Development and evaluation of a new feeding system for sheep. 1. Energy and protein nutrient requirements and feed utilisation

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Paper received May 20, 2004; accepted July 16, 2004

ABSTRACT

A new feeding system for sheep, called MIPAF, was developed by integrating previously published equations with new ones to predict energy and protein requirements as well as feed utilization of sheep. Special emphasis was given to dairy sheep, whose specific needs are not considered by most sheep feeding systems, and to some of the environmental factors that affect requirements. Original equations were added to predict fluxes in body energy reserves from body weight (BW) and body condition score. The prediction of supply of nutrients was based on the discount system of Van Soest. Thus, the MIPAF system predicts feed value as a function of the specific feeding level of the sheep that receive the ration.

The ability of the MIPAF model to predict BW variations was evaluated using data from six studies with adult sheep (13 treatments with lactating ewes and 15 with dry ewes or wethers). The model predicted the variations of BW in sheep with no bias, but with high rooted mean squared prediction error (RMSPE) (mean bias = -0.1 g/d; $P > 0.1$; RMSPE = 44.9 g/d; n = 28). Three extreme outliers were discarded because the treatment diets, made only of wheat straw and supplied to mature wethers, had very low CP concentrations (less than 3.25%, DM basis).

After the outliers were removed, the prediction error improved but the mean bias became significantly different from zero (mean bias = -12.3 g/d; $P < 0.05$; RMSPE = 29.6 g/d; n = 25). Prediction accuracy was different between lactating and non lactating sheep. Variations of BW in lactating ewes were predicted with high accuracy (mean bias = 6.8 g/d; $P > 0.1$; RMSPE = 18.7 g/d; n = 13), while for dry ewes the model was less accurate, under predicting the variations in BW (mean bias = -33.0 g/d, $P < 0.001$; RMSPE = 38.1 g/d; n = 12).

The 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 MIPAF model can be used to evaluate diets and animal performance in a variety of production settings with good accuracy.

Key words: Sheep, Models, Energy, Protein, Requirements.

RIASSUNTO

SVILUPPO E VALIDAZIONE DI UN MODELLO DI STIMA DEI FABBISOGNI NUTRITIVI E DELLA UTILIZZAZIONE DEGLI ALIMENTI NEGLI OVINI

Un nuovo sistema di alimentazione per ovini, chiamato MIPAF, è stato sviluppato, integrando nuove equazioni con equazioni già pubblicate nella letteratura scientifica, al fine di stimare i fabbisogni energetici e proteici e il valore nutritivo degli alimenti. Particolare enfasi è stata data alle pecore da latte, non considerate da molti dei sistemi di alimentazione esistenti, ed agli effetti delle condizioni ambientali sui fabbisogni energetici. Il modello MIPAF comprende equazioni originali appositamente sviluppate per migliorare la stima del flusso di riserve corporee e la relazione tra peso corporeo e stato

di ingrassamento. La stima del valore energetico e proteico è stata basata sul sistema dei discount di Van Soest, che tiene conto del livello nutritivo col quale sono alimentati gli animali per determinare l'apporto di energia e proteine derivante dalla razione alimentare.
La capacità del modello MIPAF di stimare le variazioni di peso e di riserve corporee in ovini è stata valutata utilizzando dati derivanti da sei pubblicazioni scientifiche nelle quali erano riportati esperimenti condotti su ovini adulti (13 trattamenti su pecore in lattazione e 15 su pecore in asciutta o su montoni). Il modello MIPAF ha stimato senza bias ma con un elevato errore di predizione (RMPSE = radice dell'errore quadratico medio di predizione) le variazioni di peso (bias medio = -0.1 g/d; P > 0.1; RMSPE 44.9 g/d; n = 28). Tre trattamenti su montoni sono stati esclusi dallo studio perché l'analisi statistica li ha evidenziati come outliers. Questi animali utilizzavano diete molto povere di proteina (meno del 3.25% della SS), costituite solamente da paglia di grano. In seguito alla rimozione di questi dati, l'errore di predizione è diminuito ma il bias medio è cresciuto (bias medio = -12.3 g/d; P < 0.05; RMSPE = 29.6 g/d; n = 25). La capacità di predizione del modello è risultata diversa tra pecore in lattazione e pecore in asciutta. Le variazioni di peso delle pecore in lattazione sono state stimate in maniera accurata (bias medio = 6.8 g/d; P > 0.1; RMSPE 18.7 g/d; n = 13), mentre quelle delle pecore in asciutta sono state sottostimate (bias medio = -33.0 g/d, P < 0.001; RMSPE = 38.1 g/d; n = 12). La validazione del modello MIPAF è stata condotta utilizzando pubblicazioni che consideravano ovini di diverso peso corporeo e stadio fisiologico, alimentati con razioni molto diverse somministrate a diversi livelli nutritivi. Ciò suggerisce che il modello proposto possa essere utilizzato per valutare con buona capacità previsionale le razioni e le prestazioni produttive degli ovini in condizioni ambientali e di allevamento molto diverse.

Parole chiave: *Ovini, Modelli, Energia, Proteine, Fabbisogni.*

Introduction

Many studies have been conducted to determine the nutrient requirements of sheep, mainly because this species has often been used as a model for cattle. Indeed, sheep are easier to handle and less expensive to work with.

Many scientific organizations have published systems to estimate energy and protein requirements of sheep. The most diffused feeding systems are those proposed by AFRC (1995), CSIRO (1990), INRA (1989) and NRC (1985). These systems and their estimates on requirements have been recently compared by Cannas (2000; 2002), who found that they are often less developed, based on simpler approaches, and biologically more empirical than the cattle systems. The sheep feeding systems are mostly based on data obtained on meat or wool sheep breeds. Only the INRA (1989) system was designed for use with dairy sheep. None of the sheep systems accounts for the effect of the feeding level on the digestibility of slowly degraded feed fractions. Thus, all of them assign a unique nutritive value to the feeds, regardless the feeding level at which sheep are fed. This is in contrast to the approach of the newest models for cattle, such as the NRC (1996; 2001) and the CNCPS (Fox *et al.*, 2004), and to the fact that when fed at the same feeding level of cattle, sheep usually have a higher feed rumen passage rate (Van Soest, 1994). A new feeding system for sheep was recently published by Cannas *et al.* (2004). This system is based on the structure of the Cornell Carbohydrate and Protein System for cattle (Fox *et al.*, 2004) and accounts for many animal and environmental variables not considered by previous sheep systems. In addition, it predicts the effect of feeding level on diet utilization. However, this system requires a characterization of feedstuffs which is often not easily obtained in the areas in which most dairy sheep are raised.

Considering the shortcomings of the above mentioned sheep systems, the objective of this study was to develop a feeding system able to account for many of the variables that affect sheep performances. This was done by integrating new equations specifically developed for this model with published information on sheep requirements and feed utilisation. Development of a model to formulate diets of dairy sheep was a major goal. The model was called MIPAF to give credit to the Italian Ministry of Agriculture (Ministero delle Politiche Agricole e Forestali), which financially supported the development of the model. This model shares many equations on energy and protein requirements with the model published by Cannas *et al.* (2004), while the nutritive value of the feeds is based on the discount system of Van Soest and Fox (1992). In the model of Cannas *et al.* (2004) the prediction of the nutritive

value of the diet was based on the mechanistic approach used by the Cornell Carbohydrate and Protein System for cattle (Fox *et al.*, 2004).

The first section of the paper is devoted to explaining the equations included in the model and the second portion presents an evaluation of different aspects of the model using published data.

Material and methods

Energy requirements

Energy requirements are expressed as kcal of NE of lactation (NEL) requirements.

Maintenance energy requirements

Energy maintenance requirements are calculated following the CSIRO (1990) approach, except for the value assigned to k_m, which differs from the CSIRO (1990) value:

$$NEL\ (M)\ (kcal/d) = BW^{0.75} \times a1 \times \exp(-0.03 \times AGE) \times S \times a2 + ((0.09 \times MEI) \times k_m) + ACT + NE_{mcs} \quad [1]$$

where:

- BW = body weight, in kg;
- a1 = the thermal neutral maintenance requirement for fasting metabolism (CSIRO, 1990); it is assumed to be 62 kcal of NE_m per kg of $BW^{0.75}$;
- AGE = AGE of animals in years; it corrects maintenance requirements for the effect of age, using the CSIRO (1990) exponential equation exp (-0.03 x AGE), which decreases the maintenance requirements from 62 kcal to 51.9 kcal of NE_m per kg of $BW^{0.75}$ as the animal ages from 0 to 6 y;
- S = a multiplier for the effect of gender on maintenance requirements; it is assumed to be 1.0 for females and castrates and 1.15 for intact males (ARC, 1980).
- a2 = adjustment factor for the effects of previous temperature on acclimatization of animals to environmental temperature. It is (1 + 0.0091 x 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. In accordance with the suggestions of CSIRO (1990), it was also included in this sheep model. This adjustment increases maintenance requirements when animal are acclimatized to low temperatures and decreases them when they are acclimatized to high temperatures;
- (0.09 x MEI) x k_m = where MEI is metabolizable energy (ME) intake in kcal/d and k_m is dimensionless and in the decimal form. It is based on the CSIRO (1990) adjustment to account for the increase in the size of the visceral organs as nutrient intake increases;
- $k_m = k_l$ = the efficiency coefficient k_m is fixed at 0.64, and it is equal to the efficiency of conversion of ME to NE for milk production, based on the assumption that lactating sheep use energy with a similar degree of efficiency for maintenance and milk production, as already demonstrated for dairy cows (Moe *et al.*, 1972; Moe, 1981); differences in this efficiency between sheep and cows are unlikely (Van Soest *et al.*, 1994).
- ACT = energy required for activity, in kcal of NE_m/d; the factor a1 already 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):

$$ACT = 0.62 \times BW \times \text{flat distance} + 6.69 \times BW \times \text{sloped distance} \quad [2]$$

where:

- flat distance is the horizontal distance, km/d, and 0.62 is the energy cost per kg of BW of the horizontal component of walking, in kcal of NE_m per km; sloped distance is the vertical component of the movement, km/d, and 6.69 is the energy cost per kg of BW of the vertical component of walking, kcal of NE_m per km.
- $NE_{mcs} = NE_m$, in kcal/d, necessary to balance energy losses due to cold stresses. The equations used for this estimate are reported in Table 1 and are derived from the CSIRO (1990) model. The prediction of NE_{mcs} takes into account many environmental (temperature, wind, rain) and animal (body heat production, acclimatization to cold environments, tissue and external insulation) factors.

Table 1. Equations to estimate the extra net energy of maintenance (NEmcs) required for cold stress based on the CSIRO (1990) model.

NE_{mcs} (NE_m, kcal/d) = ((SA x (LCT -Tc))/(I_{tot})) x 0.239 x k_m

LCT = 39 + (1.3/SA) x (EI) -(HE/SA) x (I_{tot})

HE (MJ/d) = (ME_m+(MEI-ME_m) x (1-k_l)) x 4.184

I_{tot} = total insulation = TI + [1 - 0.3 x (1-exp(-1.5 RAIN/HAIR))] x EI

TI = tissue insulation (°C m^2 d/MJ) = 1.3

EI = external insulation (MJ/°C m^2 d) = (r/(r+HAIR)) x (1/(0.481 + 0.326 x (WIND + 0.36)$^{0.5}$)) + r x $\log_e$ ((r + HAIR)/r) x (0.141-0.017 x (WIND + 0.36)$^{0.5}$)

k_m = 0.64, i.e. diet NE_m/diet ME_m; SA = body surface area = 0.09 kg $FBW^{0.67}$ (m^2); HE = heat production (MJ of ME/d); MEI = metabolizable energy intake (Mcal/d) ; ME_m = ME required for maintenance (all adjustments but cold stress included); k_l = 0.64, i.e. efficiency of conversion of ME to NEL; LCT = lower critical temperature, °C; Tc = current mean daily (24 h) air temperature, °C; r = radius of the animal = 120 mm adult sheep, 50 mm lambs; HAIR = effective fleece depth (mm); WIND = wind speed, (km/h); RAIN = daily rainfall, (mm/d).

Regarding other possible factors of variation of maintenance requirements, Farrel *et al.* (1972) found that activity requirements of sheep were not affected by their body condition score. In cattle, Mathers e Sneddon (1985) found that activity requirements were not affected by environmental temperatures. It is likely that this is true for sheep as well. Energy cost of maintenance may be affected by the cost of production and excretion of urea in sheep overfed proteins. While the MIPAF system does not include a rumen model, and therefore cannot account for this cost, other systems do (Fox *et al.*, 2004; Cannas et al, 2004).

Energy requirements for milk production

These are based on the content of NE of milk based on the equation of Pulina *et al.* (1989):

NEL (L) (kcal/d) = [(251.73 + 89.64 x F + 37.85 x (P/0.95)) x Y] [3]

where:
- Y (kg/d) = daily milk yield;
- F (%) = milk fat concentration;
- P (%) = milk true protein concentration.

Requirements for growth

The sheep growth model developed by CSIRO (1990) was used for the MIPAF system. This model 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 (EBG, which equals 0.92 x BW gain) depend on energy balance, rate of gain or loss, and ratio between current BW and mature BW. The model is reported in Table 2.

Body energy reserve variations

The prediction of BW and body reserve variations is done differently for ewe lambs or primiparous ewes and pluriparous ewes.

In the case of ewe lambs and primiparous ewes (i.e. ewes up to the end of the first lactation) the MIPAF system estimates the energetic and proteic cost of BW variations based on the cost of the gain as predicted by the growth curves and growth model used by CSIRO (1990) for growing lambs. This system assumes that the composition and the cost of the empty body depend on:

Table 2. Equations to estimate BW changes (BWv) and energy and protein requirements for growth for sheep based on the CSIRO (1990) model.

ENERGY REQUIREMENTS

When energy intake is known, BWv is predicted as follows:

BW_v (kg/d) = RE/(EVG x 0.92)

- RE (kcal/d) = net energy available for gain = k_g (EB/k_m) except for intake smaller than ME_m and 0.8 efficiency of use of energy from loss in W, when it is = 1.25 x EB
- EB = NEL energy balance from equation [12], kcal/d
- EVG (energy content of empty body gain, kcal/kg of EBG) = ((6.7 + R) + (20.3 - R) / [1 + exp (-6 x (P - 0.4))]) x 239
- EBG (kg/d) = BWv x 0.92
- P = current BW in kg/SRW, in kg
- SRW = BW 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 BCS 3 in sheep.
- R = adjustment for rate of gain or loss when energy intake is known and gain or loss must be predicted = 2 x [RE/(NEL (M) – 1)]
- k_g = (1.42 x MEC – 0.174 x MEC^2 + 0.0122 x MEC^3 – 1.65) / MEC
- MEC is metabolizable energy concentration of the diet, Mcal/kg of DM

When BW_v is known, the energetic cost of this variation is predicted as follows:

NEL (BW_v) (kcal of NEL/d) = ((BW_v x 0.001 x EVG x 0.92)/k_g) x 0.64

EVG is predicted as previously described, except that its coefficient R is estimated as follows: R = BWv x 0.001 x 0.92/(4.0 x SRW 0.75) - 1

PROTEIN REQUIREMENTS

Net Protein (g/kg EBG) = (212 - 4 R) - (140 - 4R)/ [1 + exp (-6 x (P-0.4))]
Efficiency of NP/MP for growth = 0.7

MP_{BWv} (g/d) = Net Protein/0.7

a) the ratio between the BW in a certain growth phase and the mature weight (standard reference weight, SRW), which represents the BW that a certain animal of a certain breed and sex will have when its skeletric growth is completed and when its empty body has 250 g of fat/kg net weight. In sheep this corresponds to a BCS 3 (scale 0-5). The SRW of several breeds is reported by CSIRO (1990) and Cannas and Boe (2003). The ratio between current weight and mature weight, therefore, defines the stage of growth at which the ewe lamb finds itself;
b) the growth rate of the ewe lambs, which in turn depends on energy intake in excess of maintenance requirements.

This information is used to define growth curves specific for each animal and the corresponding composition of gain and the energetic and proteic cost of gain. The equations used to predict growth requirements are reported in Table 2.

For adult ewes, when BW variation (BWv) is known, the energetic cost of this variation is based on body condition score (BCS, scale 0-5) (Russel *et al.*, 1969) variations. The same approach is used by the INRA (1989) and CSIRO (1990) systems. The prediction of BCS variations and the associated energy cost is based on the following inputs:

- $BCS_{current}$ = BCS at the moment of diet balancing;
- BCS_{target} = BCS to which the ewes are brought;
- Days for the BCS_{target} = days required to pass from the $BCS_{current}$ to the BCS_{target};
- SRW = mature weight of the ewes, as previously defined.

Based on these inputs, it is possible to estimate the energetic cost of BW variations in mature animals with equations that relate BCS to BW, body fat (BF), and BF variations (BF_v):

$$BW_{current} \text{ (kg)} = (7.679 \times BCS_{current} + 23.463) \times SRW/42.7 \quad [4]$$

$$BW_{target} \text{ (kg)} = (7.679 \times BCS_{target} + 23.463) \times SRW/42.7 \quad [5]$$

$$\text{Total } BW_v \text{ (g)} = (BW_{target} - BW_{current}) \times 1000 \quad [6]$$

$$BW_v \text{ (g/d)} = \text{total } BW_v / \text{days for } BCS_{target} \quad [7]$$

$$BF_{current} \text{ (kg)} = (6.537 \times BCS_{current} + 2.186) \times 0.01 \times BW_{current} \quad [8]$$

$$BF_{target} \text{ (kg)} = (6.537 \times BCS_{target} + 2.186) \times 0.01 \times BW_{target} \quad [9]$$

$$\text{Daily } BF_v \text{ (g/d)} = [(BF_{target} - BF_{current}) \times 1000]/\text{days for } BCS_{target} \quad [10]$$

$$NE_l \text{ } (BW_v) \text{ (kcal/d)} = [(9.6 \times \text{daily } BF_v)/0.6] \times k_m \quad [11]$$

The net energy value of BF variations is converted to ME using the coefficient 0.6 for lactating ewes and dry ewes, similar to that proposed for sheep by the INRA (1989), CSIRO (1990) and AFRC (1995) systems. ME is then multiplied by 0.64 to obtain the corresponding NEL value.

When energy intake and energy balance are known, BWv is predicted by first calculating the energy balance (EB) as:

$$EB \text{ (kcal/d)} = NEL_d \text{ intake} - NEL \text{ (M)} - NEL \text{ (L)} - NEL \text{ (preg)} \quad [12]$$

where NEL intake is the total daily intake of NEL^d, and NEL (M), NEL (L), NEL (preg) are daily requirements for maintenance, lactation and pregnancy, as defined for the equation [17]. Body weight gain or losses are then predicted as:

$$BW_v \text{ (kg/d)} = EB/((9600/0.6) \times k_m) \quad [13]$$

where EB is energy balance (equation [12]) and k_m is equal 0.64.

Pregnancy energy requirements

Pregnancy requirements are estimated in accordance with the CSIRO (1990) pregnancy sub model, which is fundamentally based on ARC (1980) data. The energy content of the gravid uterus in the last 63 days before lambing is estimated using a Gompertz model:

$$Et \text{ (MJ/d)} = \exp(7.649 - 11.465 \times \exp(-0.00643 \times t)) \times \text{Lambweight}/4 \quad [14]$$

where t is the time after mating and Lambweight/4 corrects Et prediction, based on a total lamb weight of 4 kg at 147 d of pregnancy for different lamb weights.

The daily requirements of NE for pregnancy (NE_{preg}) at day t is calculated with the previous equation after converting the energy units from MJ to kcal using the 239 factor:

$$NE_{preg} \text{ (kcal of NE/d)} = dEt/dt = Et\ 0.0737 \exp(-0.00643 \times t) \times 239 \quad [15]$$

The NE_{preg} is then converted to ME_{preg} with an efficiency of 0.13. Then, ME_{preg} is multiplied by 0.64 to express pregnancy requirements in terms of NEL:

$$NEL(_{preg}) = (NE_{preg}/0.13) \times 0.64 \quad [16]$$

Total energy requirements

Total energy requirements are calculated as the sum of energy requirements of maintenance, lactation, BW variations and pregnancy:

$$NEL\ (TOT)\ (kcal/d) = NEL\ (M) + NEL\ (L) + NEL\ (BW_v) + NEL_{preg} \quad [17]$$

Protein requirements

Protein requirements are expressed as metabolizable protein (MP) requirements.

Protein requirements for maintenance

Maintenance metabolizable protein (MPM) requirements are the sum of dermal (wool) protein, urinary endogenous protein, and faecal endogenous protein losses (CSIRO, 1990). The system of equations used by CSIRO (1990) was adopted for use in the MIPAF as shown below.

$$S\text{-}CP_E = (CLEAN\ WOOL/\ 365) \quad [18]$$

$$U\text{-}CP_E = (0.147 \times FBW + 3.375) \quad [19]$$

$$F\text{-}CP_E = (15.2 \times DMI) \quad [20]$$

$$MP_M\ (g/d) = (S\text{-}CP_E / 0.7) + (U\text{-}CP_E / 0.7) + (F\text{-}CP_E / 0.7) \quad [21]$$

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 faecal endogenous CP, g/d; 0.7 is the efficiency of conversion of MP to net protein for $S\text{-}CP_E$, $U\text{-}CP_E$, and $F\text{-}CP_E$; CLEAN WOOL is the clean wool produced per head, g/yr; BW is body weight, kg; and DMI is dry matter intake, kg/d.

The efficiency of conversion of MP to net protein (NP) for $U\text{-}MP_E$ and $F\text{-}MP_E$ was assumed to be 0.7, which is the same coefficient used by CSIRO (1990).

Since $F\text{-}MP_E$ 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. 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 milk true protein content:

$$MP_L = (10 \times Prot \times Yn) / 0.58 \quad [22]$$

where Yn is measured milk yield on a particular day of lactation, kg/d, and Prot is measured milk true protein for a specific day of lactation, %. If only milk CP is known, Prot can be estimated as 0.95 x 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 (1985), CSIRO (1990), and AFRC (1995). The lower efficiency is likely because sheep have higher requirements than cattle for sulphur-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. Since 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 increase microbial yield and efficiency in dairy cattle (Robinson, 1983; Van Soest, 1994), which may offset the lower efficiency of MP from feed escape protein.

Protein requirements for pregnancy

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

$$\ln(Pr_t) = 11.347 - 11.220 \times \exp(-0.00601 \times t) \quad [23]$$

where Pr is protein content of the gravid uterus at time t (days) after conception, g; t is days of pregnancy; ln is natural logarithm.

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:

$$MP_{preg} = dPr/dt = Pr \times (LBW/4) [0.0674 \times \exp(-0.00601 \times t)]/0.7 \quad [24]$$

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; and the efficiency of utilization of MP to NP for gestation is equal to 0.7 for sheep (CSIRO, 1990), which is much higher than that adopted by the INRA (1989) systems for the same species. Therefore, even though NP requirements are similar between the CSIRO (1990) system (and thus the MIPAF system) and the INRA (1989) system, their MP requirements for pregnancy are markedly different, with higher values for the latter system (Cannas, 2000).

Protein growth requirements

Net protein requirements for growth (NP_{BWv}) are based on the CSIRO (1990) equation:

$$NP_{BWv} (g/kg\ BW) = \{(212 - 4R) - (140 - 4R)/[1 + \exp(-6 \times (P - 0.4))]\} \times 0.92 \quad [25]$$

The terms used in this equation are explained in Table 2. The efficiency of conversion of NP to MP for BW variations in growing animals is 0.7, therefore:

$$MP_{BWv} (g/d) = NP/0.7 \quad [26]$$

where MP_{BWv} are the MP requirements for BW variations in growing sheep.

Body protein reserves

This system does not account for variations in protein reserves in adult animals.

Total protein requirements

Total protein requirements (MP_{TOT}) are calculated as the sum of energy requirements of maintenance, lactation, BW variations and pregnancy:

$$MP_{tot} (g/d) = MP_m + MP_L + MP_{BWv} + MP_{preg} \quad [27]$$

Energy and protein feed value and supply

Energy feed value

The NEL value of the diet and its MP content are predicted with the method of the discounts of Van Soest and Fox (1992), originally developed for cattle. With this method the energy content of the feed is estimated assuming a level of nutrition of 3 times maintenance:

$$NEL_{3m} (kcal/kg\ DM) = 10 \times TDN_{1m}\ \% [2.86 - (35.5/(100 - NDF))] \quad [28]$$

where TDN_{1m} are the feed total digestible nutrients (% of DM), estimated at maintenance feeding level, and NDF is the feed NDF concentration (% of DM). The TDN_{1m} is predicted by the MIPAF model by using the summative equations of Weiss as reported in the Table 25.7 of Van Soest (1994). When sheep are fed at feeding levels different from three, NEL_{3m} is corrected with the discount equation of Mertens (1983), which estimates the percentage of decrease (increase) of NEL for each increase (decrease) of feeding level compared to 3 times maintenance:

$$D (\%) = 0.033 + 0.132\ NDF(\%) - 0.033\ TDN_{1m} (\%) \quad [29]$$

where D is the discount, and TDN_{1m} and NDF were already defined for the previous equation.

The NEL concentration of the diet is then predicted at the specific feeding level of the animals to which the diet is given:

$$NEL_d (kcal/kg\ DM) = NEL_{3m} (1 - (LN - 3) \times (D \times 0.01)) \quad [30]$$

where NEL_d is the feed dietary concentration at the actual feeding level d, and LN is the feeding level, in multiples of maintenance requirements.

The feeding level is estimated as the ratio between total daily NEL intake and daily NEL requirements for maintenance. However, the feeding level estimated with this ratio is, for sheep only, increased by one unit. For example, if the actual feeding level is 2, the one used in equation [30] is 3. This correction, not included in the Van Soest and Fox (1992) method, considers the fact that when fed at the same feeding level of cattle, sheep have higher rumen feed passage rate and lower rumen digestibility of slowly degraded fractions (Van Soest *et al.*, 1994).

Protein feed value

The Van Soest and Fox (1992) method allows the prediction of feed and dietary MP, which is the sum of the dietary protein that escaped rumen fermentation (escape protein, EP) and microbial protein (BP) digestible in the intestine. Conceptually the MP of Van Soest and Fox (1992) is similar to the PDI of the INRA (1989) system, even though they are estimated with different procedures.

The prediction of MP of each feed is done at the specific feeding level at which the sheep are fed:

$$MP\ (g/kg\ of\ DM) = EP + BP \quad [31]$$

$$EP\ (g/kg\ of\ DM) = CP \times 0.1\ (100 - DP_d - ADIP) \quad [32]$$

$$BP\ (g/kg\ of\ DM) = 1.05 \times EP + 112/[LN \times (CP - 4)] \quad [33]$$

where:

CP = feed dietary CP (% of DM)

DP_d = CP degraded in the rumen (% of CP) at a certain feeding level:
- if LN is 3, $DP_d = DP_{3m}$
- if LN is lower than 3, $DP_d = DP_{3m} \times (1 + (LN - 3) \times (D \times 0.01))$
- if LN is higher than 3, $DP_d = DP_{3m} \times (1 - (LN - 3) \times (D \times 0.01))$

DP_{3m} = is rumen CP digestibility when the feeding level is 3. It varies among feeds and can be predicted using the values published by Van Soest (1994), by NRC (1989) or by Licitra *et al.* (1993). The latter values, however, were estimated assuming a feeding level of 4;

D = the energy discount predicted by equation [29];

LN = feeding level; the same value used in equation [30] is used here. Even for MP prediction, the LN is increased by one unit when the approach of Van Soest and Fox (1992) is used for sheep;

ADIP = protein associated to ADF, as % of CP.

The Van Soest and Fox (1992) system allows the prediction of the MP values for any feed. However, these MP values assume that the feeds are used as ingredients of diets balanced to avoid a shortage of nitrogen (Van Soest and Fox, 1992).

The MIPAF model is associated with a feed library that contains, for a variety of feeds, all the inputs required by the model to predict feed energy and protein value.

Assessing model accuracy

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

$$\text{Mean bias} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \quad [34]$$

where n is the number of pairs of values predicted by the model and observed being compared and Pi and Oi 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):

$$\text{MSPE} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2 \quad [35]$$

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

$$\text{MSPE} = (\bar{P} - \bar{O})^2 + s_P^2(1-b)^2 + (1-r^2)s_O^2 \quad [36]$$

where s^2_P and s^2_O 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 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 unexplained variation in observed values 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 zero and a slope equal to one. Dent and Blackie (1979) proposed testing for these two values simultaneously with an appropriate F statistic. If the model is accurate, the F will be small and the null hypothesis that the slope is one and the intercept is zero will not be rejected.

Linear regression of observations (y) on predictions (x) were analysed 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).

Model Evaluation

The MIPAF was evaluated as follows: by comparing its predictions of energy and protein requirements with those of other feeding systems; by performing a sensitivity analysis of its environmental sub model; and by comparing the predicted effect of dietary treatments on FBW variations versus observed values.

Comparison of the predictions of energy and protein requirements for maintenance and lactation of the MIPAF model with those of other feeding systems

Energy requirements for maintenance and lactation as estimated by the MIPAF were compared with those predicted by the RAZI-O (Pulina *et al.*, 1996) and INRA (1989) feeding systems. The RAZI-O system (Pulina *et al.*, 1996) is a modification of the INRA (1989) system, developed to reduce the underestimation of dietary allowances observed in dairy sheep whose diets were balanced with the INRA (1989) system. The RAZI-O system (Pulina *et al.*, 1996) estimates feed energy content by using the method described by INRA (1989) but intentionally over-predicts sheep requirements to account for the fact the feed energy value is estimated at maintenance feeding level and is not discounted in sheep fed at higher feeding levels.

The comparison was conducted by estimating the requirements for dry or lactating 4-yr old ewes weighing 50 kg of BW. Net energy requirements were calculated separately for maintenance and lactation with the equations belonging to each feeding system.

Metabolizable protein requirements for maintenance and lactation predicted by the MIPAF system were compared with those of the INRA (1989) system. The RAZI-O system was not included in the comparison because it integrally adopts the equations of INRA (1989) to predict sheep MP requirements. To estimate maintenance MP requirements, the MIPAF requires daily DMI. The intake used was that predicted by the equations of Pulina *et al.* (1996).

Sensitivity analysis of the MIPAF environmental sub model

The effect of cold stress on maintenance requirements was simulated considering the effects of wind, rain, temperature, wool depth and physiological stage on sheep. The simulation was conducted testing the effect of the above mentioned variables on 50 kg non-lactating ewes with a NE intake sufficient to satisfy maintenance requirements in thermo-neutral conditions and on 50 kg lactating ewes, producing 1.5 kg/d of milk with 6.5% fat and with NE intake sufficient to satisfy maintenance and milk production requirements in thermo-neutral conditions.

Evaluation of the prediction of weight gain and loss in adult sheep

The BW variations reported in 6 different 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 MIPAF system. The predicted gain or losses of BW reflects 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, while 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 BW, feed intake and composition, milk yield and composition as input into the MIPAF system. The feeds most similar to those cited in the publications were

selected from the feed library of the MIPAF feed library. Feed composition was then modified according to the chemical composition reported in each publication for each feed. The TDM_{1m}, required to predict feed NEL (equations [28] and [29]), was predicted by using the summative equations of Weiss as reported in the Table 25.7 of Van Soest (1994). Since most publications did not give complete information on the N fractions of the feeds, those in the MIPAF feed library were used for missing values. The same approach was used for the rumen digestibility of CP, which is required by the model to predict feed escape protein and bacterial protein (equations [32] and [33]).

Variations in BW were predicted by first calculating the energy balance (equation [12]). Body weight gain or losses were then predicted using equation [13] and 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 MIPAF model with those of other feeding systems

While the INRA (1989) system and the *RAZI-O* (Pulina *et al.*, 1996) systems have fixed basic requirements (56.1 kcal/kg of $BW^{0.75}$), the MIPAF model has basic requirements which vary (60.3-51.9 kcal/kg of $BW^{0.75}$) depending on the age of the animals (Table 3). The latter correction stems from the well-known fact that for all mammals the metabolic rates decrease as the age increases.

The MIPAF uses fixed k_m and k_l (0.64 for both), while the RAZI-O (Pulina *et al.*, 1996) and INRA (1989) systems have conversion efficiencies of ME to NE for maintenance and lactation that vary depending on the quality of the diet (Table 3).

Table 3. Basic energy requirements and corrections applied to estimate maintenance energy requirements of adult sheep calculated with the MIPAF, the RAZI-O (Pulina *et al.*, 1996), and the INRA (1989) systems.

	MIPAF 2001	RAZI-O	INRA
Basic requirements:			
NE: kcal/kg $BW^{0.75}$	60.3-51.9 [1]	56.1	56.1
k_m or k_l	0.64	as INRA	0.563-0.637 [2]
Corrections:			
Breed	no	no	no
Age	1.0÷0.84 (0÷6 y)	no	no
Grazing activity	yes	yes	yes
Cold stress	yes	no	no
temperature	yes	no	no
rain	yes	no	no
acclimatization	yes	no	no
wool depth	yes	no	no
Production	0.09 NEL-I [3]	yes [4]	no

[1] it varies depending on the age of the animals; the range reported refers to sheep from 1 (highest value) to 6 years old (lowest value); the requirements are highest for newborn lambs (62.1 kcal/kg $BW^{0.75}$ of NE) and lowest for sheep 6 year-old or older;

*[2] the range of k_l (k_l = 0.249*q_m+0.463) is obtained considering q_m ranging from 0.4 to 0.7;*

[3] multiplicative factor; NEL-I = daily intake of NEL;

[4] total requirements are increased, with respect to the INRA system, to account for the fact that the French system does not discount feed energy value when sheep are fed above maintenance feeding level; the increase varies from 30% (when milk yield is 0.5 kg/d) to 10% (when milk yield is 2.0 kg/d) of total requirements.

These systems do not consider the effect of the 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.

Basic requirements are then corrected for many climatic variables in the case of the MIPAF system, while the other two systems assume that sheep are always in conditions of thermo neutrality.

The MIPAF system increases maintenance requirements in proportion to the total daily NEL (Table 3), considering that the increase in feed intake associated with milk production or gain triggers changes in both size and rate of metabolism of organs and tissues. Similar findings were reported by Ferrell (1988) and Ortigues and Doreau (1995). Graham (1982; cited by CSIRO, 1990) maintained that because the effects of variations in feeding level on maintenance energy requirements occur slowly, they could not be detected by short-term calorimetric studies. The INRA (1989) system does not take into account this effect. The RAZI-O system (Pulina *et al.*, 1996), which predicts feed energy values by integrally adopting the INRA (1989) UFL system, suggests a correction of total requirements of lactating animals to account for the reduction of digestibility that occurs at high feeding levels (Table 3). Therefore, the RAZI-O system (Pulina *et al.*, 1996) proposes an artificial increase in the requirements to avoid modifications of the feed value of the diets. The increase varies from 30% (when milk yield is 0.5 kg/d) to 10% (when milk yield is 2.0 kg/d) of total energy requirements.

As a result of the corrections made proportionally to daily NEL intake, the MIPAF system has maintenance energy requirements that vary depending on the level of production (Table 4), while the other two systems have constant maintenance requirements. RAZI-O (Pulina *et al.*, 1996) production requirements are very high, to account for the depressive effect of intake on digestibility as discussed before.

Total (maintenance + lactation) energy requirements estimated by the MIPAF system are

Table 4. Energy requirements for 4 year-old sheep in free stalls, expressed as kcal of NEL/d and assuming zero energy balance, calculated with the MIPAF, the RAZI-O (Pulina *et al.*, 1996), and the INRA (1989) systems.

6.5% FCM [1]	MIPAF mant.	MIPAF prod.	MIPAF total	RAZI-O mant.	RAZI-O prod.	RAZI-O total	INRA [2] mant.	INRA [2] prod.	INRA [2] total
				45 kg of body weight					
0.0	1052	0	1052	975	0	975	974	0	974
0.5	1103	512	1615	1497	488	1985	974	544	1518
1.0	1154	1023	2177	1497	976	2473	974	1088	2062
1.5	1204	1536	2740	1497	1464	2961	974	1632	2606
2.0	1254	2047	3301	1497	1952	3449	974	2176	3150
				55 kg of body weight					
0.0	1224	0	1224	1133	0	1133	1133	0	1133
0.5	1274	512	1786	1741	488	2229	1133	544	1677
1.0	1325	1023	2348	1741	976	2717	1133	1088	2221
1.5	1375	1535	2910	1741	1464	3204	1133	1632	2765
2.0	1425	2047	3472	1741	1952	3692	1133	2176	3306

[1] *6.5%fat corrected milk yield = milk yield x (0.3688 + 0.0971 x % fat) (Pulina et al., 1989).*
[2] *fed diets having a ratio: qm = ME/gross energy = 0.6.*

higher than those of INRA (1989), but lower than those of RAZI-O (Pulina *et al.*, 1996) (Table 4).

The MP requirements of the MIPAF system are higher than those of INRA (1989), because the MIPAF maintenance requirements increase as level of production increases (Table 5). Variable maintenance requirements are justified because the increase in DMI associated with milk production or gain increases both the size and rate of protein turnover of visceral organs, thus increasing their maintenance costs (Ferrell, 1988; CSIRO, 1990).

Sensitivity analysis of the MIPAF environmental sub model

The sensitivity analysis of MIPAF predicted NEm to the effects of wind, rain, temperature, wool depth and physiological stage is shown in Table 6. The results of this simulation indicated that lactating ewes are less affected by cold stress than 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 6), because of its insulation properties. However, wind or rain can markedly reduce the protection given by wool. In the simulation, the combined effects of all these factors increased the maintenance requirements up to almost three times. These effects are much higher than those found in a similar evaluation with dairy cows (Cannas, 2000). Since small animals have more body surface per kg 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 effect does not offset the effects of their smaller body size on heat loss.

Dairy sheep breeds tend to have less subcutaneous fat as well as 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. The submodel for

Table 5. Metabolizable protein requirements, expressed as g/d, for adult sheep producing 1.5 kg/y of wool, calculated with the MIPAF and the INRA (1989) systems.

5% TP [1] milk (kg/d)	MIPAF [2]			INRA		
	mant.	prod.	total	mant.	prod.	total
	45 kg of body weight					
0.0	45	0	45	39	0	39
0.5	52	43	95	39	42	81
1.0	59	86	145	39	85	124
1.5	66	129	195	39	127	166
2.0	73	172	245	39	169	208
	55 kg of body weight					
0.0	53	0	53	46	0	46
0.5	60	43	103	46	42	88
1.0	67	86	163	46	85	131
1.5	74	129	203	46	127	173
2.0	81	172	253	46	169	215

[1] *TP = true protein*

[2] *based on the hypothesis that DMI is equal to 1.11, 1.43, 1.76, 2.08 and 2.41 kg/d for ewes of 45 kg of body weight producing 0.0, 0.5, 1.0, 1.5 and 2.0 kg/d of milk, respectively, and that DMI is equal to 1.37, 1.70, 2.02, 2.35 and 2.66 kg/d for ewes of 55 kg of body weight producing 0.0, 0.5, 1.0, 1.5 and 2.0 kg/d of milk, respectively.*

Table 6. Predicted effects of coat depth, wind, rainfall and current mean daily (24 h) temperature on MIPAF predicted maintenance requirements of adult ewes.

	Wool depth, 25 mm				Wool depth, 50 mm			
Wind, km/h	Calm		30		Calm		30	
Rainfall, mm/d	0	30	0	30	0	30	0	30
	% of thermo-neutral conditions [1]							
Adult, dry [2]								
Temp. +5 °C	110	135	200	230	100	100	158	177
Temp. 0 °C	121	148	221	254	100	106	174	195
Temp. −5 °C	131	160	241	276	100	114	189	212
Adult, dry [3]								
Temp. +5 °C	100	100	135	160	100	100	100	115
Temp. 0 °C	100	100	155	183	100	100	113	132
Temp. -5 °C	100	103	174	205	100	100	128	149

[1] Thermo-neutral conditions are from 15 to 20 °C. Total maintenance requirements are expressed as a percentage of maintenance requirements at thermal neutral conditions.

[2] Based on non-lactating ewes with BW of 50 kg and with ME intake sufficient to satisfy maintenance requirements.

[3] Lactating ewes with BW of 50 kg, producing 1.5 kg/d of milk with 6.5% fat and with ME intake sufficient to satisfy maintenance and milk production requirements.

cold stress (Table 1) used by the MIPAF system was integrally taken from the CSIRO (1990) model, which was developed and tested for meat and wool breeds. Thus, its utilization with dairy breeds may require modifications of the estimates related to differences in tissue and external insulation.

Evaluation of the prediction of BW variations

The database used to evaluate the MIPAF prediction of BW 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, for a total of 29 dietary treatments. A total of 13 treatments were reported in experiments conducted with lactating ewes, while the others were on dry ewes or mature wethers. One treatment from Wales *et al.* (1990) was excluded because the NDF of the diet, made of wheat straw only, was so high (88.4%) that it exceeded the range of validity of equation [28], giving negative NEL values. The remaining database included a wide range of BW, DMI, diet composition and production (Table 7). As expected, dry matter intake, diet quality, level of feeding and energy intake were higher in lactating ewes than in dry ewes or wethers.

The MIPAF model accounted for 71% of the gains and losses in BW (Table 8 and Figure 1). The predicted - observed variations in BW did not differ from zero (-0.1 g/d; $P > 0.1$); there was no systematic bias over the range of losses to gains in BW. The regression bias was small (5.6% of MSPE). However the RMSPE was quite large (44.9 g/d). The regression of observed on predicted BW gain or loss was not different ($P > 0.1$) from the equivalence line ($y = x$) (Table 8 and Figure 1).

In the database, the three largest prediction errors of BW gain or loss, clearly visible in Figure 1, were with the Wales *et al.* (1990) diets, which had very low CP (equal or less than 3.25% of DM) and were made by wheat straw only. All other diets of the database had at least 10% CP (DM basis). Since the Van Soest and Fox (1992) method to predict feed energy value assumes that diets are balanced for nitrogen, the data of Wales *et al.* (1990) were excluded from the database. Without these outliers the prediction of BW variations improved, as shown by the decrease of the RMSPE from 44.9 g/d to 29.6 g/d (Table 8). However, the

Table 7. Description of the database used to evaluate the MIPAF model prediction of mature sheep BW gains and losses.

Item	BW kg	BW change g/d	DMI kg/d	Concentrates % DM	CP % DM	NDF % DM	LN[1]	NEL intake[2] kcal/d	NEL required[2] kcal/d	NEL balance[2] kcal/d	MP balance[2] g/d	Milk yield kg/d
45 kg of body weight												
n.	13	13	13	13	13	13	13	13	13	13	13	13
Mean	51.1	32	1.87	22.25	15.3	43.5	2.42	2839	2414	425	1	1.07
SD	12.1	56	0.49	13.11	4.0	6.5	0.37	714	646	442	96	0.48
Min	37.8	-49	1.14	0.00	10.2	31.3	1.65	1870	1666	-238	-102	0.55
Max	76.0	144	2.85	49.18	21.3	53.7	2.87	4250	4029	1394	178	2.04
55 kg of body weight												
n.	15	15	15	15	15	15	15	15	15	15	15	
Mean	72.9	-36	1.05	13.2	11.22	68.3	1.64	1071	1513	-425	32	
SD	8.7	91	0.32	8.4	4.67	8.5	0.33	561	170	425	33	
Min	56.0	-230	0.39	0.0	2.13	56.1	1.18	272	1190	-918	-16	
Max	77.1	69	1.46	24.6	15.75	83.4	2.20	2006	1666	357	81	

[1] LN = level of feeding, as estimated by the MIPAF model (i.e., total NEL intake/NEL required for maintenance);
[2] Estimated with the MIPAF model

regression bias increased (8.3% of MSPE), and the regression of observed on predicted BW gain or loss became different ($P < 0.05$) from the equivalence line ($y = x$) (Table 8 and Figure 2). As a whole, the MIPAF model predicted without bias at high observed BW variations and under predicted at low observed BW variations.

To better understand the causes of the regression bias, the database without the 3 outliers was divided into two subgroups, one with lactating ewes, and the other with dry ewes. The separate analysis of the two databases showed that the MIPAF predicted BW variations for lactating sheep (P-O = 6.8 g/d, $P > 0.05$; RMSPE = 18.7 g/d) very well, while for dry ewes the prediction was worse (P-O = -33.0 g/d, $P < 0.001$; RMSPE = 38.1 g/d) (Table 8 and Figure 2). The cause of the observed differences between lactating and dry ewes is not clear. The 12 data on dry ewes were all from the same publication (Fonseca *et al.*, 1998). Thus, it is difficult to determine if the large error of prediction observed for this category was due to the poor prediction power of the MIPAF model, an effect of experimental methodology, or an effect of the physiological stage.

The predictions of the MIPAF model were as good as those of the CNCPS for Sheep (Cannas *et al.*, 2004), which based its evaluation on the same database used for the MIPAF model. This occurred despite the much simpler approach used by the MIPAF model and the fewer inputs required to estimate dietary nutrient supply compared to the CNCPS Sheep system. However, the lack of experiments in which all input variables required by the MIPAF are reported limited the scope of this evaluation.

Conclusions

The MIPAF system accounts for many animal and dietary variables not considered by the most diffused sheep systems. Besides the CNCPS Sheep, it is the only feeding system for sheep that accounts for the effect of feeding level on dietary nutritive value. The evaluations presented indicate that the MIPAF system for sheep accurately

Table 8. Evaluation of the MIPAF model for sheep predicted BW gains and losses.

Item	Obs. g/d	Pred. - Obs. g/d	n.	Components of MSPE, % Mean bias	Regression bias	Unexpl. variation	RMSPE g/d	r^2	P
				All data					
MIPAF	-4.3	-0.1^{ns}	28	0.0	5.6	94.4	44.9	0.71	ns
				The 3 data of Wales *et al.* (1990) discarded					
MIPAF	-4.3	-12.3*	25	16.5	8.3	75.2	29.6	0.75	< 0.05
lactating ewes only	32.4	6.8^{ns}	13	12.5	20.2	67.4	18.7	0.92	ns
dry ewes + wethers only	2.4	-33.0**	12	73.5	0.7	25.9	38.1	0.82	< 0.01

MSPE = mean squared error of prediction.
RMSPE = root of the mean squared error of prediction.
r^2 = coefficient of determination of the best fit regression line not forced through the origin.
**, ** are the significance of the differences between predicted and observed values when subjected to a paired t-test (P < 0.05, P < 0.001 and P > 0.05, respectively); ns = not significant.*
P = probability associated to a 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.

Figure 1. Relationship between the body weight (BW) predicted by the MIPAF model for sheep and observed BW gains and losses. The solid line indicates unitary equivalence (Y = X). The regression equation of observed on predicted BW was: y = 1.18 (0.15) x + 0.89 (8.56), r^2 = 0.71, SE = 45.3 (- - - - line). This line was not different from the Y = X line (P > 0.1).

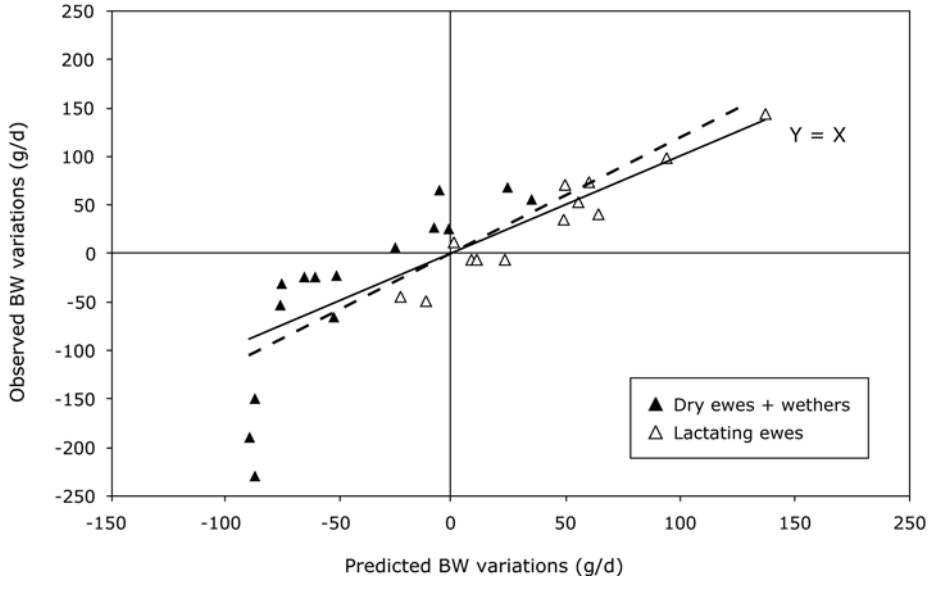
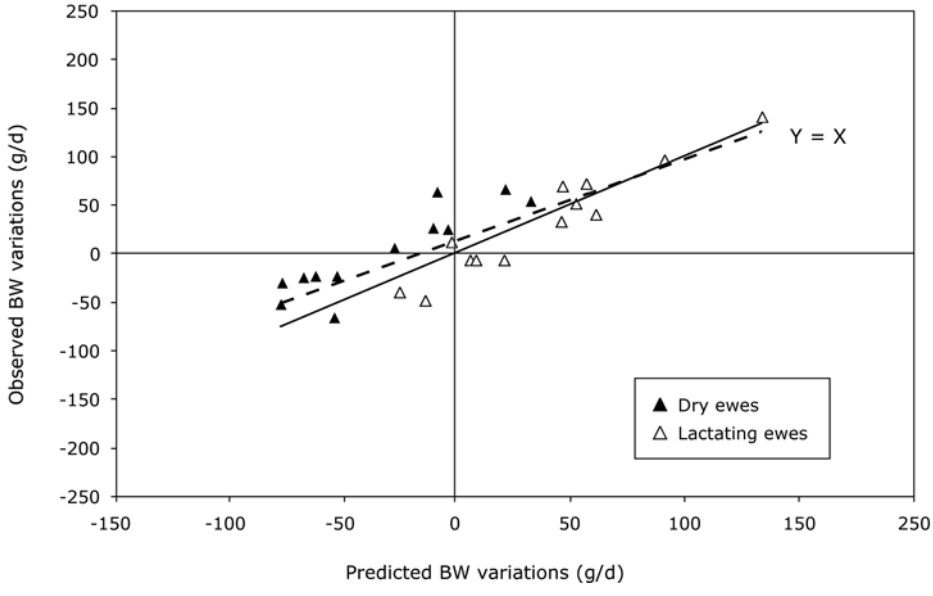


Figure 2. Relationship between the body weight (BW) predicted by the MIPAF model for sheep and observed BW gains and losses when the three data of Wales *et al.* (1990) were discarded. The regression equation of observed on predicted BW was: y = 0.84 (0.10) x + 13.28 (5.34), r^2 = 0.75, SE = 26.6 (- - - - line). This line was different from the Y = X line (P < 0.05).



predicted nutrient requirements, feed biological values and body weight gains and losses in lactating ewes. However, its predictions for dry mature ewes were less accurate. The 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 MIPAF model can be used to evaluate diets and animal performance in a variety of production settings.

Further research is needed to improve the ability of the MIPAF model to predict dry ewe performances. Further evaluation with experimental data that contain all inputs required by the model is needed.

This research was supported by a grant of the Ministry of Agricultural and Forestry Policies, Italy (Project: Further development of a diet formulation model for sheep and goat. National Coordinator: Prof. Giuseppe Pulina).

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