat	Nigeria	15.9	24	3	34.0	Akinsoyinu (1992)
	West African goat	Nigeria	16.5	15	3	30.0	Adeloye (1992)
	West African goat	Nigeria	7.8	12	3	0.0	Adeloye and Yousouf (2001)
	West African goat	Nigeria	7.5	15	3	100.0	Bamikole et al. (2001)
	East African goat	Zimbabwe	17.0	16	4	42.5	Kadzere and Jingura (1993)
	Spanish	USA		16	4	100.0	Nastis and Malechek (1981)
	Spanish	USA	40.0	24	6	100.0	Dick and Urness (1991)
	Spanish	USA	19.8	16	4	100.0	Sidahmed et al. (1981)
	Spanish	Mexico	32.6	9	3	85.0	Ramirez et al. (1992)
	Spanish	Mexico	33.6	12	3	100.0	Ramirez (1997)
	Spanish	Mexico	33.3	12	3	100.0	Ramirez (1998)
	No description	India	11.2	15	3		Verma et al. (1995)
	No description	India	21.4	22	2	84.8	Murthy et al. (1996)
	No description	India	10.7	48	4	32.8	Anandan et al. (1996)
	No description	Nigeria	14.8	12	3	30.0	Aregheore (1996)
	No description	Nigeria	16.0	12	3	36.5	Aregheore (2000)
	Scottish cashmere	UK	40.8	30	6	60.0	Souri et al. (1998)
	Scottish cashmere	UK	39.2	24	6	100.0	Hadjigeorgiou et al. (2001)
	Australian cashmere	Australia	16.9	16	4	5.6	Galgal and Norton (1991)
	Australian cashmere	Australia	18.0	52	14	30.0	Ash and Norton (1987)
	Australian cashmere	Australia	33.9	24	8	96.6	Norton and Waterfall (2000)
	Native goat	Brazil	25.0	5	1	100.0	de Araujo and de Queiroz Vieira (1987a,b)
	Native goat	Brazil	25.0	4	1	100.0	de Araujo and de Queiroz Vieira (1987a,b)
	Native goat	Brazil	22.0	5	1	100.0	de Cavalho and Bueno (1987)
	Native goat	Bangladesh	10.7	5	1	72.4	Kibria et al. (1996)

Table 1 (*Continued*)

Biotype	Breed	Country[a]	BW[b] (kg)	Goats[c]	Treatments[d]	Forage (%)	Source
	Native goat	Guyana	21.0	41	9	31.5	Osuji (1987)
	Native goat	Trinidad and Tobago Tobgago	21.7	41	9	31.5	Lallo (1996)
	Desert goat	Iraq	20.0	20	2	24.6	Al Jassim et al. (1991)
	Native goat	India	47.2	10	10	49.5	Rajpoot et al. (1980)
	Native goat	India	19.6	8	2	62.1	Girdhar et al. (1991)
	Native goat	India	7.6	10	2	100.0	Panda et al. (1983)
	Native goat	Thailand	24.3	48	4	40.0	Cheva-Isarakul and Rengsirikul (1991)
	Black Bengal × Beetal	India	10.7	20	4	41.1	Virk et al. (1994)
	Black Bengal × Beetal	India		15	3	52.8	Tewatia et al. (1995)
	Anglo-Nubian × native goat	Thailand	18.8	48	7	11.0	Pralomkarn et al. (1995)
	Marwari goat	India		15	3	65.0	Wadhwani et al. (1992)
	Ibex	Israel	15.0	16	4	100.0	Degen et al. (1997)
	Fiji × New Zealand feral	Western Samoa	25.5	16	4	100.0	Ash (1990)
	Fiji × New Zealand feral	Western Samoa	14.3	12	3	100.0	Ash et al. (1992)
	Malawi goat	Malawi	29.9	16	4	69.0	Reynolds (1981)
	Bedouin goat	Israel	17.7	12	3	100.0	Silanikove (1999)
	Native goat	Japan	25.9	32	8	63.9	Islam et al. (2000)
	Malabari goat	India		17	3	16.7	James and Chandran (1975)
	Mamber goat	Israel	34.9	36	6	82.8	Silanikove et al. (1997)
	Mamber goat	Israel	34.4	10	2	100.0	Perevolotsky et al. (1993)
	Feral goat	Australia		9	2	100.0	McSweeney and Cross (1992)
	Beetal goat	India	16.6	27	3	19.7	Singh and Mudgal (1991)
	Etawah goat	Indonesia	20.0	20	4	55.1	Kiranadi et al. (1994)
	Etawah goat	Indonesia	21.5	20	4	55.5	Sastradipradja et al. (1994)
	Etawah goat	Indonesia	28.5	81	9	13.0	Katipana and Sastradipradja (1994)
	Etawah goat	Indonesia	13.8	20	5		Astuti et al. (1997)
	Beetal × Assamese	India	10.1	60	9	41.0	Saikia et al. (1995)
	Gwembe Valley goat	Zambia	24.5	9	3	55.3	Aregheore et al. (1992)
	Dwarf goat	Cameroon	11.6	12	4	47.2	Njwe (1992)
	Desert goat	Sudan	21.0	10	2	38.0	El-Hag et al. (1985)
	Native goat	Morocco	20.0	16	2	100.0	Narjisse et al. (1995)
	Maradi goat	Nigeria	11.4	8	2	80.0	Adeloye (1995)
	Maradi goat	Nigeria	20.7	24	4	31.2	Adu et al. (1987)
	Maradi goat	Nigeria	6.8	18	6	51.7	Adeloye et al. (1993)
	Kambing Kacang goat	Indonesia	9.7	16	4	100.0	Van Eys et al. (1986)
	Native goat	Greece	27.4	8	2	100.0	Papachristou (1997)
	Native goat	Burkina Faso	24.7	16	4	91.8	Bosma and Bicaba (1997)
	Native goat	Uganda		15	3	100.0	Ebong (1995)
	Creole goat	Trinidad and Tobago	26.6	16	4	58.8	Sooden-Karamath and Youssef (1999)

Table 1 (*Continued*)

Biotype	Breed	Country[a]	BW[b] (kg)	Goats[c]	Treatments[d]	Forage (%)	Source
	Sarda goat	Italy	31.3	9	3	74.0	Decandia et al. (2000)
Mohair	Angora	USA	20.1	12	4	48.5	Qi et al. (1994b)
	Angora	USA	41.2	10	2	35.0	Toerien et al. (1999)
	Angora	USA	31.7	4	1	100.0	Nunez-Hernandez et al. (1991)
	Angora	USA	45.4	32	4	78.2	Qi et al. (1992)
	Angora	USA	41.0	18	3	95.0	Villena and Pfister (1990)
	Angora	USA	33.0	32	4	100.0	Boutouba et al. (1990)
	Angora	USA	41.0	36	9	100.0	Nunez-Hernandez et al. (1989)
	Angora	USA	27.1	4	1	46.9	Sahlu et al. (1993)
	Angora	USA	27.1	25	5	43.7	Shenkoru (2001)
	Angora	USA	25.4	25	5	44.3	Shenkoru (2001)
	Angora	South Africa	24.0	25	5		Cronjé (1992)
	Angora	South Africa		20	5	60.4	Gevers and Wentzel (1985)
	Angora	Australia	56.5	9	3	100.0	Doyle et al. (1984)
	Angora	UK	35.0	30	6	60.0	Souri et al. (1998)
	Angora × feral	New Zealand	42.5	7	1	100.0	Domingue et al. (1991)

[a] The country where the experiment was conducted.

[b] Mean body weight of goats for all treatments. When not listed, sufficient body weight information was not reported.

[c] Number of goats in the experiment.

[d] The number of treatments in the experiment.

equations from the entire database, it was split into a subset to develop multiple regression equations and one for evaluation. The intention was to have 60% of observations in the development subset. Splitting was done according to reference rather than observation; in other words, each observation in a reference was in the same subset. For the initial split, the first reference was assigned to the development subset, the second to the evaluation subset and so on. Subsequent splits were accomplished by moving entire references from one subset to the other.

The effectiveness of each split was evaluated by comparing subsets according to means for CP, CPD, DCP, DMI, Fpct and Bpct. References were moved until the means and standard deviations were similar. References were chosen to be moved according to the mean of the reference in comparison with means of the two split subsets. In some cases, individual observations were examined, but never moved by themselves. Also, DCP was regressed on CP in each subset to make sure that there was no major difference between subsets in this critical aspect of the study. There were a total of 12 splits. Characteristics of the resultant development and evaluation subsets after the last split are given in Table 4.

Response variables considered for inclusion in models included CP, CP^2, DMI, DMI^2, Fpct, $Fpct^2$, Bpct, $Bpct^2$ and linear interactions among these terms. The interactions with DMI were expressed as g/day. Multiple variable models were developed in a two-stage procedure. First, PROC REG of SAS (1990) with the RSQUARE selection and CP option (to avoid overfit-

Table 2

Means of observations for the entire database used to estimate apparently digestible CP in goats

Variable	*n*	Mean	S.D.	Minimum	Maximum
CP (% of DM)	622	13.3	4.4	0.2	29.2
CP digestibility (%)	622	58.1	63.3	−1390.9	91.5
Digestible CP (% of DM)	622	8.7	4.1	−3.7	23.3
Diet DM intake (g/day)	612	915	581	52	3140
Dietary forage percentage	604	60.3	30.3	0	100
Dietary browse percentage	622	8.1	23.0	0	100

Table 3
Means of browse-containing diets in the entire database used to estimate apparently digestible CP in goats

Variable	*n*	Mean	S.D.	Minimum	Maximum
CP (% of DM)	88	13.6	4.9	5.6	28.8
CP digestibility (%)	88	50.9	23.4	−33.4	83.7
Digestible CP (% of DM)	88	7.3	4.7	−3.7	20.7
Diet DM intake (g/day)	85	636	365	52.4	1512
Dietary forage percentage	88	87.1	24.9	16.7	100
Dietary browse percentage	88	57.1	30.9	12.0	100

ting) was used to explore the data and determine variables to be included. In the second stage, PROC REG was used to determine regression coefficients for chosen variables. When a squared term or interaction was included, linear terms were also included. When the correlation (*r*) between two linear variables or interactions was greater than 0.7, only one of the variables was included in the multiple regression model.

Simple and multiple regression models were developed using five groups of data. However, in final models, observations involving supplementation with polyethylene glycol were excluded because this additive can counteract positive effects of condensed tannins on fecal CP (Reed, 1995). In addition, two references (Onwuka and Akinsoyinu, 1989; Degen et al., 1997) were deleted because of observations that differed markedly from other data. Therefore, numbers of observations in these groups are slightly less than expected based on numbers given in Table 4. There are 350 observations with both DMI and Fpct listed. Group 1 included all observations that had Fpct given regardless of a DMI value ($n = 360$); group 2 had all observations with DMI available regardless of a listing for Fpct ($n = 353$); group 4 included all observations that provided a Bpct value irrespective of listings of DMI and Fpct ($n = 363$); and group 3 excluded all observations in which browse was a dietary component ($n = 310$). Group 1 equations were

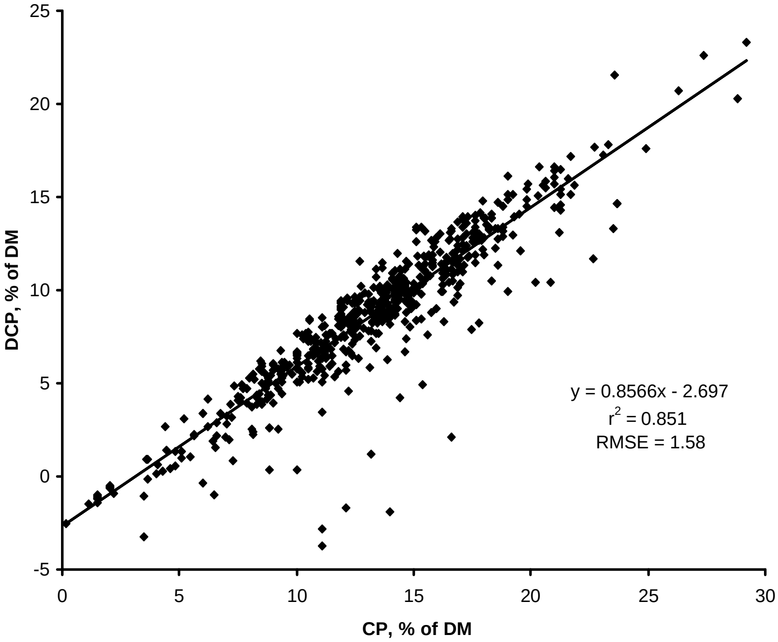

Fig. 1. Regression of apparently digestible CP (DCP) concentration against dietary CP concentration for goats (entire database; $n = 622$; RMSE: root mean square error).

Table 4
Means of data subsets used to develop and evaluate models for estimating apparently digestible CP in goats (D = development, E = evaluation)

Variable	Set	*n*	Mean	S.D.	Minimum	Maximum
CP (% of DM)	D	374	13.5	4.6	0.2	29.2
	E	248	12.9	4.1	2.2	23.3
CP digestibility (%)	D	374	56.3	79.4	−1390.9	91.5
	E	248	61.0	21.0	−91.8	88.8
Digestible CP (% of DM)	D	374	8.8	4.3	−3.7	23.3
	E	248	8.4	3.8	−3.2	17.8
Diet DM intake (g/day)	D	364	922	566	52	3140
	E	248	905	603	127	3070
Dietary forage percentage	D	366	59.4	29.6	0	100
	E	238	61.9	31.4	0	100
Dietary browse percentage (browse-containing diets)	D	50	61.3	30.8	15.7	100
	E	38	51.6	30.7	12.0	100

not evaluated because Fpct did not enter. There was a total of 12 equations developed and evaluated. But, because many of the models were quite similar, only seven were chosen for presentation and discussion.

Estimated DCP (EDCP) concentration was calculated for each observation in the evaluation subset using the coefficients and variables from the development regression equations. Models were evaluated by regressing observed DCP against EDCP. Regression criteria included r^2, RMSE and P values for $b_0 = 0$ and $b_1 = 1$ (for both intercept and non-intercept models). In addition, models were evaluated in terms of differences (DIFF) between observed DCP and EDCP. In calculating DIFF, DCP was subtracted from EDCP so that DIFF was negative when EDCP was less than DCP. In this approach, each DIFF is compared with an "acceptability limit." Ideally, an acceptability limit should be based on an external measure of variability among animals fed alike. As such a measure was not available in this study, a "relative acceptability limit (RAL)" was used for the purpose of making comparisons among equations. The RAL used here was the RMSE of the regression of DCP against CP using the evaluation subset, with exclusion of observations with residuals from the overall regression less than -1.58; thus, only observations part of subset 2 of the entire database were used. The resultant equation was:

$$\mathrm{DCP} = -2.624 + 0.8772 \times \mathrm{CP}; \quad r^2 = 0.940,$$
$$\mathrm{RMSE} = 0.92, \quad \mathrm{CV} = 10.5\%, \quad n = 225$$

Thus, the RAL was 0.92, and absolute values of DIFF were compared with the RAL and twice the RAL (1.84) to determine acceptability of EDCP values, as follows:

$$\text{If DIFF } > 1.84 \text{ then EDCP is unacceptable.}$$

$$\text{If DIFF } < 1.84 \text{ and DIFF } > 0.92 \text{ then EDCP is marginally acceptable.}$$

$$\text{If DIFF } < 0.92 \text{ and DIFF } \geq 0.92 \text{ then EDCP is acceptable.}$$

$$\text{If DIFF } \leq 0.92 \text{ and DIFF } \geq 1.84 \text{ then EDCP is marginally acceptable.}$$

$$\text{If DIFF } \leq 1.84 \text{ then EDCP is unacceptable.}$$

Equations were compared with each other on the basis of the percentage distribution of observations in the acceptable, marginal and unacceptable categories.

3. Results and discussion

3.1. *Lucas tests*

Parameters for regressions of DCP against CP for all models are in Table 5. For the regression of DCP

Table 5
Summary of regression parameters for Lucas test equations (DCP $= b_0 + b_1 \times$ CP) used to estimate apparently digestible CP (DCP) in goats

Database	Residual deleted	n	r^2	RMSE[a]	b_0 = MFCP[b]	b_1 = true CPD[c]
Entire	None	622	0.851	1.58	2.697 ± 0.202	85.66 ± 1.44
Subset 1	≤1.58, >1.58	515	0.965	0.71	2.635 ± 0.099	86.89 ± 0.73
Subset 2	≤1.58	562	0.952	0.86	2.670 ± 0.116	88.31 ± 0.84
Subset 3	≤3.16	601	0.927	1.06	2.620 ± 0.138	86.63 ± 0.99

[a] Root mean square error.

[b] Metabolic fecal CP.

[c] True CP digestibility.

against CP with the entire database, there were some observations with lower than predicted DCP. However, much tighter relationships are shown in Figs. 2–4 for models based on subsets 1–3, respectively. These estimates of MFCP and true CP digestibility are in general agreement with results of other ruminant studies (Swanson, 1982; NRC, 1984, 1985; Owens, 1987; Reed, 1995; Preston, 2000; Hove et al., 2001).

The model for subset 1 had the smallest RMSE, followed by the subset 2 model. Each of these models used the more restrictive outlier criterion, 1.58% of DM. For each model, estimates of MFCP, expressed by the intercept of the regression, were similar (2.62–2.67% of DM). Examination of the standard deviations suggested that estimates of MFCP were not likely different statistically among the models. It therefore appeared that the large negative residuals seen with the Lucas equation for the entire database (Fig. 1) were because of depressed true digestibility of CP rather than to increased MFCP.

Each of the models for the database subsets provided similar estimates of true CP digestibility (0.866–0.883), with a tendency for the equation from subset 2 to have a larger value than that of the model for the entire database (0.857). In this regard, of the 39 observations in the entire database having residuals between −1.58 and −3.16, 22 were with diets that contained browse. Therefore, models for the en-

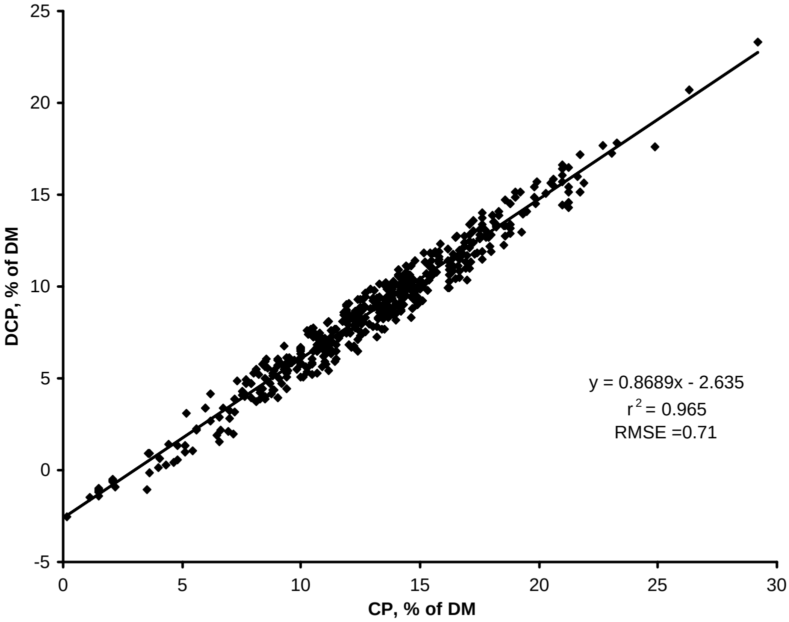

Fig. 2. Regression of apparently digestible CP (DCP) concentration on dietary CP concentration for goats (subset 1, deletion of observations having residuals ≤1.58 and >1.58; $n = 515$).

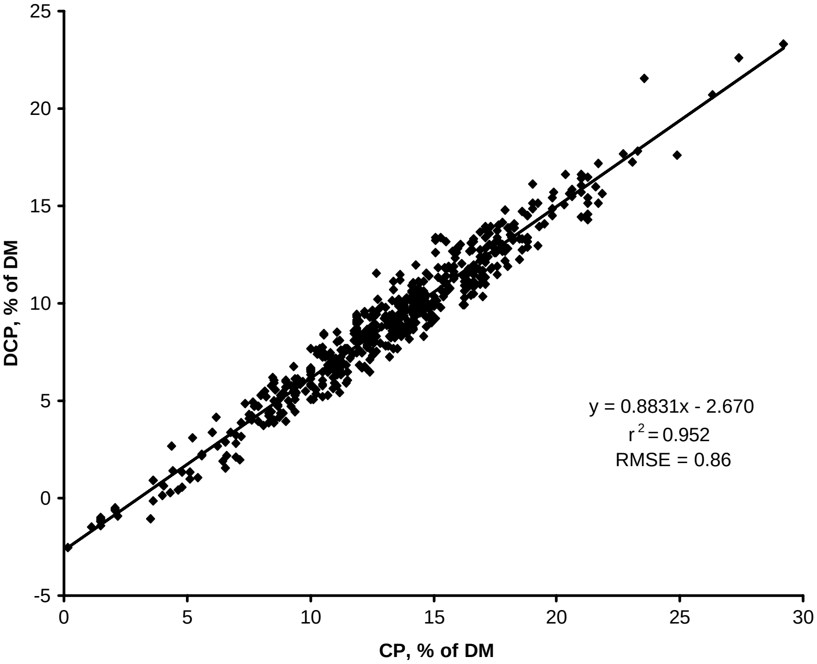

Fig. 3. Regression of apparently digestible CP (DCP) concentration on dietary CP concentration for goats (subset 2, deletion of observations having residuals $\leq$1.58; $n = 562$).

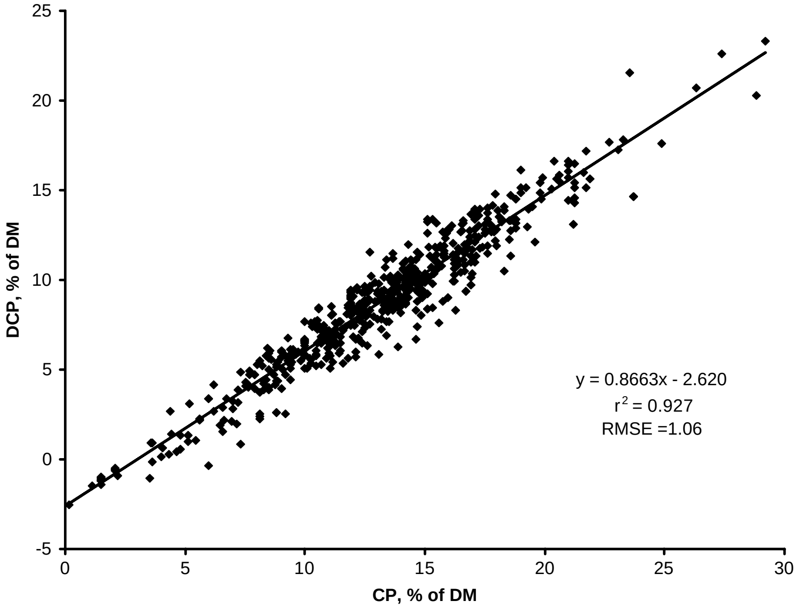

Fig. 4. Regression of apparently digestible CP (DCP) concentration on dietary CP concentration for goats (subset 3, deletion of observations having residuals $\leq$3.16; $n = 601$).

tire database and subset 3 do not seem appropriate as baseline or general equations.

There were 47 observations that had residuals >1.58. Of those 47 observations, 32 had residuals <2.0, and only three observations had residuals >3.0. There were no consistent characteristics of the diets with residuals >1.58. The diets consisted of a wide range of forages (30 were grass hay, straw or by-products) and forage percentages. Because observations with larger positive residuals were included in the subset 2 model, its slope or estimate of true CP digestibility was slightly greater than for other subset models. Thus, use of this model gives somewhat smaller predictions of fecal CP excretion than the others. It is suggested that the model for subset 2 can be considered appropriate as a baseline equation, and should be used when no other information about the diet is known. It should not, however, be used for diets containing browse.

3.2. Multiple regression equations to enhance prediction of DCP

As mentioned previously, there were some observations with DCP not estimated well by the Lucas test equation based on the entire database (Fig. 1) and, to some extent, by the model from subset 3 (with omission of observations with residuals ≤ 3.16; Fig. 4). Therefore, there were dietary characteristics that depressed DCP below expectations based on CP concentration alone. Because there was little variation among the Lucas test equations in the intercept (MFCP), it may be concluded that factors depressing DCP acted by depressing true CP digestibility.

Development-set parameters for the seven simple and multiple regression equations are in Table 6. The equations were:

Group 1, simple: $\mathrm{DCP} = -2.489 + 0.8510 \times \mathrm{CP}$
Group 1, multiple A: $\mathrm{DCP} = -2.649 + 0.8806 \times \mathrm{CP} - 0.03587 \times \mathrm{Bpct}$
Group 1, multiple B: $\mathrm{DCP} = -2.753 + 0.8827 \times \mathrm{CP} - 0.03671 \times \mathrm{Bpct} + 0.001403 \times \mathrm{Fpct}$
Group 2, simple: $\mathrm{DCP} = -2.456 + 0.8467 \times \mathrm{CP}$
Group 2, multiple: $\mathrm{DCP} = -2.543 + 0.8840 \times \mathrm{CP} - 0.03724 \times \mathrm{Bpct} - 0.000183 \times \mathrm{DMI}$
Group 3, simple: $\mathrm{DCP} = -2.625 + 0.8784 \times \mathrm{CP}$
Group 3, multiple: $\mathrm{DCP} = -2.966 + 0.9211 \times \mathrm{CP} + 0.000109 \times \mathrm{DMI} - 0.000000137 \times \mathrm{DMI}^2 + 0.006032 \times \mathrm{Fpct} - 0.000705 \times \mathrm{CP} \times \mathrm{Fpct}$

The simple equations from groups 1 and 2 were similar in coefficients and parameters. Omitting the browse diets (group 3) improved the fit of the single variable equation and increased the intercept and slope (i.e., MFCP and true CP digestibility, respectively). Inclusion of Bpct in the group 1, multiple A equation improved the fit of the equation slightly, and increased MFCP and true CP digestibility. MFCP and true digestibility estimates from group 1, multiple and from group 3, simple equations were similar to those of the model for subset 2 derived from the entire database (Fig. 3; Table 5). Addition of Fpct and DMI to equations had little effect on regression parameters whether the data subset included (group 1, multiple B and group 2, multiple) or excluded observations with diets containing browse (group 3, multiple).

The seven equations were evaluated on the evaluation set by linear regression of DCP on EDCP, and by determining acceptability of differences between

Table 6
Regression parameters of equations developed to estimate digestible CP in goats (development subset)

Equation	X variables[a]	*n*	r^2	RMSE[b]	CV[c]
Group 1, simple	CP	360	0.887	1.40	15.6
Group 1, multiple A	CP, Bpct	360	0.919	1.19	13.2
Group 1, multiple B	CP, Bpct, Fpct	360	0.919	1.19	13.2
Group 2, simple	CP	353	0.883	1.41	15.8
Group 2, multiple	CP, Bpct, DMI	353	0.916	1.19	13.4
Group 3, simple	CP	310	0.941	0.956	10.7
Group 3, multiple	CP, DMI, DMI[b], Fpct, CP × Fpct	310	0.944	0.940	10.5

[a] Bpct: dietary concentration of browse; Fpct: dietary concentration of forage; DMI: DM intake.
[b] Root mean square error.
[c] Coefficient of variation.

Table 7
Evaluation of equations to estimate digestible CP in goats (evaluation subset)

Equation	n	r^2	RMSE[a]	P			Acceptability (%)[b]		
				$b_0 = 0$	$b_1 = 1$	$b_1 = 1$[c]	Acc	Mar	Unacc
Group 1, simple	248	0.889	1.28	0.08	0.14	0.73	61.7	26.2	12.1
Group 1, multiple A	248	0.901	1.21	0.25	0.17	0.43	60.1	28.2	11.7
Group 1, multiple B	248	0.898	1.23	0.23	0.16	0.42	58.9	28.6	12.5
Group 2, simple	248	0.889	1.28	0.07	0.09	0.99	62.5	25.0	12.5
Group 2, multiple	248	0.901	1.21	0.25	0.22	0.68	62.9	25.0	12.1
Group 3, simple	210	0.920	1.11	0.14	0.42	0.16	62.9	29.0	8.1
Group 3, multiple	210	0.925	1.08	0.04	0.14	na[d]	64.8	27.1	8.1

[a] Root mean square error.
[b] Acc: acceptable; Mar: marginal; Unacc: unacceptable.
[c] No-intercept model.
[d] na: not available.

DCP and EDCP (Table 7). There was little difference among equations in either regression parameters or acceptability percentages. Multiple regression equations gave slightly greater r^2 and smaller RMSE values than did comparable simple equations. For the simple variable equations, except for group 3 (excluding browse diets), the regression of DCP on EDCP gave intercepts that tended not to equal zero ($P = 0.08$ and 0.07). Each multiple equation except, again, that from group 5, gave intercepts equal to 0 and slopes of the non-intercept model equal to 1.

The addition of Bpct (group 1, multiple A) improved the r^2, intercept and slope parameters slightly, but had no effect on relative acceptability (Table 7). There was no advantage of adding either Fpct or DMI to equations that included Bpct (group 1, multiple B, and group 2, multiple, respectively). Furthermore, for the data subset that did not include browse-containing diets (group 3), adding Fpct and DMI to CP gave only a marginal improvement in regression parameters and acceptability, and resulted in an intercept not equal to 0.

An examination of individual observations in the evaluation data subset with unacceptable estimates (DIFF $>$ 2 × RAL) provided insight into reasons for the lack of improvement made by including Bpct in equations (Table 8). With group 1, adding Bpct decreased the number of unacceptable positive estimates, but increased the number of unacceptable negative estimates. There was only one new observation added to the unacceptable positive estimates, and this observation was a non-browse treatment. Also, although adding Bpct decreased the number of unacceptable positive estimates for browse diets (10 versus 1), there was an increase in the number of unacceptable negative estimates for browse diets (2 versus 8). With group 3, addition of Fpct and DMI had very little effect on the number and identity of unacceptable estimates.

There was consistency among equations in the reference and treatment identity of the observations having unacceptable (DIFF $>$ 2 × RAL) positive and negative estimates, especially with respect to the non-browse observations. This consistency suggests that the discrepancy between observed and estimated

Table 8
Evaluation of the numbers of unacceptable estimates of digestible CP in goats (evaluation subset)

Equation	Positive (EDCP > DCP)[a]			Negative (EDCP < DCP)		
	Reference	Total	Browse	Reference	Total	Browse
Group 1, simple	14	21	10	4	10	2
Group 1, multiple A	9	11	1	9	19	8
Group 3, simple	8	11	na	3	6	na
Group 3, multiple	9	12	na	3	5	na

[a] EDCP: estimated digestible CP; DCP: digestible CP; na: not available.

DCP concentrations for some observations was due to factors other than those identified and quantified in this study. Also, it may be that experimental error accounted for some of the discrepancies.

4. Summary and conclusions

Estimates of MFCP were remarkably consistent among equations from the entire database and subsets constructed by deletion of observations with high residuals. Similarly, estimates of true CP digestibility varied little among simple regression equations derived from data subsets with extreme outliers deleted, some of which were from browse-containing diets, and for multiple regression equations that accounted for browse-containing diets. A regression of DCP against dietary CP from a data subset with deletion of observations having residuals ≤ 1.58 yielded MFCP and true CP digestibility estimates of 2.67% of DM and 0.88, respectively, which seem appropriate as general or baseline values for goats. Therefore, for goats consuming diets not containing browse, DCP and fecal CP excretion may be calculated as follows:

$$\text{DCP (\% of DM intake)} = -2.67 + 0.88 \times \text{CP (\% of DM intake)}$$

$$\text{fecal CP (\% of DM intake)} = \text{CP} - \text{DCP} \times \text{(\% of DM intake)}$$

An alternative factorial calculation is as follows:

$$\text{MFCP (g/day)} = 0.0267 \times \text{DM intake (g/day)}$$

$$\text{undigested CP excretion (g/day)} = (100 - 0.88) \times \text{CP intake (g/day)}$$

$$\text{total fecal CP excretion (g/day)} = \text{MFCP} + \text{undigested CP excretion (g/day)}$$

Because metabolic fecal nitrogen is most commonly expressed relative to DM intake or excreted in feces, it would seem that the expression derived in this study is applicable to goats regardless of breed or nutritional plane.

Several observations in the database demonstrated lower DCP than expected based on the Lucas test and dietary CP concentration. Multiple regression equations including both CP and Bpct accounted for a very small amount of the variability in DCP not explained by CP alone. Addition of Fpct and DM intake provided no additional benefit in addressing these discrepancies. Some of these observations were associated with browse-containing diets, and some were not. There was no evidence that the depressed DCP values were due to elevated MFCP excretion, but rather appeared related to relatively low true CP digestibility.

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