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A mechanistic model for predicting the nutrient requirements and feed biological values for sheep[1]

A. Cannas*[2], L. O. Tedeschi†, D. G. Fox†, A. N. Pell†, and P. J. Van Soest†

*Dipartimento di Scienze Zootecniche, Università di Sassari, 07100 Sassari, Italy and †Department of Animal Science, Cornell University, Ithaca, NY 14852

ABSTRACT: The Cornell Net Carbohydrate and Protein System (CNCPS), a mechanistic model that predicts nutrient requirements and biological values of feeds for cattle, was modified for use with sheep. Published equations were added for predicting the energy and protein requirements of sheep, with a special emphasis on dairy sheep, whose specific needs are not considered by most sheep-feeding systems. The CNCPS for cattle equations that are used to predict the supply of nutrients from each feed were modified to include new solid and liquid ruminal passage rates for sheep, and revised equations were inserted to predict metabolic fecal N. Equations were added to predict fluxes in body energy and protein reserves from BW and condition score. When evaluated with data from seven published studies (19 treatments), for which the CNCPS for sheep predicted positive ruminal N balance, the CNCPS for sheep predicted OM digestibility, which is used to predict feed ME values, with no mean bias (1.1 g/100 g of OM; $P > 0.10$) and a low root mean squared prediction error (RMSPE; 3.6 g/100 g of OM). Crude protein digestibility, which is used to predict N excretion, was evaluated with eight published studies (23 treatments). The model predicted CP digestibility with no mean bias (–1.9 g/100 g of CP; $P > 0.10$) but with a large RMSPE (7.2 g/100 g of CP). Evaluation with a data set of published studies in which the CNCPS for sheep predicted negative ruminal N balance indicated that the model tended to underpredict OM digestibility (mean bias of –3.3 g/100 g of OM, $P > 0.10$; RMSPE = 6.5 g/100 g of OM; n = 12) and to overpredict CP digestibility (mean bias of 2.7 g/100 g of CP, $P > 0.10$; RMSPE = 12.8 g/100 g of CP; n = 7). The ability of the CNCPS for sheep to predict gains and losses in shrunk BW was evaluated using data from six studies with adult sheep (13 treatments with lactating ewes and 16 with dry ewes). It accurately predicted variations in shrunk BW when diets had positive N balance (mean bias of 5.8 g/d; $P > 0.10$; RMSPE of 30.0 g/d; n = 15), whereas it markedly overpredicted the variations in shrunk BW when ruminal balance was negative (mean bias of 53.4 g/d, $P < 0.05$; RMSPE = 84.1 g/d; n = 14). These evaluations indicated that the Cornell Net Carbohydrate and Protein System for Sheep can be used to predict energy and protein requirements, feed biological values, and BW gains and losses in adult sheep.

Key Words: Energy, Models, Protein, Sheep Requirements

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Introduction

Sheep production is an economically important enterprise in many countries (FAO, 2003). Many feeding studies have been conducted with sheep to determine their requirements and dietary utilization. However, there are fewer diet evaluation systems for sheep than there are for cattle and they are often less developed, based on simpler approaches, and biologically more empirical than the cattle systems (Cannas, 2000). None of the sheep diet formulation systems except INRA (1989) were designed for use with dairy sheep.

The Cornell Net Carbohydrate and Protein System for Cattle (**CNCPS-C**) is a diet evaluation and formulation system developed for use in diverse animal, feed, and environmental production situations for all classes of beef, dairy, and dual-purpose cattle (Fox et al., 2004). The ability of the CNCPS-C structure to account for differences in feeds of diverse characteristics fed at different levels of intake, widely varying animal characteristics, and environmental effects led us to consider its modification to provide a more robust sheep model

[1]The software model can be downloaded from http://www.cncps.cornell.edu. This research was partially supported by a grant of the Italian Ministry for Agriculture and Forestry (project: Further development of a diet formulation model for sheep and goats. National coordinator: G. Pulina).

[2]Correspondence: via De Nicola 9 (phone: + 39-079-229305; e-mail: cannas@uniss.it).

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(**CNCPS-S**), with the hypothesis that this sheep model would have the same level of flexibility as does the CNCPS-C.

Therefore, the objective of the study was to integrate the published information on sheep requirements and feed utilization into the structure of the CNCPS-C model and to evaluate the new sheep model with published data. The development of a model to formulate diets for dairy sheep was a second goal. The first section of the paper is devoted to explaining the equations included in the CNCPS-S, and the second portion presents an evaluation of various aspects of the CNCPS-S using published data.

Materials and Methods

The CNCPS-C model as described by Fox et al. (2003) was used as the structure for the CNCPS-S model. The components of the CNCPS-C model that were considered inadequate for sheep were modified based on an extensive review of published equations and reported values. When the information available in the literature was inadequate, new equations were developed as needed to adapt the CNCPS for sheep. Table 1 contains a list of abbreviations used throughout the paper and in tables and figures.

Model Development

The CNCPS-C model separately calculates NE requirements for maintenance, growth, pregnancy, lactation, and body reserves, which then are converted to ME using ME efficiency coefficients for each of these physiological functions (Fox et al., 1992). This structure was used to develop sheep requirements, for the CNCPS-S model.

Energy Requirements for Maintenance. The maintenance requirement is defined as the amount of feed energy intake that results in no loss or gain of energy from the tissue of the animal (NRC, 2000). The submodels for energy and protein requirements of the CNCPS-C were modified to include equations and values developed specifically for sheep. Maintenance requirements were developed for sheep primarily from equations of the ARC (1980) and CSIRO (1990) systems.

The energy requirements for basal metabolism, expressed as NE_m, are adjusted for age, gender, physiological state, environmental effects, activity, urea excretion, acclimatization, and cold stress in order to estimate total NE_m and metabolizable energy requirements for maintenance (**ME_m**), as shown in Eq. [1].

$$ME_m = \{[SBW^{0.75} \times a1 \times S \times a2 \times \exp(-0.03 \times AGE)] + (0.09 \times MEI \times k_m) + ACT + NE_{mcs} + UREA\}/k_m \quad [1]$$

where shrunk BW (**SBW**) is defined as 96% of full BW (**FBW**), kg; ME_m, Mcal/d; SBW, kg; and $SBW^{0.75}$ is the metabolic weight, kg. The factor a1 in Eq. [1], the thermoneutral maintenance requirement per kilogram of metabolic weight for fasting metabolism (CSIRO, 1990), is assumed to be 0.062 Mcal of NE_m/kg$^{0.75}$. This value is corrected for the effect of age on maintenance requirements, using the CSIRO (1990) exponential expression exp(−0.03 × AGE), where AGE is in years, which decreases the maintenance requirements from 0.062 Mcal to 0.0519 Mcal of NE_m per kilogram of $SBW^{0.75}$ as the animal ages from 0 to 6 yr. The requirements of animals 6 yr of age or older are similar to those of NRC (1985a), INRA (1989), and AFRC (1995). The CNCPS-C uses different values for a1, depending on the cattle breed being evaluated. Unlike cattle, none of the existing sheep systems adjust the requirements to account for breed differences despite the fact that the variability among sheep breeds for morphology, genetic merit, and productivity has been shown to be at least as high as for cattle. Differences in maintenance requirements were observed among Italian dairy sheep breeds and even among groups of sheep of differing genetic merit within the same breed (Pilla et al., 1993). However, these effects could have been caused by differences in the previous plane of nutrition and in body fat content of the groups considered. Indeed, no differences in the metabolic rate of mature ewes were found by other studies (Olthoff et al., 1989; Freetly et al., 2002). For this reason, the same a1 value is used for all sheep breeds.

The S factor in Eq. [1], a multiplier for the effect of gender on maintenance requirements, is assumed to be 1.0 for females and castrates and 1.15 for intact males (ARC, 1980). The factor a2, an adjustment for the effects of previous temperature, is (1 + 0.0091 × C), where C = (20 − Tp) and Tp is the average daily temperature of the previous month (NRC, 1981). This adjustment was adopted by NRC (1981) from the studies of Young (1975) with beef cows. Following the suggestions of CSIRO (1990), it was also included in this sheep model.

Also in Eq. [1], the term [(0.09 × MEI) × k_m], where MEI is in megacalories per day and k_m is dimensionless and in decimal form, is based on the CSIRO (1990) adjustment to account for the increase in the size of the visceral organs as nutrient intake increases. The efficiency coefficient k_m is fixed at 0.644, and it is equal to the efficiency of conversion of ME to NE for milk production, based on the assumption that lactating cows use energy with a similar degree of efficiency for maintenance and milk production (Moe et al., 1972; Moe, 1981) and that differences in this efficiency between sheep and cows are unlikely (Van Soest et al., 1994).

The ACT factor, Mcal of NE_m/d, in Eq. [1] is the effect of activity on maintenance requirements. The factor a1 includes the minimum activity for eating, rumination, and movements of animals kept in stalls, pens, or yards (CSIRO, 1990). Then, for grazing animals only, we added the energy expenditure of walking on flat and sloped terrains as indicated by ARC (1980):

$$ACT = 0.00062 \times FBW \times \text{flat distance} + 0.00669 \times FBW \times \text{sloped distance} \quad [2]$$

Table 1. Definitions for the abbreviations used in the Equations describing the Cornell Net Carbohydrate and Protein System for Sheep

a1	Thermoneutral basal maintenance requirements, Mcal/kg of $FBW^{0.75}$
a2	Adjustment for previous temperature
ACT	Activity requirements for horizontal and slope walking, Mcal/d of NE_m
Af	Adjustment factor for particle size
AF	Proportion of fat in the empty body
AGE	Adjustment for age effect on maintenance requirements, yr
AP	Proportion of protein in the empty body
CLEAN WOOL	Clean wool produced, g/yr
BCS	Body condition score, 0-to-5 scale
Distance flat	Horizontal component of the distance traveled daily, km
Distance sloped	Vertical component of the distance traveled daily, km
E_t	Total energy content of the gravid uterus at day t, MJ
EB	ME balance, Mcal/d
EBG	Empty-body gain = 0.92 FBW gain, g/d
EBW	Empty-body weight = 0.851 SBW, kg
EVG	Energy content of EBG, Mcal of NE_g/kg
FBW	Full-body weight, kg
FBWc	Full-body weight change, g/d
$FBW_{BCS2.5}$	FBW in mature sheep when BCS = 2.5
$FBW_{BCS3.0}$	FBW in mature sheep when BCS = 3.0
FCM	6.5% fat-corrected milk, kg
F-ASH_{M+E}, F-ASH_U	Fecal metabolic (microbial + endogenous) and feed ash, respectively, g/d
F-CP_M, F-CP_E, F-CP_U	Fecal microbial, endogenous, and feed CP, respectively, g/d
F-FAT_{M+E}, F-FAT_U	Fecal metabolic (microbes + endogenous) and feed fat, respectively, g/d
IDM	Indigestible dry matter intake, kg/d
K	Correction factor for intake in pregnant animals
k_m, k_l, k_g	Efficiency of conversion of ME to NE_m, NE_l, NE_g, respectively
k_r	Efficiency of conversion of ME to NE for gain or loss in adult sheep
Kp	Passage rate (for forages, solids, liquids), %/h
LBW	Total litter birth weight, kg
ME	Metabolizable energy, Mcal
MEC	Feed or diet ME concentration, Mcal/kg of DM
MEI	Metabolizable energy intake, Mcal/d
ME_m	ME requirement for maintenance, Mcal/d
ME_l	ME requirement for lactation, Mcal/d
ME_{preg}	ME requirement for pregnancy, Mcal/d
MP	Metabolizable protein, g/d
MP_m	MP required for maintenance, g/d
MP_l	MP required for lactation, g/d
MP_{preg}	MP required for pregnancy, g/d
NE_m	Net energy requirement for maintenance, Mcal/d
NE_{preg}	Net energy required for pregnancy, Mcal/d
NE_{mcs}	NE_m required for cold stress, Mcal/d
NP	Net protein, g/d
P	Body maturity index
peNDF	Physically effective NDF, % of NDF
PP	Measured milk true protein for a particular day of lactation, %
PQ	Measured milk fat for a particular day of lactation, %
Pr	Total protein content of the gravid uterus at day t, g/d
R	Adjustment factor for rate of gain or loss
RE	NE available for gain, Mcal/d
SBW	Shrunk body weight, defined as 96% of full body weight, kg
S-CP_E	Scurf and wool endogenous crude protein, g/d
t	Time, d
T_c	Current mean daily (24 h) air temperature, °C
T_p	Previous month mean daily (24 h) air temperature, °C
TE	Total body energy, Mcal of NE
TF	Total body fat, kg
TP	Total body protein, kg
UREA	Cost of excreting excess N as urea, Mcal of NE_m/d
U-CP_E	Urinary endogenous crude protein, g/d
Yn	Measured milk yield at a particular day of lactation, kg/d

where ACT is NE_m required for walking, Mcal/d; FBW is full BW, kg; flat distance is the horizontal distance, km/d; 0.00062 is the energy cost per kilogram of FBW of the horizontal component of walking, Mcal of NE_m/km; sloped distance is the vertical component of the movement, km/d; and 0.00669 is the energy cost per kilogram of FBW of the vertical component of walking, Mcal of NE_m/km.

Farrell et al. (1972) found that in sheep the energy cost of walking (energy per km per kg FBW) was not affected by body condition, and Mathers and Sneddon (1985) found that in cattle ambient temperature did not affect the cost of walking. Therefore, these two factors were not considered in calculating ACT.

The NE_{mcs} factor in Eq. [1] is based on CSIRO (1990) estimates of extra maintenance energy required to counterbalance the effect of cold stress. Included in the CSIRO (1990) model are equations to account for many environmental (temperature, wind, rain, radiant heat losses) and animal factors (body heat production, acclimatization to cold environments, tissue and external insulation).

The energy cost of excreting excess N as urea (UREA in Eq. [1]) is calculated as in the CNCPS-C model (Fox et al., 2003). This cost is added to the NE_m required for maintenance.

$$\text{UREA} = [(\text{g ruminal N balance} - \text{g recycled N} + \text{g excess N from MP}) \times 0.0073] \times k_m \quad [3]$$

where UREA is in megacalories of NE_m per day and ruminal N balance, recycled N, and excess N from metabolizable protein (**MP**) are estimated as in the CNCPS-C.

Even though heat stress may have a direct effect on NE_m, due to the energy cost of dissipating excess heat (Blaxter, 1977; NRC, 1981), no prediction equations were available for sheep and therefore no adjustment was included in the sheep model.

Energy Requirements for Lactation. Metabolizable energy requirements for milk production (**ME_l**) are estimated from the net energy value of milk, which is predicted with the equation of Pulina et al. (1989):

$$ME_l = \{[251.73 + 89.64 \times PQ + 37.85 \times (PP/0.95)] \times 0.001 \times Yn\}/k_l \quad [4]$$

where ME_l is metabolizable energy required for lactation, Mcal/d; Yn is measured milk yield at a particular day of lactation, kg/d; PQ is measured milk fat for a particular day of lactation, %; PP is measured true milk protein for a particular day of lactation, %; and k_l is efficiency of ME utilization for milk production, which is equal to 0.644.

The efficiency of conversion of ME to NE for maintenance and milk production is the same as that adopted by the CNCPS-C and NRC (1989) for cattle, which was derived from Moe et al. (1972) and Moe (1981).

Energy Requirements for Pregnancy. Pregnancy energy requirements are estimated using the CSIRO (1990) equation, which were derived from the ARC (1980) model. The energy gains of the gravid uterus during pregnancy in sheep from 63 d after conception to delivery are estimated using a Gompertz equation as shown in Eq. [5].

$$\ln(E_t) = 7.649 - 11.465 \times \exp(-0.00643 \times t) \quad [5]$$

where E_t is the total energy content, MJ, of the gravid uterus at day t and exp is the exponential function.

Equation [5] estimates the total energy content of the gravid uterus at time t, assuming that the ewe will produce a 4-kg lamb at 147 d of gestation (or 4.3 kg at 150 d). For different birth weights or for more than one lamb, E_t is adjusted based on expected total lamb birth weight (**LBW**). By differentiation, the equation allows for the calculation of the daily net energy requirements for pregnancy. The estimate is converted from megajoules to megacalories using the factor 0.239:

$$\begin{aligned} NE_{preg} &= dE/dt = E_t \times 0.0737 \times \exp(-0.00643 \times t) \times (LBW/4) \times 0.239 \quad [6] \\ &= 36.9644 \times \exp[-11.465 \times \exp(-0.00643 \times t) - 0.00643 - t] \times (LBW/4) \end{aligned}$$

where NE_{preg} is the net energy required for pregnancy, Mcal/d, and LBW is the expected total lamb or lambs birth weight, kg.

The efficiency of utilization of ME for gestation is 0.13, which is the same as used by most nutrient requirement systems for cattle and for sheep (Cannas, 2000). Therefore, the metabolizable energy requirements for pregnancy (**ME_{preg}**) are computed as follows:

$$ME_{preg} = NE_{preg}/0.13 \quad [7]$$

Protein Requirements for Maintenance. Maintenance metabolizable protein (**MP_m**) requirements are the sum of dermal (wool) protein, urinary endogenous protein, and fecal endogenous protein losses (CSIRO, 1990). The system of equations used by CSIRO (1990) was adopted for use in the CNCPS-S as shown in the following.

$$MP_m = (S - CP_E/0.6) + (U\text{-}CP_E/0.67) + (F\text{-}CP_E/0.67) \quad [8]$$

$$S\text{-}CP_E = (\text{CLEAN WOOL}/365) \quad [9]$$

$$U\text{-}CP_E = (0.147 \times FBW + 3.375) \quad [10]$$

$$F\text{-}CP_E = (15.2 \times DMI) \quad [11]$$

where MP_m represents the maintenance requirement of metabolizable protein, g/d; $S\text{-}CP_E$ is the endogenous

CP lost from dermal tissues (scurf and wool), g/d; $U\text{-}CP_E$ is the urinary endogenous CP, g/d; $F\text{-}CP_E$ is the fecal endogenous CP, g/d; 0.6, 0.67, and 0.67 are the efficiencies of conversion of MP to net protein for $S\text{-}CP_E$, $U\text{-}CP_E$, and $F\text{-}CP_E$, respectively; CLEAN WOOL is the clean wool produced per head, g/yr; FBW is full body weight, kg; and DMI is dry matter intake, kg/d.

The efficiency of conversion of MP to NP for $U\text{-}MP_E$ and $F\text{-}MP_E$ was assumed to be 0.67, which is the same coefficient as is used in the CNCPS-C model and is similar to the 0.7 value used by CSIRO (1990).

Because $F\text{-}MP_E$ is a function of DMI, MP requirements for maintenance will be higher in high producing animals, as their intakes are higher. This approach differs from that of INRA (1989) and AFRC (1995), whose maintenance requirements for protein depend only on FBW and wool production. In the CNCPS-C model, fecal endogenous protein for cattle is computed from indigestible dry matter. Variable maintenance requirements are justified because the increase in DMI associated with milk production or gain increases both the size and rate of metabolism of visceral organs and tissues, thus increasing the maintenance costs of these tissues (Ferrell, 1988; CSIRO, 1990).

Protein Requirements for Lactation. Metabolizable protein requirements for milk production (**MP_l**, g/d) are predicted from true milk protein content:

$$MP_l = (10 \times PP \times Yn)/0.58 \quad [12]$$

where Yn is the measured milk yield on a particular day of lactation, kg/d, and PP is the measured milk true protein for a specific day of lactation, %. If only milk CP is known, PP can be estimated as 0.95 × CP.

The coefficient for conversion of MP to NP (0.58) is that suggested specifically for sheep in the INRA system (Bocquier et al., 1987; INRA, 1989). This efficiency is lower than that used for cattle by most feeding systems, including NRC (1985a), CSIRO (1990), and AFRC (1995). The low efficiency is likely because sheep have higher requirements than cattle for sulfur-containing amino acids, due to their wool production (Bocquier et al., 1987). Lynch et al. (1991) demonstrated that the supplementation of rumen-protected methionine and lysine to lactating sheep caused a significant increase in the growth rate of the suckling lambs. At similar physiological stages, sheep tend to have higher passage rates than cattle (Van Soest, 1994) and subsequently greater escape of feed protein. Because feed protein often has a lower biological value than bacterial protein (Van Soest, 1994), there could be a lower efficiency of MP utilization in lactating sheep than in lactating cows. However, higher flow rates increased microbial yield and efficiency in dairy cattle (Robinson, 1983; Van Soest, 1994), which may offset the lower efficiency of MP from microbial protein.

Protein Requirements for Pregnancy. Protein requirements are calculated using the recommendations of CSIRO (1990), which were also derived from the ARC (1980) system.

$$\ln(Pr_t) = 11.347 - 11.220 \times \exp(-0.00601 \times t) \quad [13]$$

The coefficients are for a lamb weighing 4 kg at 147 d of gestation or 4.3 kg at 150 d. For different birth weights or for more than one lamb, Pr is adjusted based on expected total lamb birth weight. By differentiation and by converting NP to MP, the daily requirements are as follows:

$$\begin{aligned} MP_{preg} &= (dPr/dt) = Pr \times (LBW/4) \\ &[0.0674 \times \exp(-0.00601 \times t)]/0.7 = \\ &\{(LBW/4) \times 0.0674 \times \exp[11.347 - 11.22 \\ &\times \exp(-0.00601 \times t) - 0.00601 \times t]\}/0.7 \end{aligned} \quad [14]$$

where MP_{preg} is daily net protein requirements for pregnancy, g/d; Pr is protein content of the gravid uterus at time t (days) after conception, g; t is days of pregnancy; LBW is expected total lamb or lambs birth weight, kg; ln is the natural logarithm; and the efficiency of utilization of MP to NP for gestation is equal to 0.7 for sheep (CSIRO, 1990), which is more than twice as large as that adopted by the NRC (2001) for dairy cows (0.33).

Energy Balance. The energy available for growth (young sheep) or for changes in body reserves (mature ewes or rams) depends on the energy balance after maintenance, lactation, and pregnancy requirements are satisfied:

$$EB = MEI - (ME_m + ME_l + ME_{preg}) \quad [15]$$

where EB is ME balance, Mcal/d; MEI is ME intake, Mcal/d; ME_m is ME required for maintenance, Mcal/d; ME_l is ME required for milk production, Mcal/d; and ME_{preg} is ME required for pregnancy, Mcal/d.

Protein Balance. The MP available for growth (young sheep) or for body reserves changes (mature ewes or rams) depends on the MP balance after maintenance, lactation and pregnancy requirements are satisfied:

$$\text{MP balance} = \text{MP intake} - (MP_m + MP_l + MP_{preg}) \quad [16]$$

where MP intake is from the supply submodel, g/d; MP_m is MP required for maintenance, g/d; MP_l is MP required for milk production, g/d; and MP_{preg} is MP required for pregnancy, g/d.

Requirements for Growth. The sheep growth model developed by CSIRO (1990) was used for the CNCPS-S. This model is unique because it uses the same set of equations for all sheep breeds and for most cattle breeds, except for non-English European breeds. The variations in the relative proportion of fat, protein, and water in the empty-body gain (which equals 0.92 × FBW gain) depend on energy balance, rate of gain or loss, and ratio between current FBW and mature FBW. The model predicts FBW variations based on the energy available for gain and on the energy content of empty-body gain:

$$FBWc = [RE/(0.92 \times EVG)] \times 1{,}000 \quad [17]$$

$$RE = k \times EB \quad [18]$$

$$k_g = (1.42 \times MEC - 0.174 \times MEC^2 + 0.0122 \times MEC^3 - 1.65)/MEC \quad [19]$$

$$MEC = MEI/DMI \quad [20]$$

$$EBG = FBWc \times 0.92 \quad [21]$$

$$EVG = ((6.7 + R) + (20.3 - R)/\{1 + \exp[-6 \times (P - 0.4)]\}) \times 0.239 \quad [22]$$

$$R = 2 \times [(RE/NE_m) - 1] \quad [23]$$

$$P = \text{current } FBW/FBW_{BCS3.0} \quad [24]$$

where FBW_C is FBW changes, g/d; RE is NE available for gain, Mcal/d; k is k_g (the efficiency of conversion of ME to NE_g) when EB is positive, or is $k = 1.25 \times k_m$ (the efficiency of conversion of ME to NE_m) when EB is negative; MEC is metabolizable energy concentration of the diet, Mcal/kg of DM; MEI is ME intake, Mcal/d; DMI is DM intake, kg/d; EBG is empty-body gain, kg/d; EVG is the energy content of EBG, Mcal/kg of EBG; R is the adjustment for rate of gain or loss when ME intake is known and gain or loss must be predicted; P is a maturity index; and $FBW_{BCS3.0}$ is the FBW that would be achieved by a specific animal of a certain breed, age, sex, and rate of gain when skeletal development is complete and the empty body contains 250 g of fat/kg. This corresponds to body condition scores (**BCS**) 2.8 to 3.0 in ewes using a 0-to-5 scale.

Energy and Protein Reserves in Adult Sheep. Body condition score, body weight, and body composition are used to calculate changes in energy and protein reserves after first lambing. Equations were developed to estimate the relationships among these variables in sheep following the same approach used by the beef NRC (2000) for adult cows and adopted by the CNCPS-C model, as shown below.

$$AF = 0.0269 + 0.0869 \times BCS \quad [25]$$

$$AP = -0.0039 \times BCS^2 + 0.0279 \times BCS + 0.1449 \quad [26]$$

$$EBW = 0.851 \times 0.96 \times FBW \quad [27]$$

$$TF = AF \times EBW \quad [28]$$

$$TP = AP \times EBW \quad [29]$$

$$TE = 9.4 \times TF + 5.7 \times TP \quad [30]$$

where AF is proportion of empty-body fat; AP is proportion of empty-body protein; BCS is body condition score; EBW is empty-body weight ($0.851 \times$ SBW), kg; SBW is shrunk body weight ($0.96 \times$ FBW), kg; FBW is current full-body weight, kg; TF is total body fat, kg; TP is total body protein, kg; and TE is total body energy, in Mcal of NE.

The relationship between FBW and BCS (Eq. [35]) was developed based on 10 publications (Russel et al., 1969; Guerra et al., 1972; Teixeira et al., 1989; Sanson et al., 1993; Susmel et al., 1995; Treacher and Filo, 1995; Frutos et al., 1997; Oregui et al., 1997; Zygoyiannis et al., 1997; Molina Casanova et al., 1998) in which this relationship was studied in mature ewes of 12 breeds (seven dairy breeds and five meat or wool breeds). From these data, FBW could be predicted by BCS with simple linear regressions, in which the intercept indicated the FBW at BCS 0 and the slope predicted the variations of FBW for each unit of BCS variation. Only Teixeira et al. (1989) found a curvilinear relationship, which we refitted to a simple linear regression to be used in the development of the prediction equation. Both the intercepts and the slopes of the 12 simple linear equations (one for each breed) were fitted against the mature weight of the ewes at BCS = 2.5 (**$FBW_{BCS2.5}$**), when the empty body contains 240 g of fat/kg (196 g of fat/kg of FBW). Both parameters were linearly and significantly associated with the $FBW_{BCS2.5}$, as shown below (the SE of the coefficients are in parentheses).

$$INTERCEPT = -5.31(5.87) + 0.69(0.11) \times FBW_{BCS2.5} \quad [31]$$

Equation [31] had an r^2 of 0.80 and SE of 3.58. However, because the intercept of this equation was not significant (Figure 1), we fitted a linear regression through the origin (Eq. 32):

$$INTERCEPT = 0.594(0.02) \times FBW_{BCS2.5} \quad [32]$$

The slope was estimated to be

$$SLOPE = 2.80(2.43) + 0.11(0.05)FBW_{BCS2.5} \quad [33]$$

Equation [33] had an r^2 of 0.37 and SE of 1.49. However, because the intercept of this equation was not

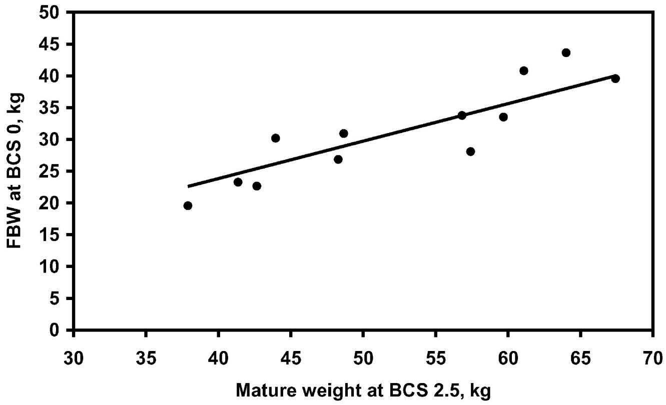

Figure 1. Relationship between mature full-body weight (FBW) of ewes at body condition score (BCS) 2.5 and FBW at BCS 0. Each point represents a different breed. Each point represents the intercept of a simple linear regression between the mature FBW of ewes at BCS 2.5 and FBW variation calculated for a specific breed. (Data from Russel et al., 1969; Guerra et al., 1972; Teixeira et al., 1989; Sanson et al., 1993; Susmel et al., 1995; Treacher and Filo, 1995; Frutos et al., 1997; Oregui et al., 1997; Zygoyiannis et al., 1997; Molina Casanova et al., 1998.) The regression equation was (the SE of the coefficients are in parentheses): $y = -5.31(5.87) + 0.69(0.11)x$, $r^2 = 0.80$; $P < 0.001$; SE = 3.58. Because the intercept of this equation was not significant, the equation became $y = 0.594(0.02)x$. The regression line in the figure refers to the latter equation.

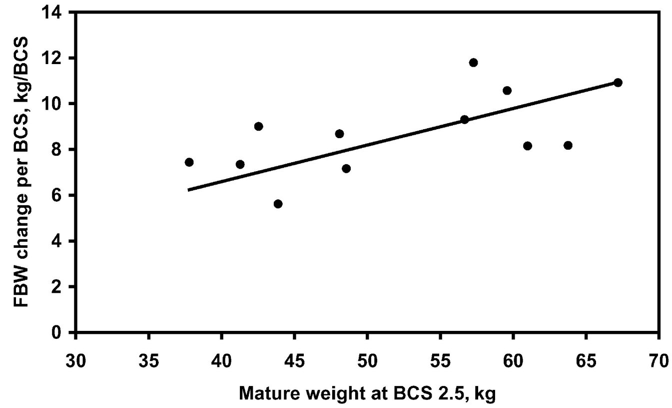

Figure 2. Relationship between mature full-body weight (FBW) of ewes at body condition score (BCS) 2.5 and FBW change for each unit of change in BCS. Each point represents the slope of a simple linear regression between the mature FBW of ewes at BCS 2.5 and FBW variation calculated for a specific breed. (Data from Russel et al., 1969; Guerra et al., 1972; Teixeira et al., 1989; Sanson et al., 1993; Susmel et al., 1995; Treacher and Filo, 1995; Frutos et al., 1997; Oregui et al., 1997; Zygoyiannis et al., 1997; Molina Casanova et al., 1998.) The regression equation was (the SE of the coefficients are in parentheses): $y = 2.80(2.43) + 0.11(0.05)x$, $r^2 = 0.37$; $P < 0.035$; SE = 1.49. Because the intercept of this equation was not significant, the equation became $y = 0.163(0.01)x$. The regression line in this figure refers to the latter equation.

significant (Figure 2), we fitted a linear regression through the origin (Eq. 34):

$$SLOPE = 0.163(0.01)FBW_{BCS\ 2.5} \quad [34]$$

These relationships were combined to develop Eq. [35], which allows the prediction of FBW at any BCS for breeds with different $FBW_{BCS2.5}$:

$$FBW = INTERCEPT + SLOPE \times BCS = 0.594 \times FBW_{BCS2.5} + 0.163 \times FBW_{BCS2.5} \times BCS = (0.594 + 0.163 \times BCS) \times FBW_{BCS2.5} \quad [35]$$

where FBW is current full-body weight, kg; $FBW_{BCS2.5}$ is FBW at BCS 2.5, kg; and BCS is current body condition score, 0-to-5 scale.

If current BCS and $FBW_{BCS2.5}$ are known inputs, FBW of Eq. [27] can be estimated for all other BCS using Eq. [35].

If current BCS and FBW are known, $FBW_{BCS2.5}$ can be estimated by rearranging Eq. [35]:

$$FBW_{BCS\ 2.5} = FBW/(0.594 + 0.163 \times BCS) \quad [36]$$

Then, $FBW_{BCS2.5}$ can be used in Eq. [35] to estimate FBW at any other BCS.

The gain or loss of FBW is estimated dividing the EB by the energy content of each kilogram of gain or loss:

$$FBW_C = (EB \times k_r)/[(TE \text{ of FBW at next BCS} - TE \text{ of FBW at current BCS})/(FBW \text{ at next BCS} - FBW \text{ at current BCS})] \times 1,000 \quad [37]$$

where FBW_C is FBW changes, g/d; FBW is full body weight, kg; EB is ME balance, Mcal/d of ME; TE is total body energy, in Mcal of NE; BCS is body condition score; k_r is the ratio between reserves NE and ME and is 0.6 for all sheep categories, as suggested by CSIRO (1990). This value is similar to that suggested by INRA (1989) and AFRC (1995).

Based on Moe (1981), 1 Mcal of reserve energy provides 0.82 Mcal of NE_l or NE_m. In the case of BCS and weight losses, net protein (**NP**) from reserves is used for milk protein synthesis with an efficiency of 0.8 (CSIRO, 1990). The BCS is measured with a descriptive score ranging from 0 to 5, as proposed by Russel et al. (1969). This scale is the most frequently used in Europe and in Australia (CSIRO, 1990).

The relationship between the proportion of fat in the empty body (**AF**) and BCS (Eq. [25]) was originally developed by Russel et al. (1969) for Scottish Blackface ewes. The relationship between the proportion of protein in the empty body (**AP**) and BCS (Eq. [26]) was estimated assuming that the ratio AF/AP for various

BCS reported by Fox et al. (2003) for cattle is also valid in sheep. The relationship between empty-body weight and full-body weight (Eq. [27]) is the same as that used by the CNCPS-C.

Predicting Dry Matter Intake. Dry matter intake is predicted by the CNCPS-S by using the equations developed by Pulina et al. (1996) for sheep fed indoors. For lactating ewes:

$$DMI = (-0.545 + 0.095 \times FBW^{0.75} + 0.65 \times FCM + 0.0025 \times FBW_C) \times K \quad [38]$$

For dry ewes:

$$DMI = (-0.545 + 0.095 \times FBW^{0.75} + 0.005 \times FBW_C) \times K \quad [39]$$

For lambs and ewe-lambs up to first pregnancy:

$$DMI = -0.124 + 0.0711 \times FBW^{0.75} + 0.0015 \times FBW_C \quad [40]$$

For rams:

$$DMI = 0.065 \times FBW^{0.75} \quad [41]$$

where DMI is DM intake, kg/d; FBW is full-body weight, kg; and FCM is 6.5% fat-corrected milk yield, kg/d, based on the equation of Pulina et al. (1989):

$$FCM = (0.3688 + 0.0971 \times PQ) \times Yn \quad [42]$$

where Yn is measured milk yield at a particular day of lactation, kg/d; PQ is measured milk fat at a particular day of lactation, %; and FBW_C is FBW changes, g/d. The factor K is a correction factor for pregnant animals; if total birth weight of the litter is more than 4.0 kg, then K is 0.82, 0.90, 0.96, and 1.0 for wk 1 and 2, 3 and 4, 5 and 6, and >6 after lambing, respectively; if total birth weight of the litter is less than 4.0 kg, then K is 0.88, 0.93, 0.97, and 1.0 for wk from lambing for wk 1 and 2, 3 and 4, 5 and 6, and >6, respectively.

Prediction of Supply of Nutrients. The submodel for predicting the supply of nutrients is based on the corresponding submodels of the CNCPS-C, version 5.0 (Fox et al., 2003) except for the equation used to predict ruminal passage rate and fecal protein content. Degradation rates used by the CNCPS-C are from in vitro measurements (Fox et al., 2003) and are assumed to be the same for cattle and sheep. Because microbial activity and efficiency are considered to be similar in sheep and cows in similar conditions (NRC, 1985b; CSIRO, 1990), the degradation rates in the CNCPS-C feed library were included in the CNCPS-S.

Prediction of Ruminal Passage Rates for Forages, Concentrates, and Liquids. In the CNCPS-C, the prediction of ruminal feed passage rate (**Kp**) is one of the most important steps in estimating the ruminal digestibility of nutrients. Passage rate is affected by many animal and feed variables. The CNCPS-C predicts the passage rate of solids based on equations from Sauvant and Archimede (1990, unpublished data, cited by Lescoat and Sauvant, 1995), specifically developed for cattle. Three separate equations are used to estimate Kp of forages, concentrates, and liquids. The passage rates of forages and concentrates are then adjusted for particle size based on the physically effective NDF content of each feed (Mertens, 1997). When CNCPS-C predictions were applied to small ruminants, the Kp was underestimated compared to the measurements in sheep using external markers, as reported by Cannas (2000). For this reason, the equations proposed by Cannas and Van Soest (2000) were used to predict forage and concentrate ruminal passage rates, whereas, for liquid ruminal passage rate, a new equation was developed, as described below.

The passage rate of forages was estimated with an allometric model (Eq. [43]; $r^2 = 0.53$ and SE = 0.80) based on experiments in which Kp was measured by applying external markers to the feeds (Cannas and Van Soest, 2000). This model was based on 157 dietary treatments and passage rate measurements reported in 36 published papers. Forty-five treatment means were from experiments carried out on sheep, 100 were from cattle, 4 on buffaloes, and 8 on goats.

$$Kp[forages] = 1.82 \times D\text{-}NDFI^{0.40} \times \exp(0.046 \times D\text{-}CP\%) \quad [43]$$

where Kp[forages] is the ruminal passage rate of the forages of the diet, %/h; D-NDFI is the total dietary intake of NDF as percentage of FBW, kg of NDF intake/kg of FBW × 100; and D-CP% is the dietary concentration of CP, % of DM.

The ruminal Kp of concentrates (Eq. [44]; $r^2 = 0.65$ and SE = 1.10) was estimated by using linear regression on a data set with 36 dietary treatments and passage rate measurements, reported in 7 published papers, in which both forage and concentrate Kp were measured with external markers (Cannas and Van Soest, 2000). There were 26 measurements with cattle, 6 with sheep, and 4 with goats.

$$Kp[conc.] = 1.572 \times Kp[forages] - 0.925 \quad [44]$$

where Kp[forages] is the ruminal passage rate of the forages of the diet, %/h; and Kp[conc.] is the ruminal passage rate of the concentrates of the diet, %/h.

Some of the experiments (Hartnell and Satter, 1979; Shaver et al., 1986; Shaver et al., 1988; Colucci et al., 1990; Nelson and Satter, 1992) in which the Kp of concentrates was measured also reported liquid Kp, measured with external markers. There were 18 treatments from experiments with lactating cows, 4 with dry cows, and 6 with growing wethers. Kp[liquid] and Kp[conc.] were linearly associated (Eq. [45]; $r^2 = 0.45$ and SE = 2.07) as shown in Figure 3.

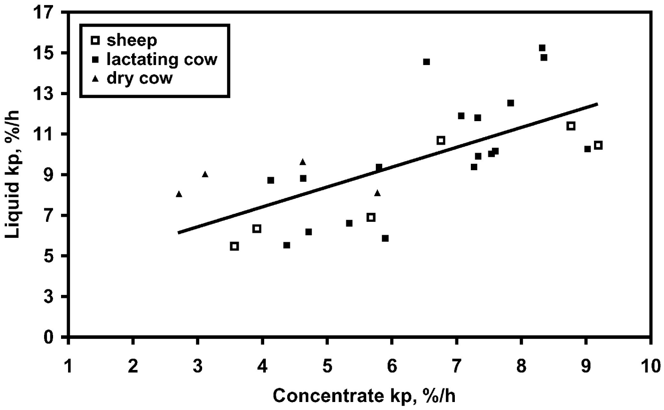

Figure 3. Relationship between the ruminal passage rate of concentrate and that of liquid, both measured with external markers. (Data from Hartnell and Satter, 1979; Shaver et al., 1986; Shaver et al., 1988; Colucci et al., 1990; Nelson and Satter, 1992.) The regression equation was y = 0.976(0.213)x + 3.516(1.370), $r^2 = 0.45$, $P < 0.001$; SE = 2.07.

$$\text{Kp[liquid]} = 0.976 \times \text{Kp[conc.]} + 3.516 \quad [45]$$

where Kp[conc.] is the ruminal passage rate of the concentrates of the diet, %/h, and Kp[liquid] is the passage rate of the liquid phase of the rumen, %/h.

As in the CNCPS-C, Kp is adjusted for individual feeds using a multiplicative adjustment factor (**Af**) for particle size using diet physically effective NDF (**peNDF**):

$$\text{Af[forages]} = 100/(\text{peNDF} + 70) \quad [46]$$

$$\text{Af[conc.]} = 100/(\text{peNDF} + 90) \quad [47]$$

where peNDF is the proportion of physically effective NDF concentration in individual feeds. These equations were used because they were the only ones available to account for the effects of particle size on passage rate. However, these effects are probably different between small and large ruminants (Van Soest et al., 1994). Clearly, additional research is needed in this area.

Prediction of Fecal Protein. The CNCPS-C estimates of total CP in the feces are the sum of three components: undegraded feed protein ($\mathbf{F_U}$), metabolic microbial CP residues ($\mathbf{F_M}$), and metabolic endogenous CP ($\mathbf{F_E}$). The latter fraction is estimated by the CNCPS-C as in the NRC (1989). The intercept of linear equations obtained by regressing digestible protein on intake protein represents the endogenous protein. The mean value for the intercept was 30 g/kg of DMI (Boekholt, 1976; Waldo and Glenn, 1984). On the basis of this estimate, the NRC (1989) calculates F_E as a proportion of the indigestible DM (**IDM**), assuming an average digestibility of 67%, which is 33% dietary indigestibility (333 g/kg): 30/333 = 0.09. Thus, $F_E = 0.09 \times \text{IDM}$ (i.e., 90 g/kg of IDM). The CNCPS-C then corrects this value to account for the fact that IDM includes some endogenous matter.

$$\begin{aligned}\text{Fecal CP} &= \text{F-CP}_U + \text{F-CP}_M + \text{F-CP}_E \\ &= \text{F-CP}_U + \text{F-CP}_M + 90 \times \text{IDM}\end{aligned} \quad [48]$$

where fecal CP is total CP in the feces, g/d; F-CP_U is undegraded feed CP in the feces estimated by using the CNCPS-C approach, g/d; F-CP_M is fecal endogenous CP estimated by using the CNCPS-C approach, g/d; F-CP_E is the fecal microbial crude protein, g/d; IDM is the indigestible dry matter intake, kg/d; and 90 is the number of grams of endogenous CP in the feces.

The approach used by the CNCPS-C and by the NRC (1989) has two main problems. The first difficulty is that the intercept of the linear equation obtained by regressing digestible protein on intake protein does not represent an estimate of the F-CP_E; it is the sum of metabolic microbial and endogenous protein (metabolic fecal protein, F-CP_{M+E}) (Van Soest, 1994). This means that microbial residues in the feces are counted twice in both the NRC (1989) and the CNCPS-C systems. The second problem is that the assumption of a constant dietary indigestibility (equal to 33%) is unrealistic. For these reasons, the prediction of fecal CP was modified, using two approaches. In the first approach, total CP in the feces was considered equal to the sum of undegraded feed CP (F-CP_U) and metabolic fecal CP (F-CP_{M+E}), in which the latter was estimated with the method used by the CNCPS-C and by NRC (1989) to estimate F-CP_E. The estimates of the CNCPS-C for microbial residues were not included in fecal CP to avoid double accounting:

$$\text{Fecal CP} = \text{F-CP}_U + \text{F-CP}_{M+E} = \text{F-CP}_U + 90 \times \text{IDM} \quad [49]$$

where fecal CP is total CP in the feces, g/d; F-CP_U is undegraded feed protein in the feces estimated by using the CNCPS-C approach, g/d; F-CP_{M+E} is the sum of fecal microbial and endogenous crude protein, g/d; IDM is the indigestible dry matter intake, kg/d; and 90 is the number of grams of microbial and endogenous crude protein in the feces. In the second approach, it was assumed that the total CP in the feces equaled the sum of undegraded feed CP, F-CP_U, and metabolic fecal CP, F-CP_{M+E}, but the latter was equal to

$$\text{Fecal CP} = \text{F-CP}_U + \text{F-CP}_{M+E} = \text{F-CP}_U + 30 \times \text{DMI} \quad [50]$$

where fecal CP is total CP in the feces, g/d; F-CP_U is undegraded feed protein in the feces as estimated by the CNCPS-C after correcting for Kp prediction, g/d; F-CP_{M+E} is the sum of fecal microbial and endogenous crude protein, g/d; DMI is dry matter intake, kg/d; and 30 is the number of grams of microbial and endogenous crude protein in the feces, as originally estimated by Boekholt (1976) and Waldo and Glenn (1984). The estimates of the CNCPS-C for microbial residues were not included in the fecal CP. This approach was chosen for the CNCPS-S. However, diet digestibility and FBW variations were also calculated with the other two approaches (the CNCPS-C method, Eq. [48], and the method of Eq. [49]) to highlight the scope of the correction proposed and its effects on prediction accuracy.

Prediction of Fecal Fat. The CNCPS-C estimates of total fat in the feces are the sum of three components: undegraded feed fat, metabolic microbial fat residues, and metabolic endogenous fat. The latter fraction is estimated by the CNCPS-C using the Lucas and Smart (1959) value of 11.9 g/kg of DMI. This value was the mean value for the intercept obtained by regressing dietary digestible fat concentration on dietary fat concentration. As pointed out by Lucas and Smart (1959), the intercept of this regression gives an estimate of the fecal fat material not coming from feed and not, as erroneously assumed by the CNCPS-C, the endogenous fat in the feces. Therefore, the CNCPS-S estimates the total fat in the feces as

$$\text{Fecal fat} = \text{F-FAT}_U + \text{F-FAT}_{M+E} = \text{F-FAT}_U + 11.9 \times \text{DMI} \quad [51]$$

where fecal fat is total fat in the feces, g/d; F-FAT_U is undegraded feed fat in the feces as estimated by the CNCPS-C, g/d; F-FAT_{M+E} is the sum of fecal microbial and endogenous fat, g/d; DMI is dry matter intake, kg/d; and 11.9 is the number of grams of microbial and endogenous fat in the feces, as originally estimated by Lucas and Smart (1959).

Prediction of Fecal Ash. The CNCPS-C estimate of total ash in the feces is the sum of three components: undegraded feed ash, metabolic microbial fat residues, and metabolic endogenous fat. The latter fraction is estimated by the CNCPS-C using the Lucas and Smart (1959) value of 17.0 g/kg of DMI. This was the mean value for the intercept obtained by regressing dietary digestible ash concentration on dietary ash concentration. As pointed out by Lucas and Smart (1959), the intercept of this regression gives an estimate of the fecal ash material not coming from feed. Again, the CNCPS-C erroneously assumed that the intercept predicted the endogenous ash in the feces. Therefore, the CNCPS-S estimates the total fat in the feces as

$$\text{Fecal ash} = \text{F-ASH}_U + \text{F-ASH}_{M+E} = \text{F-ASH}_U + 17 \times \text{DMI} \quad [52]$$

where fecal ash is total ash in the feces, g/d; F-ASH_U is undegraded feed fat in the feces as estimated by the CNCPS-C, g/d; F-ASH_{M+E} is the sum of fecal microbial and endogenous ash, g/d; DMI is dry matter intake, kg/d; and 17.0 is the number of grams of microbial and endogenous ash in the feces, as originally estimated by Lucas and Smart (1959).

Assessing the Model Accuracy

All statistical analyses were performed using Minitab 12.1 (Minitab, Inc., State College, PA). The accuracy of the predictions of the CNCPS-S was assessed by computing the mean bias (i.e., the average deviations between model prediction and actual observations) (Haefner, 1996):

$$\text{Mean bias} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)$$

where n is the number of pairs of values predicted by the model and observed being compared and P_1 and O_1 are the ith predicted and observed values, respectively.

The magnitude of the error was estimated by the mean square prediction error (**MSPE**) (Wallach and Goffinet, 1989) or by its root (**RMSPE**):

$$\text{MSPE} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2$$

The MSPE can be decomposed into three components (Haefner, 1996):

$$\text{MSPE} = (\overline{P} - \overline{O})^2 + s_P^2(1 - b)^2 + (1 - r^2)s_O^2$$

where s_P^2 and s_O^2 are the variances of predicted and observed values, respectively; b is the slope of the regression of O on P; and r^2 is the coefficient of determination of the same equation. The first term on the right side of this equation is the mean bias (i.e., when the regression of observations on predictions has a nonzero intercept). The second term is the regression bias, defined as the systematic error made by the model. When large, it indicates inadequacies in the ability of the model to predict the variables in question. The last term represents the variation in observed values unexplained after the mean and the regression biases have been removed. The results of each of these three components of the MSPE have been presented as a percentage of the total MSPE. The RMSPE was also calculated so that the MSPE could be expressed with the same units of the observed and predicted variables.

If the model were perfect, the linear regression of observations (y) on predictions (x) would have an intercept equal to 0 and a slope equal to 1. Dent and Blackie (1979) proposed testing for these two values simultaneously with an appropriate *F*-statistic. If the model is accurate, *F* will be small and the null hypothesis that slope is 1 and intercept is 0 will not be rejected.

Linear regression of observations (y) on predictions (x) were analyzed for outliers (Neter et al., 1996). Observed and predicted measurements were also compared with a paired *t*-test, as suggested by Mayer and Butler (1993). Another test of model adequacy was based on the proportion of deviant points (CNCPS-S predicted minus observed) that were within acceptable

Table 2. Energy and protein requirements of dry and lactating ewes for maintenance and lactation estimated by four published systems and by the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S)[a]

Item	AFRC (1995) System	CNCPS-S System	CSIRO (1990) System	INRA (1989) System	NRC (1985a) System
			ME requirements, Mcal/d[c]		
Milk yield, kg/d[b]					
0	1.69	1.71	1.76	1.87	1.44
1	3.42	3.47	3.67	3.62	na[d]
2	4.97	5.23	5.49	5.22	na
3	6.45	6.98	7.17	6.78	na
			MP requirements, g/d[e]		
Milk yield, kg/d[b]					
0	54	46	44	41	73
1	127	139	133	126	190
2	201	225	216	211	292
3	274	309	296	296	388

[a]Abbreviations are defined in Table 1.
[b]Milk yield with 6.5% fat, 5% true protein, and energy content of 1.03 Mcal of NE/kg produced by adult sheep with full BW of 50 kg and clean wool production of 1.5 kg/yr.
[c]Assuming that the ratio ME/gross energy is equal to 0.4 for dry ewes and 0.46, 0.54, and 0.60 for lactating ewes producing 1, 2, and 3 kg/d of milk, respectively, and that total ME intake is equal to total maintenance + lactation requirements.
[d]No lactation requirements are provided.
[e]It assumes DMI is 1.0 kg/d for dry ewes and 1.83, 2.34, and 2.74 kg/d for lactating ewes producing 1, 2, and 3 kg/d of milk, respectively.

limits (Mitchell, 1997; Mitchell and Sheehy, 1997). Van Soest (1994) stated that in carefully conducted digestion trials with controlled intake, the difference among replications is approximately 2 units of digestibility. For example, Aufrere and Michalet-Doreau (1988) found for 25 different feeds an accuracy of prediction of ±2.5 units of digestibility. When various experiments are compared, the differences are usually much larger (Schneider and Flatt, 1975), especially with animals fed ad libitum, due to other sources of experimental variation. Considering that the evaluation of the CNCPS-S was based on the data from 13 different publications, these limits were set as –5 and +5 units of digestibility.

Model Evaluation

The CNCPS-S was evaluated by comparing its predictions of energy and protein requirements with those of other feeding systems; with a sensitivity analysis of its environmental submodel; by comparing predicted total-tract digestibility of DM, OM, NDF, and CP vs. observed values; and by predicted effect of dietary treatments on FBW variations vs. observed values.

Comparison of the Predictions of Energy and Protein Requirements for Maintenance and Lactation of the CNCPS-S with Those of Other Feeding Systems. Energy requirements for maintenance and lactation as estimated by the CNCPS-S were compared with those predicted by the NRC (1985a), INRA (1989), CSIRO (1990), and AFRC (1995) feeding systems (Table 2). The comparison was conducted by estimating the requirements for dry or lactating 4-yr-old ewes weighing 50 kg (FBW). Net energy requirements were calculated separately for maintenance and lactation with the equations inherent in each feeding system. They were then converted to ME requirements by using, for each feeding system and function, the appropriate equations that estimate the efficiency of conversion of ME to NE. For this purpose, INRA (1989), CSIRO (1990), and AFRC (1995) require the knowledge of the ratio of ME to gross energy of the diet. This assumed ratio was 0.40 for dry ewes and 0.46, 0.54, and 0.60 for lactating ewes producing 1, 2, and 3 kg/d of milk, respectively.

Metabolizable protein requirements for maintenance and lactation predicted by the CNCPS-S and by other feeding systems were also compared (Table 2). To estimate maintenance MP requirements, the CNCPS-S, the NRC (1985a), and the CSIRO (1990) feeding systems require daily DMI. Intake was assumed to be 1.0 kg/d for dry ewes and 1.83, 2.34, and 2.74 kg/d for lactating ewes producing 1, 2, and 3 kg/d of milk, respectively.

Sensitivity Analysis of the CNCPS-S Environmental Submodel. The effect of cold stress on maintenance requirements was simulated considering the effects of wind, rain, temperature, wool depth, and physiological stage on sheep weighing 50 kg (FBW) (Table 3). The simulation was conducted assuming thermoneutral conditions of 15 to 20°C for nonlactating ewes with a MEI sufficient to satisfy maintenance requirements and for lactating ewes weighing 50 kg, producing 1.5 kg/d of milk with 6.5% fat and with MEI sufficient to satisfy maintenance and milk production requirements.

Table 3. Predicted effects of coat depth, wind, rainfall, and current mean daily (24 h) temperature on Cornell Net Carbohydrate and Protein System for Sheep predicted maintenance requirements of adult ewes[a]

		Coat depth, 25 mm				Coat depth, 50 mm			
	Wind, km/h:	Calm		30		Calm		30	
Item	Rainfall, mm/d:	0	30	0	30	0	30	0	30
		% of thermal neutral conditions[b]							
Adult, dry[c]									
Temp. +5°C		115	134	234	247	100	103	183	195
Temp. 0°C		129	149	267	280	100	114	208	220
Temp. –5°C		144	164	300	313	109	124	233	245
Adult, lactating[d]									
Temp. +5°C		100	100	125	133	100	100	107	114
Temp. 0°C		100	100	137	145	100	100	116	123
Temp. –5°C		100	104	149	157	100	100	125	132

[a]Abbreviations are defined in Table 1.
[b]Thermoneutral conditions are 15 to 20°C. Total maintenance requirements are expressed as a percentage of maintenance requirements at thermoneutral conditions.
[c]Based on nonlactating ewes with full BW (FBW) of 50 kg and with ME intake sufficient to satisfy maintenance requirements.
[d]Lactating ewes with 50 kg FBW, producing 1.5 kg/d of milk with 6.5% fat and with ME intake sufficient to satisfy maintenance and milk production requirements.

Evaluation of the Prediction of Feed Digestibility. The coefficients for digestibility for DM, OM, NDF, and CP reported in 13 publications (Hogan and Weston, 1967; Robles et al., 1981; Prigge et al., 1984; Aitchison et al., 1986; Caton et al., 1988; Colucci et al., 1989; Wales et al., 1990; Di Francia et al., 1994; Torrent et al., 1994; Garcés-Yépez et al., 1997; Ranilla et al., 1998; Mulligan et al., 2001; Molina et al., 2001) were compared with the values estimated by the CNCPS-S. The evaluations were carried out using the information reported in the publications on FBW, feed intake, and composition as inputs in the CNCPS-S. The feeds most similar to those cited in the publications were selected from the feed library of the CNCPS-C. Feed composition then was modified according to the chemical composition reported in each publication for each feed. Because most publications did not give complete information on the N fractions of the feeds, those in the CNCPS-C feed library were used for missing values. The same approach was used for the peNDF concentration of feedstuffs and for the degradation rates for each fraction. The submodel of the CNCPS-C that corrects ruminal degradation in N-deficient diets (Tedeschi et al., 2000) was evaluated in 13 diets that had negative ruminal N balance. The remaining 33 treatments were tested without this adjustment.

The treatments with CNCPS-S predicted ruminal pH lower than 6.2 were excluded from the database (two cases). The reason for this was that, in the CNCPS-S, the prediction of dietary digestibility is strongly affected by ruminal pH and there were too few treatments with low ruminal pH to make a proper comparison with observed digestibilities.

Dry matter, OM, and CP digestibility were predicted following either the original CNCPS-C approach or the CNCPS-S approach, in which the CP, fat, and ash in the feces were estimated following Eq. [50], [51], and [52], respectively. Crude protein digestibility was also estimated predicting CP in the feces with Eq. [49]. One extreme outlier in the NDF digestibility data from a diet of very young clover hay was excluded from the results (Aitchison et al., 1986).

Evaluation of the Prediction of Shrunk Weight Gain and Loss in Adult Sheep. The SBW reported in six publications (Manfredini et al., 1987; Wales et al., 1990; Fonseca et al., 1998; Krüger, 1999; Cannas et al., 2000; Molina et al., 2001) were compared with the values estimated by the CNCPS-S. The predicted gain or losses of FBW reflect the model prediction of energy balance. Four publications (Manfredini et al., 1987; Krüger, 1999; Cannas et al., 2000; Molina et al., 2001), for a total of 13 treatments, reported experiments conducted with lactating ewes, whereas in the other two publications (Wales et al., 1990; Fonseca et al., 1998), for a total of 16 treatments, mature ewes and wethers were used. The evaluations were conducted using the information reported in the publications on SBW, feed intake and composition, milk yield and composition as input into the CNCPS-S, following the same procedure previously described for the validation of feed digestibility. The submodel of the CNCPS-C that reduces fiber digestion in N-deficient diets (Tedeschi et al., 2000) was not used in the diets for which the CNCPS-S predicted a positive ruminal N balance (15 treatments). However, this submodel was separately tested for the 14 diets for which the CNCPS-S predicted a negative ruminal N balance.

Variations in SBW were predicted by first calculating the energy balance (Eq. [15]) and then by computing FBW gain or losses with Eq. [33]. Predicted SBW variations were compared to the observed values reported in the publications.

Results and Discussion

Comparison of the Predictions of Energy and Protein Requirements for Maintenance and Lactation of the CNCPS-S with those of Other Feeding Systems

Compared to other feeding systems, the ME maintenance requirement estimates of the CNCPS-S are similar to those of CSIRO (1990) and AFRC (1995), but are lower than those of INRA (1989) (Table 2). The ME requirements of lactating ewes are higher than those of AFRC (1995) but are lower than those of CSIRO (1990) and are similar to those of INRA (1989). The differences in observed ME requirements are mostly due to differences among systems in the efficiency of conversion of ME to NE. These efficiencies differ more for maintenance requirements than for lactation. The CNCPS-S uses fixed k_m and k_l, whereas most feeding systems (ARC, 1980; CSIRO, 1990; INRA, 1989; AFRC, 1995; NRC, 2001) have efficiencies for converting ME to NE for maintenance and lactation that vary depending on the quality of the diet. These systems do not consider, with the exception of NRC (2001), the effect of depression in digestibility that occurs when feeding level increases. Therefore, the differences among low- and high-quality diets in the efficiency of conversion of ME to NE for maintenance and lactation might be due, at least in part, to this effect. We used our database to compare the prediction of energy balance with the approach taken in the CNCPS-S (ME = $0.82 \times$ DE, $NE_m = 0.644$, and $NE_l = 0.644$) and with four alternatives, as follows; in all four of these alternatives, NE_m and NE_l are predicted NRC (2001) variable equations. The four alternatives were a) ME = 0.82 DE with NE_m and NE_l predicted with the as in NRC (2001), b) ME = $1.01 \times$ DE − 0.45 with NE_m and NE_l as in NRC (2001), c) ME = $(1.01 \times \text{DE} - 0.45) + 0.0046 \times (\text{EE} - 3)$ (Eq. 2–10, NRC 2001) and NE_m and NE_l as in NRC (2001), and d) ME = $1.01 \times$ DE − 0.45 for lactating dairy sheep and ME = $0.82 \times$ DE for meat and wool dry ewes with NE_m and NE_l as in NRC (2001).

Compared with the four methods given in the preceding paragraph, the method used by the CNCPS-S gave the highest r^2 (respectively, 0.73 vs. 0.70, 0.62, 0.62, and 0.62) and the lowest RMSPE (respectively, 30.0 vs. 33.3, 39.0, 39.0, and 39.5). The utilization of variable NE_l and NE_m increased the variability and the percentage of MSPE due to regression bias. We conclude that the fixed efficiencies for k_m and k_l, used in the CNCPS-S, improved predictions because they are consistent with the adjustment made for level of intake in predicting feed digestibility.

Compared with other feeding systems, the estimates of the CNCPS-S for MP required for maintenance are higher than those of CSIRO (1990) and INRA (1989) but are lower than those of the NRC (1985a) and AFRC (1985) systems. The MP requirements in lactating ewes are much lower than those of NRC (1985a) but are slightly higher than those of the other feeding systems (Table 2).

Sensitivity Analysis of the CNCPS-S Environmental Submodel

Table 3 shows the results of a sensitivity analysis of the CNCPS-S adjustments for environmental and physiological stage effects. The results of this simulation indicated that lactating ewes are less affected by cold stress than are dry ewes. This is because the high energy intake necessary to sustain milk production increases heat production during fermentation and metabolism. Wool depth is also very important in reducing the effects of cold stress (Table 3) because of its insulation properties. However, wind or rain can markedly reduce the protection afforded by wool. In the simulation, the combined effects of all these factors increased the maintenance requirements up to three times. These effects are much higher than those found in a similar evaluation with dairy cows with the CNCPS-C (Cannas, 2000). Because small animals have more body surface per kilogram of BW than large animals, they disperse more heat (Blaxter, 1977; CSIRO, 1990). Even though the wool of sheep is a much better insulator than the hair of cattle (Blaxter, 1977; CSIRO, 1990), its additional insulation does not offset the effects of their smaller body size on heat loss.

Dairy sheep breeds tend to have less subcutaneous fat and coarser and thinner wool than meat and wool sheep breeds. Both factors may reduce thermal insulation of dairy sheep compared to meat or wool breeds. Considering that the CSIRO (1990) model for cold stress was developed and tested for meat and wool breeds, its utilization with dairy breeds may require modifications of the estimates related to tissue and external insulation.

Evaluation of Total-Tract Digestibility Predictions

The database used for this evaluation of the CNCPS-S predictions included diets based on grass hay or straw only, grass hay plus concentrates or by-products, legume hay, legume hay plus concentrates, corn silage, alfalfa meal and concentrates, and by-products only, for a total of 46 dietary treatments. The database included a wide range of BW, diet composition, and digestibility (Table 4). All the included publications reported NDF digestibility, but several did not report DM, OM, or CP digestibilities. The DMI and the level of feeding were lower than are typical of sheep with high requirements, such as lactating ewes. This is likely because all the digestibility trials based on total fecal collection we found in the literature were carried out on growing sheep or on mature males or wethers. The diets for which the CNCPS-S predicted negative ruminal N balance were clearly of lower quality than those for which positive ruminal N balance was predicted (Table 4).

Table 4. Description of the database used to evaluate diet DM, OM, CP, and NDF total-tract digestibility predicted by the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S)[a]

Item	SBW, kg	DMI, % of SBW	Forage, % of diet DM	FL[b]	Predicted ruminal N balance, %[c]	CP, % of diet DM	NDF, % of diet DM	DM digestibility, %[d]	OM digestibility, %[d]	CP digestibility, %[d]	NDF digestibility, %
Diets with a positive ruminal N balance											
n	33	33	33	33	33	33	33	25	19	23	33
Mean	51.5	2.18	84	1.4	26.9	14.5	56.9	61.8	60.2	69.6	54.6
SD	10.3	0.63	21	0.5	29.1	3.9	16.5	10.8	8.4	8.6	9.2
Min	37.0	1.29	30	0.6	1.4	7.2	24.7	32.7	34.9	52.4	31.9
Max	77.6	3.92	100	2.4	126.0	25.0	80.1	82.3	79.6	83.5	83.9
Diets with a negative ruminal N balance[e]											
n	13	13	13	13	13	13	13	8	12	7	13
Mean	44.8	1.85	97	1.1	–32.5	7.0	68.7	51.2	56.6	42.7	54.3
SD	6.5	0.91	5	0.5	24.9	4.1	11.1	16.3	12.8	20.1	14.0
Min	37.0	0.68	86	0.4	–72.3	2.1	54.5	35.7	39.7	0.8	39.2
Max	54.5	3.67	100	2.1	–2.4	15.0	88.4	80.5	81.3	59.1	88.0

[a]Abbreviations are defined in Table 1.
[b]FL = level of feeding, as estimated by the CNCPS-S (i.e., total ME intake/ME required for maintenance).
[c]Excess or deficiency of N required for ruminal fermentation, estimated by the CNCPS-S.
[d]Only part of the publications reported DM, OM, and CP digestibility.
[e]The equations of Tedeschi et al. (2000) that reduce ruminal fiber digestibility in N-deficient diets were not used in the estimation of FL, ME intake, and ruminal N balance by the CNCPS-S.

Diets with a Positive Ruminal N Balance. The CNCPS-S accurately predicted DM apparent digestibility, with a mean difference between predicted and observed digestibility of 0.3 units, which did not differ from zero ($P > 0.1$), with a RMSPE of 4.0 units (Table 5). The regression bias accounted for 6.0% of MSPE (Table 5). The slope of the regression of observed on predicted DM digestibility (Table 5) was not different from the equivalence line ($P > 0.1$). The proportion of points lying within –5 and +5 units of digestibility was 72.0%. When DM digestibility was estimated by using the original CNCPS-C method, prediction accuracy was reduced. The mean difference between predicted and observed digestibility was equal to –2.9 units of digestibility ($P < 0.01$), and the RMSPE was increased (4.8 units), with 34.6% of the MSPE due to the mean bias (Table 5). The regression of observed on predicted DM digestibility was different from the equivalence line ($P < 0.01$) (Table 5).

The CNCPS-S accurately predicted OM apparent digestibility, which is used by this model to predict ME values, with a mean difference between predicted and observed digestibility that did not differ from zero (1.1 units, $P > 0.1$), with a RMSPE of 3.6 units (Table 5). The regression of observed on predicted OM digestibility was not different from the equivalence line ($P > 0.1$) (Table 5). The proportion of deviation points lying within –5 and +5 units of digestibility was 84.2%. When OM digestibility was estimated by using the original CNCPS-C method, prediction accuracy was reduced. The mean difference between predicted and observed digestibility was –2.0 units ($P < 0.05$), and the RMSPE was increased 4.0 units (Table 5), with 23.1% of the MSPE due to the mean bias (Table 5). The regression of observed on predicted DM digestibility was different from the equivalence line ($P < 0.05$) (Table 5). The proportion of points lying within –5 and +5 units of digestibility was unchanged.

The CNCPS-S underestimated NDF digestibility (Table 5), with a mean difference between predicted and observed values of –4.3 units of digestibility. This difference was significant ($P < 0.01$). The underprediction was evenly distributed across the range of observed digestibilities, with a small regression bias (less than 2% of the MSPE). The RMSPE was much larger than for DM and OM digestibility (6.9 units of digestibility). The majority of the MSPE (59.9%) was associated with unexplained variation. The slope of the regression of observed on predicted NDF digestibility differed from the equivalence line ($P < 0.01$; Table 5). The proportion of deviation points lying within –5 and +5 units of digestibility was 45.0%.

Apparent digestibility of dietary CP was accurately predicted by the CNCPS-S. The mean difference between predicted and observed values was not different from zero (–1.9 units of digestibility; $P > 0.1$), with 88.2% of the MSPE due to unexplained variation (Table 5). The regression of observed on predicted CP digestibility was not different from the equivalence line ($P > 0.1$) (Table 5). However, the proportion of deviation points lying within –5 and +5 units of digestibility was low (48%) and the RMSPE was high (7.2 units). The six greatest differences between predicted and observed values were on diets containing legumes. The average difference between predicted and observed values was 0.8 units of digestibility for grass-based diets and –9.4 units for legume-based diets (data not shown in Table 5). This botanical species difference was significant (*P*

Table 5. Evaluation of the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S) predictions of DM, OM, NDF, and CP total-tract digestibility when ruminal N balance was positive[a]

Item	Observed, g/100 g	Predicted minus observed, g/100 g	n	Components of the MSPE %[b] Mean bias	Regression bias	Unexplained variation	RMSPE g/100 g[c]	r^2 [d]	P[e]
DM									
CNCPS-S[f]	61.8	0.3[NS]	25	0.5	6.0	93.5	4.0	0.87	NS
CNCPS-C[g]	61.8	−2.9**	25	34.6	2.2	63.2	4.8	0.87	<0.01
OM									
CNCPS-S[f]	60.2	1.1[NS]	19	8.8	4.4	86.8	3.6	0.83	NS
CNCPS-C[g]	60.2	−2.0*	19	23.1	9.2	67.7	4.0	0.84	<0.05
NDF	54.6	−4.3**	32	38.3	1.8	59.9	6.9	0.51	<0.01
CP									
CNCPS-S[f]	69.6	−1.9[NS]	23	6.8	5.0	88.2	7.2	0.34	NS
Eq. [49][h]	69.6	−7.1**	23	47.2	23.0	29.8	10.2	0.56	<0.001
CNCPS-C[g]	69.6	−24.5**	23	90.9	5.2	3.9	25.6	0.65	<0.001

[a]Experiments in which the CNCPS-S predicted ruminal N balance was positive and ruminal pH was above 6.2.
[b]MSPE = mean squared error of prediction.
[c]RMSPE = root of the mean squared error of prediction.
[d]Coefficient of determination of the best-fit regression line not forced through the origin.
[e]Probability associated with F-test to reject the simultaneous hypothesis that the slope = 1 and the intercept = 0; when NS ($P > 0.1$), the hypothesis is not rejected.
[f]In the CNCPS-S, the digestibilities of CP, fat, and ash are predicted with the same method used by the CNCPS for cattle but with the corrections described by the Eq. [50], [51], and [52].
[g]The original procedure of the CNCPS for cattle was used.
[h]In Eq. [49], the CP content of the feces is estimated as the sum of undegraded feed CP and metabolic CP (estimated as 90 g/kg of indigestible DM intake, which contains microbial and endogenous CP).
*, **, NS are significance of differences between predicted and observed values ($P < 0.05$, $P < 0.01$, or $P > 0.10$, respectively) when subjected to a paired t-test.

< 0.001). When CP digestibility was estimated by predicting fecal CP with Eq. [49], prediction accuracy was markedly reduced; predicted values differed from those observed by −7.1 units of digestibility ($P < 0.01$) and the RMSPE reached 10.2 units of digestibility. Apparent digestibility of dietary CP was grossly underestimated when the original CNCPS-C procedure to estimate total CP in the feces (Eq. [48]) was used (mean bias = −24.5 units of digestibility; RMSPE 25.6 units of digestibility) (Table 5). The underprediction increased as observed CP digestibility decreased and none of the deviation points were within the range of ±5 units of digestibility.

Diets with a Negative Ruminal N Balance. The CNCPS-S overpredicted DM, OM, and NDF digestibility when the equations of Tedeschi et al. (2000) that reduce fiber digestion in N deficient diets were not used (Table 6). When these equations were applied, the CNCPS-S underpredicted DM, OM, and NDF digestibility. Both the differences between predicted and observed values and the RMSPE were smaller when the equations of Tedeschi et al. (2000) were used in the case of DM and OM digestibility, whereas in the case of NDF digestibility only the RMSPE was improved (Table 6). The CNCPS-S accurately predicted total-tract CP apparent digestibility (2.7 units of digestibility, $P > 0.1$, with a RMSPE of 12.8 units; Table 6). There was no effect of the equations of Tedeschi et al. (2000) on CP apparent digestibility because it does not affect protein degradation rates.

Dietary CP digestibility was grossly underestimated by the CNCPS-S when the original CNCPS-C method (Eq. [48]) was used to estimate total CP in the feces ($P < 0.01$). The underprediction increased as observed CP digestibility decreased. The prediction was improved when Eq. [49] was used (Table 5). This approach assumes that fecal CP is the sum of undegraded feed protein and metabolic matter. The latter is equal to 90 g/kg of indigestible DM intake. The prediction accuracy was further improved when the approach of Eq. [50] was used (Table 5). This approach differs from Eq. [48] and [49] because it estimates metabolic (microbial + endogenous) fecal CP as a proportion of DMI (30 g of metabolic CP per kilogram of DMI).

These results suggest that the very high underprediction of CP digestibility obtained with the approach assumed in Eq. [48] (CNCPS-C method) was due to the double accounting of fecal endogenous CP. This mistake originated in the NRC (1989), which was used by the CNCPS. This error has been recognized by the NRC (2001) feeding system for dairy cattle. The estimation of fecal metabolic matter as a proportion of DMI (Eq. [50]) rather than as a proportion of indigestible DM intake, which assumes a constant dietary indigestibility of 33%, (Eq. [49]) further improved the prediction of CP apparent digestibility (Table 5). The unrealistic assumption of constant dietary indigestibility has been recognized by NRC (2001).

Table 6. Evaluation of the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S) predictions of DM, OM, NDF, and CP total-tract digestibility when ruminal N balance was negative[a]

			No ruminal N adjustment[b]		With ruminal N adjustment[c]	
Item	Observed, g/100 g	n	Predicted minus observed, g/100 g	RMSPE g/100 g[c]	Predicted minus observed, g/100 g	RMSPE, g/100 g[d]
DM						
CNCPS-S[e]	51.2	8	9.0[NS]	13.8	–5.7**	6.6
CNCPS-C[f]	51.2	8	5.2[NS]	11.6	–9.7**	10.2
OM						
CNCPS-S[e]	56.6	12	8.0**	11.1	–3.3[NS]	6.5
CNCPS-C[f]	56.6	12	4.2[NS]	8.6	–7.3**	9.1
NDF	54.3	13	5.1[NS]	13.2	–9.1**	12.0
CP						
CNCPS-S[e]	42.7	7	2.7[NS]	12.8	2.7[NS]	12.8
CNCPS-C[g]	42.7	7	–7.8[NS]	18.2	–17.4[NS]	28.2
Eq. [48][f]	42.7	7	–47.6**	54.4	–46.3**	53.1

[a]Experiments in which the CNCPS-S predicted ruminal N balance was negative and ruminal pH was above 6.2.

[b,c]The equations of Tedeschi et al. (2000) that decrease fiber digestibility in ruminal N-deficient diets were not used ([b]) or were used ([c]).

[d]RMSPE = root of the mean squared error of prediction.

[e]In the CNCPS-S, the CP content of the feces is estimated as the sum of undegraded feed protein and metabolic (microbial + endogenous) CP (estimated as 30 g/kg of DM intake).

[f]In the CNCPS-S, the digestibilities of CP, fat, and ash are predicted with the same method used by the CNCPS for cattle (CNCPS-C) but with the corrections described by the Eq. [50], [51], and [52].

[g]The original procedure of the CNCPS-C was used.

*, **, NS are significance of differences between predicted and observed values ($P < 0.05$, $P < 0.01$, or $P > 0.10$, respectively) when subjected to a paired *t*-test.

When the two corrections were applied, the CNCPS-S accurately predicted total-tract CP digestibility but the RMSPE for CP digestibility was large, primarily due to unexplained variation. Only one of the data sets included in this analysis had data on the CP fractions required by the CNCPS (Wales et al., 1990), which may explain the large error term.

Although the CNCPS-S accurately predicted DM, OM, and CP digestibility, it underpredicted NDF digestibility (Table 5) possibly due to overprediction of passage rates, underprediction of NDF degradation rates, or both. Recently, Van Soest et al. (2001) suggested that the CNCPS digestion rates for the available NDF may be underestimated in the case of high-quality fiber sources. This would explain the underprediction by the CNCPS-S for diets with high NDF digestibilities. In the CNCPS models, total-tract NDF digestibility depends on several factors, including the prediction of the fraction of NDF that is unavailable (carbohydrate C fraction). This fraction depends on the ratio between lignin and NDF, which is then multiplied by 2.4 to estimate the fiber unavailable for digestion, as proposed by Chandler (1980) and verified by Traxler et al. (1998). In this model evaluation, most of the data sources did not specify whether the acid detergent lignin (**ADL**) included the acid-insoluble ash or not. In several cases, it appeared that acid-insoluble ash was included in the ADL value, in contrast with the method of Van Soest et al. (1991), which is recommended for use with the CNCPS model. Consequently, the carbohydrate C fraction was likely overpredicted and NDF digestibility was underpredicted. The prediction of total-tract NDF digestibility appeared to be markedly affected by small changes in ADL concentration. For the estimation of NDF digestibility, there was one extreme outlier (predicted – observed digestibility = –42.7 units). It corresponded to a diet comprised solely of a very early cut clover (Aitchison et al., 1986), for which the indigestible fraction (protein C fraction) predicted by the model was much higher than the amount of undigested NDF experimentally observed. This result highlights the importance of using standardized chemical methods to measure feed characteristics in order to accurately predict the carbohydrate C fraction and NDF digestibility.

In 13 cases, the CNCPS-S predicted an N deficiency in the rumen (Table 4). When the submodel of Tedeschi et al. (2000) was not used with N-deficient diets, the CNCPS-S tended to overpredict digestibility of DM, OM, CP, and NDF (Table 6); however, it was accurate for diets with a positive ruminal N balance model (Table 5). This evaluation demonstrates that the CNCPS-S is very sensitive to ruminal N balance and the importance of accounting for possible ruminal N deficiencies. When the equations of Tedeschi et al. (2000) were used in diets that produced a negative ruminal N balance, it reduced the difference between predicted and observed

Table 7. Description of the database used to evaluate the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S) prediction of shrunk BW gains and losses[a]

Item	SBW, kg	SBW change, g/d	DMI, kg/d	DMI, % of SBW	CP, % of DM	NDF, % of DM	FL[b]	Forage, % of DM	ME Intake, Mcal/d[c]	Ruminal N balance, %[c]	Milk yield, kg/d
Diets with positive ruminal N balance											
n	15	15	15	15	15	15	15	15	15	15	5
Mean	69.6	22	1.59	2.30	14.8	54.7	1.38	77	3.500	20.9	1.03
SD	8.7	58	0.64	1.16	3.3	13.1	0.58	10	1.632	13.5	0.63
Min	50.2	–66	0.90	1.16	11.1	30.8	0.71	50	1.704	3.8	0.57
Max	74.5	144	2.90	4.04	21.0	70.4	2.55	100	7.145	54.2	2.04
Diets with negative ruminal N balance[d]											
n	14	14	14	14	14	14	14	14	14	14	8
Mean	49.7	–57	1.21	2.51	9.5	60.4	1.59	88	3.037	–26.5	1.01
SD	11.0	122	0.53	1.31	4.0	16.7	0.80	12	1.530	25.9	0.30
Min	37.3	–350	0.32	0.66	2.1	41.2	0.39	70	0.623	–72.3	0.55
Max	74.0	74	1.80	4.34	15.5	88.4	2.48	100	4.931	–0.8	1.33

[a]Abbreviations are defined in Table 1.
[b]FL = level of feeding, as estimated by the CNCPS-S (i.e., total ME intake/ME required for maintenance).
[c]Estimated with the CNCPS-S.
[d]The equations of Tedeschi et al. (2000) that reduce fiber digestibility when ruminal N is deficient were not used in the estimation of FL, ME intake, and ruminal N balance.

values and markedly reduced the RMSPE for DM and OM digestibility. However, this submodel overcorrected DM, OM, and NDF digestibilities, causing them to be underpredicted. One possible explanation is that the CNCPS-S might have underestimated N recycling in these types of diets for sheep. The CNCPS-C equation to predict recycled N was used for the CNCPS-S. This equation, originally proposed for cattle (NRC, 1985b), bases the prediction of recycled N on the CP concentration in the diet. However, when compared at similar physiological stages and with the same diet, sheep have higher levels of DM and protein intake than cattle. This is confirmed by the fact that milk or blood urea concentration in sheep tends to be higher than in cattle at similar dietary CP concentrations (Cannas et al., 1998; Cannas, 2002). This fact cannot be accounted for by the equation proposed by NRC (1985b) to estimate N recycling. For this reason, a new equation for recycled N needs to be developed for the CNCPS-S.

The accuracy in the prediction of OM digestibility is particularly important for the CNCPS because it is used to predict TDN and ME values of feeds. Aufrere and Michalet-Doreau (1988) measured the OM digestibility of 24 feeds with in vivo digestibility trials, with wethers fed at near-maintenance level. They compared the in vivo results with OM digestibility predicted from the chemical composition of feeds, by the in vitro Tilley Terry method, and by enzymatic degradability. In vivo digestibility was predicted by the chemical composition with a residual standard deviation (**RSD**; squared root of the mean squared error) of 6.9 units of digestibility, by the in vitro Tilley and Terry method with a RSD of 5.4 units of digestibility and mean bias of –4.2 units, and by the enzymatic degradability with a RSD of 6.5 units. These results compare to a mean bias of 1.1 and RSD of 3.7 units of digestibility (not shown in the tables), corresponding to a RMSPE of 3.6 units of digestibility (Table 5), when the CNCPS-S was used to predict OM digestibility with our data set. Moreover, the predictions of Aufrere and Michalet-Doreau (1988) were based on in vivo measurements obtained by using homogeneous experimental methods on animals fed at maintenance, whereas the observed values used in our data set were derived from animals fed at various feeding levels by different research groups (Table 4).

We conclude that, at least within the range of level of intake and level of feeding in our database (Table 4), the CNCPS-S predicted OM digestibility with a greater accuracy than published for the best in vitro methods.

Evaluation of the Prediction of SBW Gain or Loss

The database used to evaluate the CNCPS-S prediction of SBW gain or loss included diets based on grass hay or straw only, grass hay plus concentrates, legume hay, legume hay plus concentrates, corn silage, alfalfa meal and concentrates, and by-products only, for a total of 29 dietary treatments. The database included a wide range of SBW, DMI, diet composition, and production (Table 7). The DMI and the level of feeding were higher than in the case of the digestibility validation (Table 4) because several treatments included lactating ewes. The diets for which the CNCPS-S predicted a negative ruminal N balance were clearly of lower quality than those for which a positive ruminal N balance was predicted (Table 7).

Diets with a Positive Ruminal N Balance. The CNCPS-S accounted for 73% of the gains and losses in SBW in diets with a positive ruminal N balance (15 treatments) (Table 8 and Figure 4). The predicted-minus-observed

Table 8. Evaluation of the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S) predicted shrunk BW gains and losses

Item	Observed, g/d	Predicted minus observed, g/d	n	Components of MSPE, %[a] Mean bias	Regression bias	Unexplained variation	RMSPE, g/d[b]	r^2 [c]	*P*[d]
Ruminal N balance positive									
CNCPS-S[e]	21.8	5.8[NS]	15	3.6	1.2	95.3	30.0	0.73	NS
CNCPS-C[f]	21.8	–7.7[NS]	15	6.4	0.1	93.5	29.4	0.74	NS
Ruminal N balance negative									
Adjusted for ruminal N deficiency									
CNCPS-S[e]	–56.9	53.4*	14	38.5	27.1	34.4	84.1	0.84	<0.01
CNCPS-C[f]	–56.9	42.9*	14	27.8	33.4	38.8	79.4	0.84	<0.01
Not adjusted for ruminal N deficiency									
CNCPS-S[e]	–56.9	70.6**	14	46.5	19.8	33.7	101.7	0.77	<0.01
CNCPS-C[f]	–56.9	60.2*	14	36.7	24.3	39.0	97.5	0.76	<0.01

[a]MSPE = mean squared error of prediction.
[b]RMSPE = root of the mean squared error of prediction.
[c]The coefficient of determination of the best-fit regression line not forced through the origin.
**, NS are the significance of the differences between predicted and observed values when subjected to a paired *t*-test ($P < 0.01$ and $P > 0.05$, respectively).
[d]Probability associated to a *F*-test to reject the simultaneous hypothesis that the slope = 1 and the intercept = 0; when NS ($P > 0.10$), the hypothesis is not rejected.
[e]In the CNCPS-S, the digestibilities of CP, fat, and ash are predicted with the same method used by the CNCPS for cattle (CNCPS-C) but with the corrections described by the Eq. [50], [51], and [52].
[f]The original procedure of the CNCPS-C was used.

variations in SBW did not differ from zero (5.8 g/d; $P > 0.1$); there was no systematic bias over the range of gains and losses in SBW. The RMSPE was 30.0 g/d and the regression bias was small (1.2% of MSPE). The regression of observed on predicted SBW gain or loss was not different ($P > 0.1$) from the equivalence line (y = x) (Table 8 and Figure 4). When the prediction of SBW gain or loss by the CNCPS-S was based on estimating OM digestibility (used by the CNCPS systems to predict dietary ME) with the original CNCPS-C method, prediction accuracy was not improved. The RMSPE was slightly smaller (29.4 g/d) but the predicted-minus-observed difference was larger than before (–7.7 g/d; $P > 0.1$). There was a very small regression bias (0.1% of MSPE), and most of the MSPE (93.5%) was associated with unexplained variation.

Diets with Negative Ruminal N Balance. When the submodel that corrects ruminal degradation in N-deficient diets (Tedeschi et al., 2000) was used, SBW gains or losses were markedly overpredicted, with a mean difference between predicted and observed digestibility of 53.4 g/d ($P < 0.01$) and a RMSPE of 84.1 g/d (Table 8 and Figure 4). The overprediction was lower, but still very large and significant, when the prediction of SBW gain or loss of the CNCPS-S was based on estimating OM digestibility with the original CNCPS-C method instead of the new method (corrections described in Eq. [50], [51], and [52]). When the equations of Tedeschi et al. (2000) that reduce fiber digestion in N-deficient diets were not used, the overprediction further increased, regardless of method used to estimate fecal CP.

When the diets had a positive ruminal N balance, the CNCPS-S accurately predicted SBW gains and losses. The average predicted-minus-observed difference was

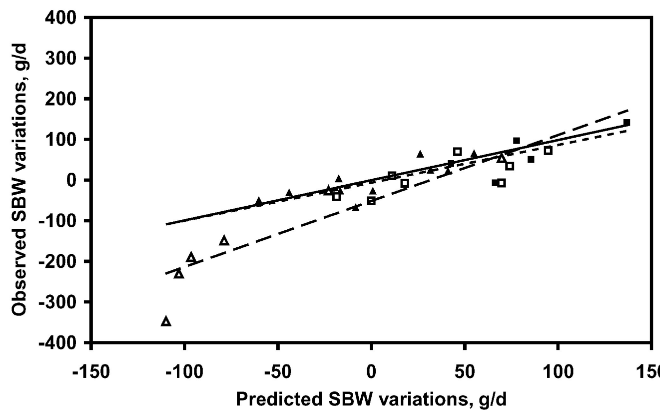

Figure 4. Relationship between the shrunk body weight (SBW) predicted by the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S) and observed SBW gains and losses. Symbols are (■) lactating ewes, ruminal N balance positive; (▲) dry ewes, ruminal N balance positive; (□) lactating ewes, ruminal N balance negative; (Δ) dry ewes, ruminal N balance negative. When the ruminal N balance was negative, predictions were adjusted with the model of Tedeschi et al. (2000). The solid line indicates unitary equivalence (Y = X). The regression equation of observed on predicted SBW for the treatments in which the CNCPS-S predicted positive ruminal N balance was y = 0.94(0.16)x – 4.10(9.20), r^2 = 0.73, SE = 31.4; (dotted line). This line was not different from the Y = X line ($P < 0.01$). The regression equation of observed on predicted SBW for the treatments in which the CNCPS-S predicted negative ruminal N balance was y = 1.63(0.20)x – 51.20(14.04), r^2 = 0.84, SE = 52.5; (dashed line). This line was different from the Y = X line ($P < 0.01$).

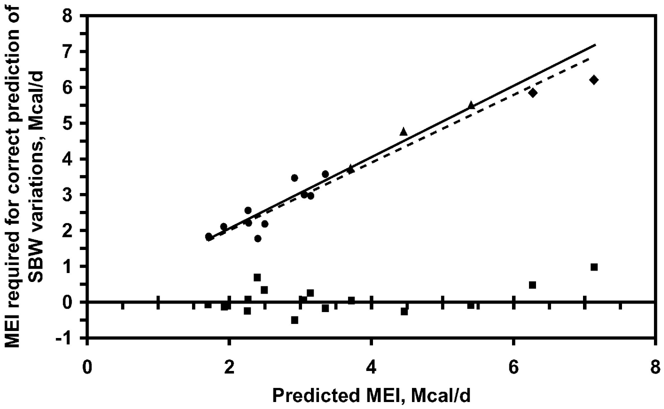

Figure 5. Relationship between the ME intake predicted by the Cornell Net Carbohydrate and Protein System for Sheep (CNCPS-S) and the ME required for the observed SBW gains and losses when ruminal N balance was positive. Symbols are (●) grass-based diets fed to dry ewes; (▲) legume-based diets fed to lactating ewes; (◆) mixed grass-legume-based diets fed to lactating ewes. The solid line indicates unitary equivalence (Y = X). The regression equation of required on predicted ME intake was y = 0.89(0.06)x + 0.31(0.23), r^2 = 0.95, SE = 0.36; because the intercept was not significant, the equation became y = 0.96(0.02)x (dotted line). This line was not different from the Y = X line (P > 0.1). Deviations shown (■) are between the CNCPS-S predicted ME intake and the ME required for no mean bias. The mean bias was 0.076 Mcal of ME/d (2.2% of the mean required value), and it did not differ from zero (P > 0.1). The root of the mean squared prediction error was 0.384 Mcal of ME/d. The mean predicted MEI was 3.500 Mcal of ME/d (SD: ±1.632 Mcal/d), and the mean ME required was 3.424 Mcal of ME/d (SD: ±1.492 Mcal/d).

not significant and the RMSPE was small and due primarily to unexplained variation. The average MEI predicted by the CNCPS-S was equal to 3.500 Mcal of ME per day (SD: ±1.632 Mcal/d) (Figure 5). The predicted-minus-observed difference for SBW gain or loss would have been equal to 0 if MEI would have averaged 3.424 Mcal of ME/d (SD: ±1.492 Mcal/d) (Figure 5). Thus, the CNCPS-S overpredicted MEI by an average of 2.2%. This accuracy of prediction is high, considering the wide range in animal and dietary characteristics included in the database and the incomplete information on protein and carbohydrate fractions in the diets.

In contrast, in the database for which the CNCPS-S predicted a negative ruminal N balance, there was a large overprediction of SBW gain or loss even when the equations of Tedeschi et al. (2000) that reduce fiber digestibility in N-deficient diets were used (Figure 4). This model improved the accuracy of prediction (Table 8), but not as much as reported by Tedeschi et al. (2000) for growing cattle. However, in their database, the mean ruminal N balance was much less negative than in our database (−12.9% vs. −26.5% of the N required to attain zero ruminal balance). In our database, the predicted-minus-observed difference was inversely correlated to the ruminal N balance (r = 0.82, P < 0.001; not reported in tables) and the four largest prediction errors of SBW gain or loss were with diets that contained the largest ruminal N deficiency (in all cases, more than 50% deficient). When these data were excluded, the prediction of SBW gain or loss for diets with negative rumen N balance was markedly improved (P − O = 21.9 g/d, P < 0.05; RMSPE = 34.6 g/d). Deficiencies of MP and large amino acid imbalances were predicted by the CNCPS-S when the N-deficient diets were used. This might explain the overprediction of SBW gain or loss in N-deficient diets by the CNCPS-S. Amino acid imbalances can markedly reduce the efficiency of MP utilization and reduce SBW variation more than would have been expected solely on the basis of ME and MP availability.

Overall, the CNCPS-S accurately predicted variations in SBW gain or loss and energy balance in the diets that did not have a ruminal N deficiency. However, the lack of experiments in which all input variables required by the CNCPS are reported limited the scope of this evaluation.

Implications

The evaluations presented indicate that the Cornell Net Carbohydrate and Protein System for Sheep can be used to accurately predict nutrient requirements, feed biological values, and body weight gains and losses when the ruminal nitrogen balance is positive. Evaluations included published experiments with sheep of diverse body sizes and physiological stages fed diverse diets at various levels of nutrition. This suggests that the Cornell Net Carbohydrate and Protein System for Sheep can be used to evaluate diets and animal performance in a variety of production settings ranging from extensive grazing situations to highly productive sheep dairies, and to predict with good accuracy nitrogen excretion by sheep, making it a valuable tool in nutrient management. Further research is needed to improve its ability to predict animal performance when a ruminal nitrogen deficiency occurs. Further evaluation is needed with experimental data that contain all inputs required by the model.

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