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The GRAZPLAN animal biology model for sheep and cattle and the GrazFeed decision support tool¹

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ABSTRACT

This paper specifies the animal biology module of a model for simulating grazing systems for ruminants on pasture. The program predicts the intake of energy and protein, allowing for selective grazing and substitution by supplementary feeds, and estimates the use of the diet for maintenance and production, according to current feeding standards. Conception and death rates are predicted from the maturity and condition of the animals. The model is designed to be of general application to any genotype of sheep or cattle on any pasture.

GrazFeed is a discrete package that uses the same procedures for predicting feed intake and productivity within a tactical decision support tool. This is designed to help graziers to assess the feeding value of specified pastures and the need for the supplementary feeding of different classes of grazing animals.

INTRODUCTION

The GrazFeed decision support tool (DST) is a component of the GRAZPLAN decision support project for Australian grazing enterprises (Donnelly *et al.*, 1997). GrazFeed is designed to help the user assess the nutritive value of a specified pasture for specified animals grazing it and to show the extent to which a desired weight gain or milk yield might be achieved through supplementation. It does this by predicting the intake of energy and protein and their use for maintenance and production according to the recommendations in CSIRO (2007). Each use of GrazFeed provides an estimate at one point in time but the same procedures for predicting intake and productivity, when combined with routines for predicting animal reproduction and mortality and pasture growth, form the dynamic biological model underlying the GrassGro DST (Donnelly *et al.*, 1997; Moore *et al.*, 1997) and the AusFarm DST (formerly known as FarmWi\$e, Moore, 2001). The animal biology model was developed from part of the grazing management model described by Christian *et al.* (1978) and a forerunner of the GrazFeed DST was described by Freer and Christian (1983). A brief description of version 1 was reported by Freer and Moore (1990) on the initial release of GrazFeed and a full specification of version 3 was published by Freer *et al.* (1997).

¹ This Technical Paper is based on the original paper published in *Agricultural Systems* (Freer *et al.*, 1997), which has been revised to match ver.5.0.4 of GrazFeed.

The animal biology model is suitable for any kind of sheep or cattle, a generality that is achieved very largely by scaling many of the functions to the mature size of the animal, as specified by the user. It is designed for the grazing of any pasture that can be described as a sward of grasses and other herbaceous plants but is not suitable for semi-arid rangelands of mainly shrub vegetation. The model may, alternatively, be used with animals removed from pasture, in a drought yard or feed lot or indoors.

This paper gives the specification of the complete animal biology model and then describes the features of GrazFeed that enable it to be used as a discrete package. Lists of the state variables and other variables that are used in more than one section of the model are shown in the Appendix and the names and values of the parameters are listed in the appropriate tables. Indices to time and to a group of similar animals are implicit in all state variables. Where the value of a state variable is updated and its value on the previous day forms part of the right-hand side of the model equation, the assignment operator (\leftarrow) is used. All model parameters are denoted by symbols starting with the letter C.

Spreadsheet programs (SheepExplorer and CattleExplorer) that allow the user to test the effect of different variable values and different parameters on the functions listed in this paper may be downloaded from the following website.

www.pi.csiro.au/grazplan

SCALING BY NORMAL WEIGHT, RELATIVE SIZE AND RELATIVE CONDITION

Many of the functions in the model depend on either the stage of development of the animal relative to its mature size or on its body condition, rather than on its current weight. The starting point is the standard reference weight, SRW , which is defined in SCA (1990) as the base weight (live weight excluding fleece and conceptus) of an animal when skeletal development is complete and condition score is in the middle of the range.

The normal weight, N , of a mature animal is its SRW and the upper limit to the normal weight, N_{max} , of a growing animal follows Brody (1945) (equation 1 and Fig.1) with the allometric scaling of the time constant for skeletal development from Taylor (1968).

$$N_{max} = SRW - (SRW - W_{birth}) \exp\left(\frac{-C_{N1}A}{SRW^{C_{N2}}}\right) \quad (1)$$

To accommodate animals with slower growth, i.e., where the weight on the previous day, W_{prev} , is less than N_{max} , normal weight increases at a lower rate (equation 1a). As a result, normal weight continues to increase slowly during seasonal periods of undernutrition even though the animal fails to gain weight, or loses weight.

$$N = \begin{cases} C_{N3}N_{max} + (1 - C_{N3})W_{prev} & W_{prev} < N_{max} \\ N_{max} & W_{prev} \geq N_{max} \end{cases} \quad (1a)$$

Relative size, Z , is defined as the ratio of normal weight to SRW , a ratio that cannot exceed 1.0, and relative condition, BC , is defined as the ratio of current base weight, W , to normal weight. Relative condition is related to condition score, as defined by Jefferies (1961) and Earle (1976), through the convention of SCA (1990) that a gain or loss of 1 unit of condition score is equivalent to a change of $0.15N$ for the 0-5 scale (sheep and beef cattle) or to $0.09N$ for the 1-8 scale (dairy cattle).

To estimate the relative condition of a pregnant animal, current weight is first corrected for the predicted weight of the conceptus.

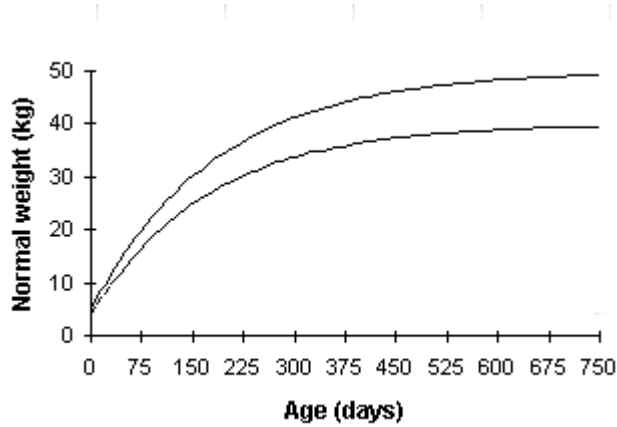


Fig.1. Upper limit to normal weight in relation to age for sheep with a standard reference weight of 50 kg (upper line) or 40 kg (lower line)

TABLE 1.

Parameters used for prediction of normal weight and potential intake: equations 1-11

Parameter	Description	Units	Sheep	Cattle
<i>Growth rate parameters</i>				
C_{N1}	Growth rate constant	$\text{kg}^{0.27} \text{d}^{-1}$	0.0157	0.0115
C_{N2}	Allometric scalar for growth rate		0.27	0.27
C_{N3}	Weighting factor for slow growth		0.4	0.4
<i>Potential intake parameters</i>				
C_{I1}	Relative size	kg kg^{-1}	0.04	0.025
C_{I2}			1.7	1.7
C_{I3}	Rumen development	d^{-1}	0.5	0.22
C_{I4}		d	25	60
C_{I5}	High temperature	-	0.01	0.02 ¹
C_{I6}		$^{\circ}\text{C}$	25.0	25.0
C_{I7}		$^{\circ}\text{C}$	22.0	22.0
C_{I8}	Lactation: peak intake time	d	28	62 ⁴
C_{I9}	intake curvature	-	1.4	1.7 ²
C_{I10}	dairy cow factors	kg^{-1}	-	0.6
C_{I11}		-	-	0.05
C_{I12}	body condition loss	-	0.15	0.15
C_{I13}		d^{-1}	0.02	0.005
C_{I14}		d^{-1}	0.002	0.002
C_{I15}	condition at parturition	-	0.5	0.5
C_{I16}		-	-	-
C_{I17}			0.01	0.01
C_{I18}			20.0	20.0
$C_{I19,n}$	peak intake level: 0 young	-		0.416 ²
	1 young		0.655 ³	0.416 ²
	2 young		0.884 ³	
	3 young		1.114 ³	
C_{I20}	Effect of body condition	-	1.5	1.5

¹ In *Bos indicus* breeds, $C_{I5} = 0.01$

² For cows of dairy type, $C_{I9} = 0.7$, $C_{I19,0} = 0.85$ and $C_{I19,1} = 0.577$

³ In Merinos, these values of $C_{I19,n}$ are multiplied by 0.8

⁴ For cows of dairy type, $C_{I8} = 81$

FEED INTAKE

The intake of feed other than milk is predicted as the product of the potential intake of food by the specified animal and the proportion of that potential (relative intake) that the animal can obtain from the available feed supply.

Potential intake

Potential intake, I_{max} , is defined as the amount eaten (kg DM d⁻¹) when unrestricted access is allowed to a feed with a DM digestibility of at least 80% (but without pasture legumes in the diet). It depends linearly on SRW (equation 2 and Fig. 2) and is basically a quadratic function of the relative size of the animal, with a peak at $Z = 0.85$. For animals with $BC > 1.0$ the factor CF (equation 3) reduces potential intake with increasing relative condition. The equation was developed empirically from a wide range of data and its predictions for mature animals in normal condition are similar to those of ARC (1980). However, predictions of potential intake by immature animals are considerably greater than those predicted by ARC, in agreement with Langlands (1972, 1973), Alden (1979) and Weston (1980).

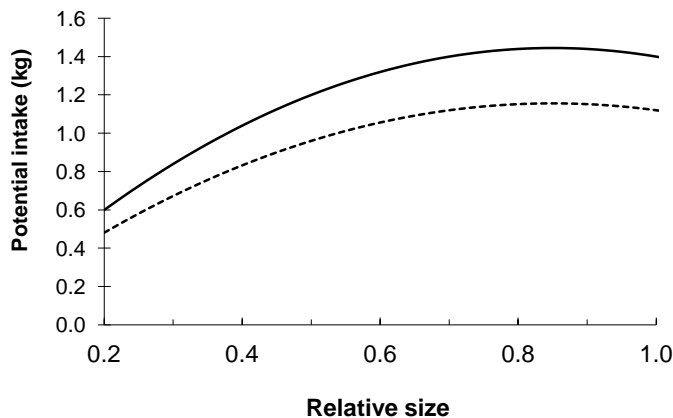


Fig. 2. Potential daily intake of dry matter by a sheep with a standard reference weight of 50 kg (solid line) or 40 kg (dashed line), in relation to its relative size, for an animal that is not lactating and has a relative condition ≤ 1.0 .

As potential intake depends on relative size, whereas the maintenance requirement for ME depends on base weight (see equation 43), the model allows growing animals recovering from a period of undernutrition to exhibit compensatory weight gain.

Potential intake is depressed in unweaned young by incomplete development of rumen function (factor YF in equation 4 varies between 0 and 1). If the ambient temperature remains high over the 24 hours (Fox, 1987), potential intake is reduced by the factor TF (equation 5) but if it falls below the lower critical temperature, T_{lc} , (equation 97) of the animal, potential intake is increased by 1% per degree (Fox, 1987); an effect that is reduced with rainfall, to disappear at 20 mm per day.

In lactating animals, potential intake is multiplied by a factor LF (equation 8 and Fig. 3) that depends primarily on the time from parturition. The function is based on the lactation

curve of Wood (1969) (see also equation 66), but lagging behind it (Davies, 1963; Corbett, 1968; Monteiro, 1972). It is adjusted for number of young and modified to relate potential intake to circumstances that may have affected potential milk yield in the current lactation. When the young are weaned or when a dairy cow's lactation is terminated, the effect of lactation on potential intake continues, but the rate of decline is accelerated by trebling the value of the time variable, A_y , in equation 9.

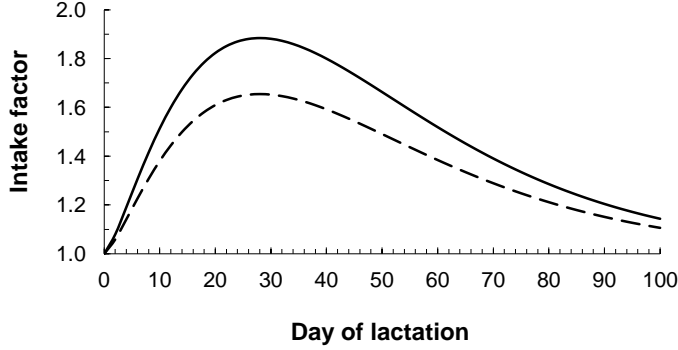


Fig. 3. Multiplier for the potential intake of lactating ewes in relation to stage of lactation; upper line for twin lambs, lower line for single lamb.

LF is modified for factors that may restrict the peak milk yield and the persistence of lactation. For animals suckling young, the factor LA (equation 10) is related to the body condition of the mother at parturition, whereas in the case of dairy cattle the adjustment, factor LC (equation 13), is based on knowledge of the peak milk yield by the cow. The parameter used by ARC (1980) was found to give insufficient response in potential intake when compared with experimental results at Kyabram, Victoria (Wales *et al.*, 1999), necessitating an increase in the value of C_{110} from 0.2 to 0.6. To account for the effect of nutrition after the time of peak lactation, LF is modified by the factor LB , which, in the dynamic model, is calculated in equation 72. In the GrazFeed DST, the same factor is estimated (equation 11) from the extent to which the lactating animal's weight loss since parturition has exceeded an arbitrary critical level.

$$I_{max} = C_{11} SRWZ(C_{12} - Z)CF YF TFLF \quad (2)$$

where

Z has a maximum value of 1.0

$$CF = \begin{cases} BC(C_{120} - BC)/(C_{120} - 1) & BC > 1.0 \\ 1.0 & \text{otherwise} \end{cases} \quad (3)$$

$$YF = \begin{cases} \frac{1 - \phi_{milk}}{1 + \exp(-C_{13}(A - C_{14}))} & \text{unweaned animals} \\ 1 & \text{other animals} \end{cases} \quad (4)$$

$$TF = \begin{cases} 1 - C_{15}(T_{mean} - C_{16}) & T_{mean} > C_{16} \text{ and } T_{min} > C_{17} \\ 1 + C_{117} T_{low} \max(0, 1 - R/C_{118}) & T_{lc} > T_{min} \\ 1 & \text{otherwise} \end{cases} \quad (5)$$

$$T_{low} = AX(T_{lc} - T_{mean}) + 0.5 \sin(AX)(T_{max} - T_{min}) / \pi \quad (6)$$

$$AX = \arccos \left(\max(-1, \min(1, (T_{mean} - T_{lc}) / (0.5(T_{max} - T_{min})))) \right) \quad (7)$$

$$LF = \begin{cases} 1 + C_{119,Y} M_i^{C_{19}} \exp(C_{19}(1 - M_i)) LA LB & \text{lactating, with young} \\ 1 + C_{119,Y} M_i^{C_{19}} \exp(C_{19}(1 - M_i)) LC LB & \text{lactating, no young} \\ 1 & \text{otherwise} \end{cases} \quad (8)$$

$$M_i = A_y / C_{18} \quad (9)$$

$$LA = 1 - C_{115} + C_{115} BC_{part} \quad (10)$$

$$LB = \begin{cases} 1 - \frac{C_{112} WL}{C_{113}} & A_y \geq C_{L2} \quad \& \quad WL > C_{114} \exp\left(-\left(C_{113} A_y\right)^2\right) \\ 1 & \text{otherwise} \end{cases} \quad (11)$$

$$WL = Z \left(\frac{BC_{part} - BC}{A_y} \right) \quad (12)$$

$$LC = 1 + C_{110} \left(\frac{WM_{peak} - C_{111} SRW}{C_{111} SRW} \right) \quad (13)$$

Relative intake

The proportion of its potential intake that an animal can satisfy is the product of two attributes of the feed supply: its 'relative availability' and 'relative ingestibility'. For the pasture component of the diet, the first is predicted mainly from pasture mass (kg DM ha⁻¹) and the second mainly from the digestibility of the selected herbage. To simulate selective grazing, the herbage mass is divided between 6 pools, each of fixed digestibility (means 0.8 to 0.3), with an additional pool for seeds (see below). The algorithm for calculating relative availability, F_d , (equation 14 and Fig. 4), is applied to each pool or class, d , in turn, starting with the most digestible. UC_d represents the proportion of appetite left unsatisfied by material selected earlier in the sequence. RR_d and RT_d represent, respectively, the relative rate of eating and the relative time spent grazing, with the form of equations 16 and 17 based on data of Alden and Whittaker (1970). The parameters used here are for herbage weights that represent the material removed if cut close to ground level with a standard shearing handpiece.

The exponents in these two equations increase with the proportion of the herbage DM that is in the class, $\phi_{avail,d}$. Also, if the sward is unusually dense or if there is much bare ground in the sward and the mean height of the herbage is judged to be lower or greater, respectively, than 3 cm (t DM ha⁻¹)⁻¹, then the ratio of these heights for each herbage pool, HR_d , decreases or increases, respectively, the availability of the feed, through factor HF_d , equation 18. The factor ZF accommodates the smaller mouth size of young cattle, allowing them to achieve their potential intake at a lower level of herbage availability than would be needed by adults.

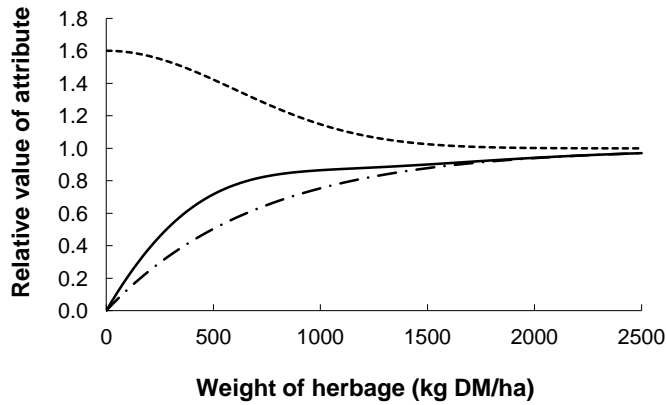


Fig. 4. Relative availability and its component attributes, for sheep, (for the first herbage class, where the unsatisfied appetite of the animal has a relative value of 1), in relation to the weight of herbage dry matter; upper line is relative time spent grazing, lower line is relative rate of eating and middle line is the product, relative availability.

Equation 21 predicts relative ingestibility from data reviewed by Freer (1981) and from Freer and Jones (1984) for a number of cultivars of sown temperate (C_3) pasture species. The intercept adjustment for the proportion of legume in the sward (equation 20) may result in intakes higher than the nominal potential intake (see above). However, the effect of legume proportion on relative ingestibility decreases as herbage availability declines.

Feeding trials with tropical pasture (C_4) species by CSIRO Tropical Agriculture (D.B. Coates, pers. comm) and Queensland Department of Primary Industries (S.R. McLennan, pers. comm) indicate that, although C_4 grasses are commonly about 15 percentage units lower in digestibility than C_3 grasses at the same stage of maturity, voluntary intake is correspondingly higher at the same level of digestibility. Coates' data show a strong relationship ($r^2 = 0.81$) between digestibility and intake for a number of tropical grasses: the same slope but a greater intercept than the relationship for C_3 grasses. This difference is expressed in the species factor, SF, which takes values of 0.0 and 0.16 for C_3 and C_4 grasses, respectively.

This model has been adapted to incorporate the grazing of seed as well as herbage. Ripe and unripe seeds of each annual species are assigned a place in the selection hierarchy and are combined with the herbage to form the array of available fodder. After the calculation of relative intake (equation 20) the respective values for herbage and each seed pool are separated out in proportion to their mass. This is necessary, as the seed pools may not have the same digestibility, protein content etc. as herbage at the same level in the selection hierarchy. This hierarchy has 7 levels, so that seeds may be placed below all 6 herbage pools.

If the simulation is of an intensive system of rotational grazing, i.e. one in which the mass of herbage would be significantly reduced during a day's grazing, then the calculations of relative intake are repeated five times during the day after taking into account the amount of herbage in each pool that has been removed by grazing and the amount that has been trampled or fouled by the animals. The latter weight has been set at 100% of the amount eaten, in line with results from Kyabram, Victoria (Wales *et al.*, 1998).

$$F_d = UC_d RR_d RT_d \quad \forall d = 1..7 \quad (14)$$

where, in the absence of supplement

$$UC_d = \max\left(0, 1 - \sum_{k=1}^{d-1} F_k\right) \quad (15)$$

$$RR_d = 1 - \exp\left(-\left(1 + C_{R13}\phi_{avail,d}\right)C_{R4}HF_d ZF B_{avail,d}\right) \quad (16)$$

$$RT_d = 1 + C_{R5} \exp\left(-\left(1 + C_{R13}\phi_{avail,d}\right)\left(C_{R6}HF_d ZF B_{avail,d}\right)^2\right) \quad (17)$$

$$HF_d = 1 - C_{R12} + C_{R12}HR_d \quad (18)$$

$$ZF = \begin{cases} 1 + (C_{R7} - Z) & \text{cattle, } Z < C_{R7} \\ 1 & \text{otherwise} \end{cases} \quad (19)$$

$$R_d = F_d RQ_d \left(1 + C_{R2} \left(\sum_{d=1}^7 F_d\right)^2 \phi_{legume}\right) \quad (20)$$

where

$$RQ_d = 1 - C_{R3} DIM(C_{R1} - (1 - \phi_{legume})SF, DMD_d) \quad (21)$$

TABLE 2
Parameters used for prediction of relative intake: equations 14-30

Parameter	Description	Units	Sheep	Cattle
C_{R1}	Digestibility: peak	0-1	0.80	0.80
C_{R2}	legume effect	-	0.17	0.17
C_{R3}	slope	-	1.7	1.7
C_{R4}	Availability: grazing rate	kg ⁻¹	1.12x10 ⁻³	0.78x10 ⁻³
C_{R5}	grazing time	-	0.6	0.6
C_{R6}		kg ⁻¹	1.12x10 ⁻³	0.74x10 ⁻³
C_{R7}	Relative size on time and rate	-	0.0	0.5
C_{R8}			n.a.	n.a.
C_{R9}		-	n.a.	n.a.
C_{R10}		-	n.a.	n.a.
C_{R11}	Substitution: supplement M/D	MJ kg ⁻¹	10.5	10.5
C_{R12}	Effect of pasture height	-	0.8	0.8
C_{R13}	Effect of proportion in class		0.35	0.35
C_{R14}	Upper limit on RQ for supplements	-	1.0	1.0
C_{R20}	Substitution factor for lactating animals	MJ kg ⁻¹	11.5	11.5

When a supplement is offered to grazing animals there is usually a depression in the intake of pasture and the ratio of this depression to the weight of supplement is called the substitution rate. The procedure used here to predict this effect involves integrating the supplement into the hierarchy of herbage pools for estimating relative intake, based on the assumption that the grazing animal will select the supplement before it selects herbage of the same or lower quality (pool d^*). For example, a supplement with an RQ_s of 0.9 would be selected after 0.09 of the second herbage pool (which, in the absence of legume, has RQ_s of mean 0.83, covering a range from 0.745 to 0.915) but before the remaining 0.91 of this class.

The proportion of herbage in each digestibility pool d that is eaten after the supplement is given by equation 22.

$$EP_s = \min\left(1.0, 0.5 + \frac{RQ_s - RQ_d}{0.1 \cdot C_{R3}}\right) \quad (22)$$

where 0.1 is the width of a digestibility pool.

In the calculation of the term F_s , analogous to the relative availability of a herbage class, either the unsatisfied capacity at this point, UC_{d^*} , or the metabolizable energy concentration of a concentrate supplement (Grovm, 1987) may restrict the intake of supplement below the amount offered (equation 23). The parameters of this function have been selected to fit the data on substitution rates from Allden and Jennings (1962), Langlands (1969), Allden (1981) Milne *et al.* (1981) and Stockdale (2000). Examples of predicted substitution rates are shown in Fig.5. In grazing situations where the effect of the supplement is to rectify a deficiency of protein, herbage intake may be increased by supplementation (Freer *et al.*, 1985,1988) and the substitution rate will be negative, an effect that is simulated through the balance of rumen degradable protein (see the discussion in relation to equations 50 to 52).

$$F_s = \min\left(\frac{DMO_s/I_{\max}}{RQ_s}, UC_{d^*}, \frac{C_{R11}}{M/D_s}\right) \quad (23)$$

where

$$UC_d = \max\left(0, 1 - \sum_{k=1}^{d-1} F_k - F_s\right) \quad \forall d > d^* \quad (24)$$

For lactating animals, C_{R11} is replaced by CR_{20} in equation 23.

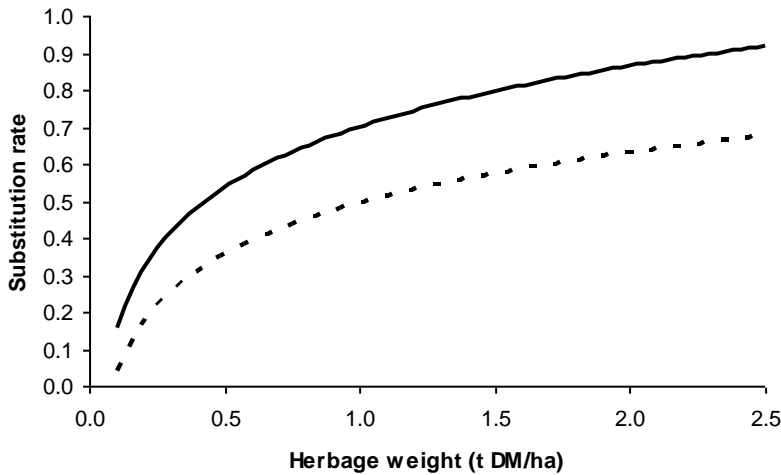


Fig. 5. Predicted substitution rate for a sheep offered 200 g of a supplement of 0.8 DMD while grazing a pasture of mean DMD 0.7 (solid line) or 0.5 (dotted line).

The relative intake of supplement is then calculated (equation 25) for each herbage class, followed by the actual intakes for each category of feed (equations 28 to 30).

$$R_s = F_s RQ_s \quad (25)$$

where

$$RQ_s = \min(C_{R14}, (1 - C_{R3} (C_{R1} - DMD_s))) \quad (26)$$

$$I_d = I_{\max} R_d \left(\frac{B_{\text{herb},d}}{B_{\text{avail},d}} \right) \quad \forall d = 1 \dots 7 \quad (27)$$

$$I_{\text{seed},k,j} = I_{\max} R_{QS_{k,j}} \left(\frac{B_{\text{seed},k,j}}{B_{\text{avail},QS_{k,j}}} \right) \quad \forall j, k \quad (28)$$

$$I_f = \sum_{d=1}^6 I_d + \sum_{j,k} I_{\text{seed},k,j} \quad (29)$$

$$I_s = I_{\max} R_s \quad (30)$$

Once the intakes of dry matter have been computed, the dry matter digestibility of consumed forage, DMD_f , and the intakes of crude protein, CPI , (including milk protein) and rumen degradable protein, $RDPI$, are calculated in proportion to the contributions of the separate components.

ENERGY AND PROTEIN USE

A flow chart of the fate of dietary energy and protein is shown diagrammatically in Fig. 6. Metabolizable energy (ME) intake from forage is calculated from equation 31, which was estimated by regression from 55 roughage feeds in MAFF (1990). Equation 32, for supplements, is of a form similar to that suggested by Thomas (1990) but estimated by regression from 49 'energy feeds and protein supplements' in MAFF (1990): $r^2 = 0.94$, compared with 0.72 for the regression that does not include ether extract, EE_s (g g^{-1}). The predicted values of MEI are used to calculate the M/D ratio of the solid part of the diet and the total ME intake, MEI_{total} , is computed as the sum of the forage, supplement and milk ME intakes.

$$MEI_f = (17.2DMD_f - 1.71)I_f \quad \text{RMS} = \pm 0.34 \quad (31)$$

$$MEI_s = (13.3DMD_s + 23.4EE_s + 1.32)I_s \quad \text{RMS} = \pm 0.25 \quad (32)$$

In the absence of comparable data for grazed pasture, the original equation for herbage (SCA, 1990) has been retained: $MEI_h = (17.0DMD_h - 2.0)I_h$.

Efficiency of energy use

Efficiencies of energy use for maintenance, lactation and the growth of conceptus, follow in general, SCA (1990), in equations 33 to 35. Similarly for the efficiency of use for weight gain of ME derived from supplements (equation 37). The proportions of milk, solid, forage and supplement in the diet: ϕ_{milk} , ϕ_{solid} , ϕ_f , ϕ_s , respectively, are calculated from the appropriate ME intakes. For the forage component of the diet, the efficiency of use for weight gain, k_{gf} (equation 38 and Fig. 7), depends on the proportion of legume in the diet, ϕ_{legume} , and the day of the year, DOY . With the convention that latitude, λ , is positive in the northern hemisphere and negative in the south, the factor DF (equation 40) is designed to be of general application. Equation 36 is computed provisionally before equation 97 and again after ME_{cold} has been added to ME_m .

$$k_m = (C_{K1} + C_{K2} M/D_{solid})\phi_{solid} + C_{K3}\phi_{milk} \quad (33)$$

$$k_l = C_{K5} + C_{K6} M/D_{solid} \quad (34)$$

$$k_c = C_{K8} \quad (35)$$

$$k_g = \begin{cases} k_l/C_{K10} & \text{lactating animals, } MEI_{total} < ME_m + ME_c + ME_l \\ C_{K9}k_l & \text{other lactating animals} \\ k_m/C_{K11} & \text{non-lactating animals, } MEI_{total} < ME_m + ME_c \\ \phi_s k_{gs} + \phi_f k_{gf} + C_{K12}\phi_{milk} & \text{other animals} \end{cases} \quad (36)$$

where

$$k_{gs} = C_{K16} M/D_s \quad (37)$$

$$k_{gf} = C_{K13} LG(1 + C_{K15} DF)M/D_f \quad (38)$$

$$LG = 1.0 + C_{K14} \phi_{legume} \quad (39)$$

$$DF = \frac{\lambda}{40} \sin(2\pi DOY/365) \quad (40)$$

TABLE 3
Parameters used for prediction of efficiency of energy use: equations 33-40

Parameter	Description	Units	Sheep and cattle
C_{K1}	k_m : M/D in solid diet	-	0.5
C_{K2}	"	kg MJ ⁻¹	0.02
C_{K3}	milk intake	-	0.85
C_{K4}		-	-
C_{K5}	k_l : M/D in solid diet	-	0.4
C_{K6}	"	kg MJ ⁻¹	0.02
C_{K7}		-	-
C_{K8}	k_c :	0-1	0.133
C_{K9}	k_g : lactating animals	-	0.95
C_{K10}	lactating animals losing weight	0-1	0.84
C_{K11}	weight loss	0-1	0.8
C_{K12}	milk intake	-	0.7
C_{K13}	herbage, zero legume, mid-winter	kg MJ ⁻¹	0.035
C_{K14}	"	-	0.33
C_{K15}	time of year effect at 40° latitude	-	0.12
C_{K16}	M/D of supplements	kg MJ ⁻¹	0.043

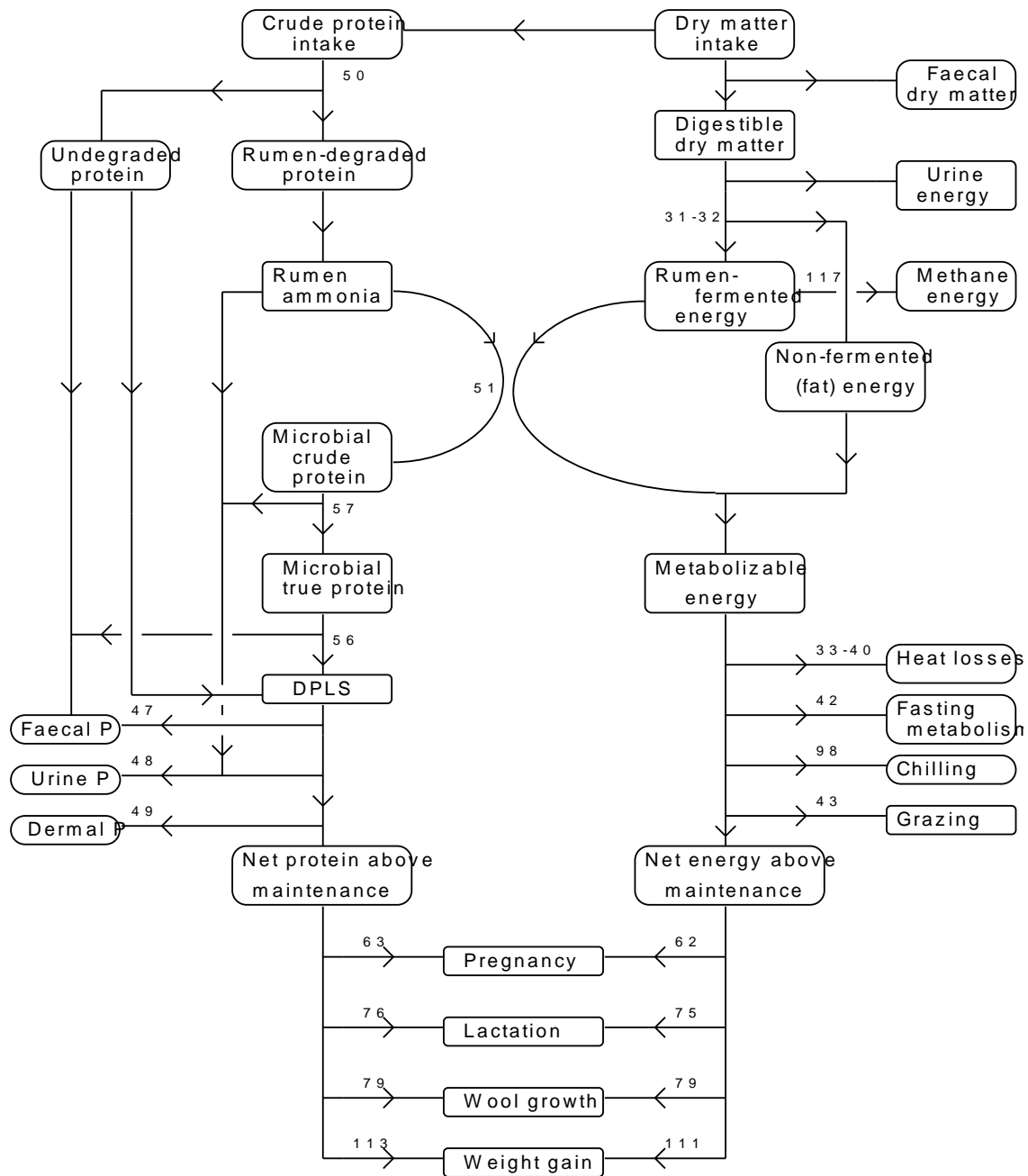


Fig. 6. Flows of dietary protein and energy through the ruminant, as represented in the animal biology model. Numbers indicate the corresponding equations in the text.

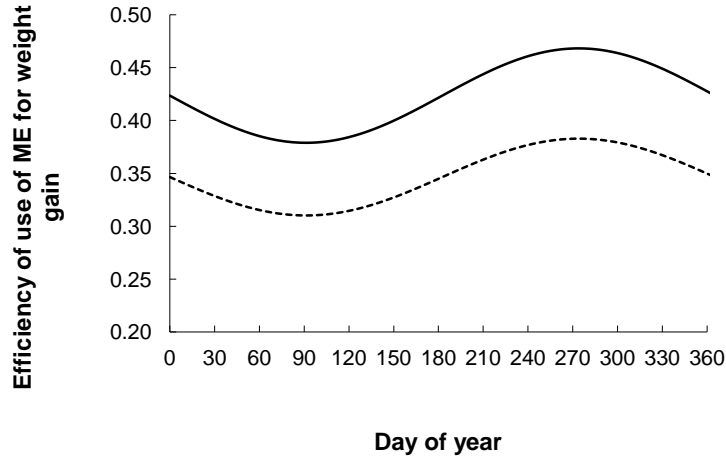


Fig. 7. The efficiency of the use of metabolizable energy for weight gain, in relation to herbage metabolizability, M/D, and time of year, for a pasture diet containing 30% legume and at a latitude of 35°S; upper line, M/D = 11; lower line, M/D = 9.

Energy and protein use for maintenance

Equation 41 for predicting ME requirements for maintenance was developed by Corbett *et al.* (1987) from the data of Graham *et al.* (1974) to include the effect of feeding level within the maintenance requirement, thus avoiding the need for variable values of k_g and k_l . For male animals, the requirement is multiplied by 1.15.

The E_{move} component of E_{graze} allows for the distance walked by the grazing animals (equation 44) and is reduced to zero for animals not grazing. If the number of animals per ha of grazing land, SD , is less than 5 for cattle or 40 for sheep, the estimated distance walked (as its horizontal equivalent), D , km, depends on the steepness of the land, S (on a scale of 1–2), the weight of green or dead herbage, plus, for dairy cows, four times the distance from the pasture to the milking shed, M . If grazing is more intensive, the distance walked is progressively reduced. The remaining part (equation 43) relates the additional energy cost of eating by grazing animals to the indigestibility of the pasture eaten. If later calculations indicate that additional energy is required to maintain body temperature (equation 100) this amount, ME_{cold} , is added to ME_m before weight gain is calculated. Relative feeding level, L , in excess of maintenance is calculated (equation 45) and this is used to modify the effective degradability of protein in the diet and the composition of weight gain.

$$ME_m = \left(\frac{E_{metab} + E_{graze}}{k_m} + C_{M1} MEI_{total} \right) \quad (41)$$

where

$$E_{metab} = C_{M2} W^{0.75} \max(\exp(-C_{M3} A), C_{M4}) (1 + C_{M5} \phi_{milk}) \quad (42)$$

$$E_{graze} = C_{M6} W I_f (C_{M7} - DMD_f) + E_{move} \quad (43)$$

$$E_{move} = C_{M16} D W \quad (44)$$

$$D = \begin{cases} S \min(1.0, C_{M17}/SD)/(C_{M8} B_{green} + C_{M9}) + S M & B_{green} > 100 \\ S \min(1.0, C_{M17}/SD)/(C_{M8} B_{dead} + C_{M9}) + S M & B_{green} < 100 \text{ \& } B_{dead} > 100 \\ 0 & \end{cases} \quad (44a)$$

$$L = \frac{MEI_{total}}{ME_m} - 1 \quad (45)$$

The maintenance protein requirement, P_m , is the sum of the endogenous urinary protein, EUP , the endogenous faecal protein, EFP , and, for cattle, the dermal protein, DP , equations 46 to 49. EFP for solid diet is estimated as a function of dry matter intake (SCA 1990).

$$P_m = EUP + EFP + DP \quad (46)$$

where

$$EFP = C_{M10} DMI_{solid} + C_{M11} MEI_{milk} \quad (47)$$

$$EUP = \begin{cases} C_{M12} \ln(W) - C_{M13} & \text{cattle} \\ C_{M12} W + C_{M13} & \text{sheep} \end{cases} \quad (48)$$

$$DP = \begin{cases} C_{M14} W^{0.75} & \text{cattle} \\ 0 & \text{sheep} \end{cases} \quad (49)$$

TABLE 4

Parameters used for prediction of energy and protein use for maintenance: equations 41-49

Parameter	Description	Units	Sheep	Cattle
C_{M1}	ME_m : liveweight gain	-	0.09	0.09
C_{M2}	Basal metabolism: weight scalar	MJ kg ^{-3/4}	0.26	0.36 ¹
C_{M3}	effect of age	d ⁻¹	8.0x10 ⁻⁵	8.0x10 ⁻⁵
C_{M4}	"	-	0.84	0.84
C_{M5}	milk intake	-	0.23	0.23
C_{M6}	E_{graze} : chewing cost	MJ kg ⁻¹	0.02	0.0025
C_{M7}	"	0-1	0.9	0.9
C_{M8}	walking cost	kg km ⁻¹	5.7x10 ⁻⁵	5.7x10 ⁻⁵
C_{M9}	"	km ⁻¹	0.16	0.16
C_{M10}	EFP from solid diet	kg kg ⁻¹	0.0152	0.0152
C_{M11}	EFP from milk diet	kg MJ ⁻¹	4.6x10 ⁻⁴	5.26x10 ⁻⁴
C_{M12}	EUP	-	1.47x10 ⁻⁴	1.61x10 ⁻² ¹
C_{M13}	"	kg	3.375x10 ⁻³	4.22x10 ⁻² ¹
C_{M14}	Dermal loss	kg ^{-3/4}	-	1.1x10 ⁻⁴
C_{M15}	Factor for males		1.15	1.15
C_{M16}	Energy cost of horizontal walking	MJ km ⁻¹ kg ⁻¹	0.0026	0.0026
C_{M17}	Threshold stocking rate	head ha ⁻¹	40	5

¹ In *Bos indicus* breeds, $C_{M2} = 0.31$, $C_{M12} = 1.29 \times 10^{-2}$, $C_{M13} = 3.38 \times 10^{-2}$

Rumen degradable protein and digestible protein leaving the stomach

The total intake of rumen degradable protein, $RDPI$, is calculated (equation 50) after adjusting the intakes from pasture and supplement for the level of feeding, to account for changes in the residence time of protein in the rumen. The slope of the adjustment for herbage depends on the digestibility of the pasture component of the diet. The intake of undegraded protein, $UDPI$, from the solid diet is calculated by difference and added to any protein consumed in milk.

The requirement for rumen degradable protein, $RDPR$, (equation 51 and Fig. 8) depends on feeding level (AFRC, 1992) and on the time of the year (in a similar fashion to k_{gf}) for consistency with the evidence presented in SCA (1990) for seasonal variation in MCP synthesis. For supplements, $RDPR$ is predicted from fermentable MEI, $FMEI_s$, which is estimated from equation 32 with ether extract set to zero; the small and usually unknown content of ether extract in the forage diet is ignored. The energy content of UDP is also subtracted. If $RDPR$ exceeds $RDPI$, then the potential intake of dry matter is reduced by the factor $RDPI/RDPR$ and all equations up to this point that involve intake are re-calculated. For *B. indicus* cattle and their crosses with *B. taurus*, the reduction is 0.5 and 0.75 of this factor, respectively. The assumption is made that recycling of urea to the rumen will offset the remaining deficiency of RDP.

$$RDPI = \begin{cases} \left(1 - (C_{RD1} - C_{RD2} DMD_f)L\right) RDPI_f + (1 - C_{RD3}L) RDPI_s & L > 0 \\ RDPI_f + RDPI_s & L \leq 0 \end{cases} \quad (50)$$

where $RDPI_f = CPI_f \text{ MIN}(0.84DMD + 0.33, 1.0)$ (from data of Bowen *et al.* (2008))

$$RDPR = \left(C_{RD4} + C_{RD5} \left(1 - \exp(-C_{RD6}(L+1))\right)\right) (RF MEI_f + FMEI_s) \quad (51)$$

$$\text{where } RF = 1 + C_{RD7} \frac{\lambda}{40} \sin\left(\frac{2\pi DOY}{365}\right) \quad (52)$$

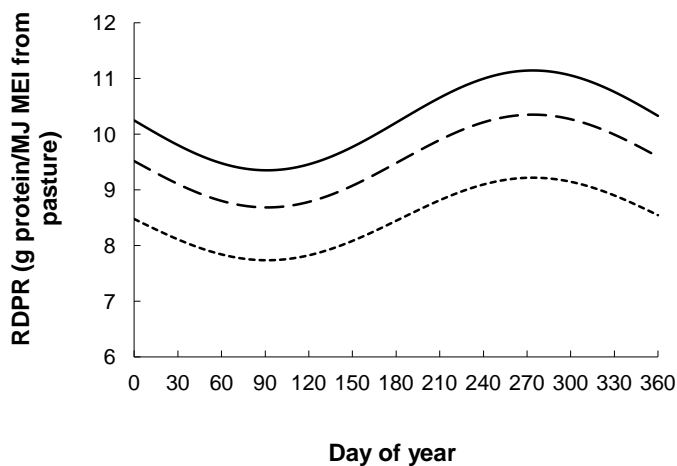


Fig. 8. The microbial requirement for rumen degradable protein as a function of feeding level (L) relative to maintenance and time of year, for a pasture diet and at a latitude of 35°S ; upper line, $L = 2$, middle line, $L = 1$, lower line, $L = 0$.

Truly digestible protein leaving the stomach, *DPLS*, comprises digestible undegraded protein and digestible *MCP*, equation 53. The digestibility of undegraded protein derived from herbage or a roughage supplement is computed from a modification of Webster *et al.* (1982), equation 54, but with a ceiling of 0.85. The digestibility of undegraded protein from a concentrate feed is calculated from its acid detergent insoluble protein, ADIP (g/g DM), using equation 55, based on Waters *et al.* (1992). Capture of *RDP* as *MCP* is assumed to be complete, its true digestibility 0.6, with 0.25 as faecal (cell wall) protein and 0.15 as the proportion of nucleic acid protein (Russell *et al.*, 1992). We have not followed AFRC (1992) in separating the quickly degraded from the slowly degraded protein, mainly because of uncertainty about whether the measured rate of solubility is a true reflection of the rate of degradation (Spencer *et al.*, 1988).

$$DPLS = D_{udp}UDPI_{solid} + DPLS_{milk} + DPLS_{mcp} \quad (53)$$

where

$$D_{udp} = \max(C_{A1}, \min(C_{A3}CP_{herb} - C_{A4}, C_{A2})) \quad \text{for herbage UDP} \quad (54)$$

$$D_{udp} = C_{A9}(1 - (ADIP_s/UDP_s)) \quad \text{for concentrate UDP} \quad (55)$$

$$DPLS_{milk} = C_{A5}CPI_{milk} \quad (56)$$

$$DPLS_{mcp} = C_{A6}C_{A7}RDPR \quad (56a)$$

TABLE 5
Parameters used for prediction of degraded and digestible protein: equations 50-56

Parameter	Description	Units	Sheep and cattle
C_{RD1}	Degradability: feeding level	-	0.3
C_{RD2}	"	-	0.25
C_{RD3}	"	-	0.1
C_{RD4}	RDPR: feeding level	kg ⁻¹	0.007
C_{RD5}	"	kg ⁻¹	0.005
C_{RD6}	"	-	0.35
C_{RD7}	time of year (forage)	-	0.1
C_{A1}	UDP digestibility	-	0.05
C_{A2}	"	-	0.85
C_{A3}	"	-	5.5
C_{A4}	"	-	0.178
C_{A5}	Milk protein digestibility	0-1	0.92
C_{A6}	DPLS in MCP		1.0
C_{A7}	"		0.60
C_{A8}	Faecal protein from MCP		0.25
C_{A9}	UDP digestibility in concentrates		0.9

Pregnancy requirements

For a mother in average condition or better, the weight of the foetus and its growth rate in relation to its age follow the Gompertz function and its first derivative (Robinson and McDonald, 1979) as used by ARC (1980) (equations 57 and 58). The basic equations are modified for foetus number, the *SRW* of the parents and the maturity of the mother. Deviations from the normal foetal weight gain, and hence foetal weight, arise if the body condition of the mother deviates from 1.0 (equation 61).

$$N_{foet} = BW \exp(C_{P2}(1 - \exp(C_{P3}(1 - RA)))) \quad (57)$$

$$\delta N_{foet} = BW \frac{C_{P2} C_{P3}}{C_{P1}} \exp(C_{P3}(1 - RA) + C_{P2}(1 - \exp(C_{P3}(1 - RA)))) \quad (58)$$

$$\delta W_{foet} = \begin{cases} \delta N_{foet} (1 + CF_{preg}) & BC \geq 1.0 \\ \delta N_{foet} (1 + C_{P14,Y} CF_{preg}) & BC < 1.0 \end{cases} \quad (59)$$

where

$$BW = (1 - C_{P4} + C_{P4} Z) C_{P15,Y} SRW \quad (60)$$

$$CF_{preg} = (BC - 1) \left(\frac{N_{foet}}{C_{P15,Y} SRW} \right) \quad (61)$$

$$RA = A_{foet} / C_{P1} \quad (61a)$$

The weight of the conceptus is estimated in a similar way to foetus weight (equation 62) so that the live weight of the pregnant ewe can be calculated.

$$W_c = Y (C_{P5} BW \exp(C_{P6}(1 - \exp(C_{P7}(1 - RA)))) + (W_{foet} - N_{foet})) \quad (62)$$

TABLE 6

Parameters used for prediction of pregnancy requirements: equations 57-65

Parameter	Description	Units	Sheep	Cattle	
C_{P1}	Gestation length	d	150	285	
C_{P2}	Foetal normal weight	-	1.304	2.20	
C_{P3}	"	-	2.625	1.77	
C_{P4}	Effect of relative size on birth weight	-	0.33	0.33	
C_{P5}	Final conceptus weight:foetus weight	kg/kg	1.43	1.80	
C_{P6}	Conceptus weight	-	3.38	2.42	
C_{P7}	"	-	0.91	1.16	
C_{P8}	Final conceptus energy content	MJ/kg	4.33	4.11	
C_{P9}	Conceptus energy	-	4.37	343.5	
C_{P10}	"	-	0.965	0.0164	
C_{P11}	Final conceptus protein content	kg/kg	0.145	0.134	
C_{P12}	Conceptus protein	-	4.56	6.22	
C_{P13}	"	d ⁻¹	0.90	0.747	
$C_{P14,Y}$	Foetal growth (poor condition):	1 young	-	1.5	1.0
		2 young	-	1.75	1.15
		3 young	-	2.0	
$C_{P15,Y}$	Normal birth weight:SRW:	1 young	-	0.10	0.07
		2 young	-	0.085	0.055
		3 young	-	0.07	

The ME and protein requirements for pregnancy (equations 63 to 65 and Fig. 9) are estimated from ARC (1980), scaled for foetus number, animal size and the body condition of the foetus.

$$ME_c = \frac{C_{P8} (Y C_{P5} BW) BC_{foet} \frac{C_{P9} \cdot C_{P10}}{C_{P1}} \exp(C_{P10}(1-RA) + C_{P9}(1-\exp(C_{P10}(1-RA))))}{k_c} \quad (63)$$

$$P_c = C_{P11} (Y C_{P5} BW) BC_{foet} \frac{C_{P12} \cdot C_{P13}}{C_{P1}} \exp(C_{P13}(1-RA) + C_{P12}(1-\exp(C_{P13}(1-RA)))) \quad (64)$$

where

$$BC_{foet} = \frac{W_{foet}}{N_{foet}} \quad (65)$$

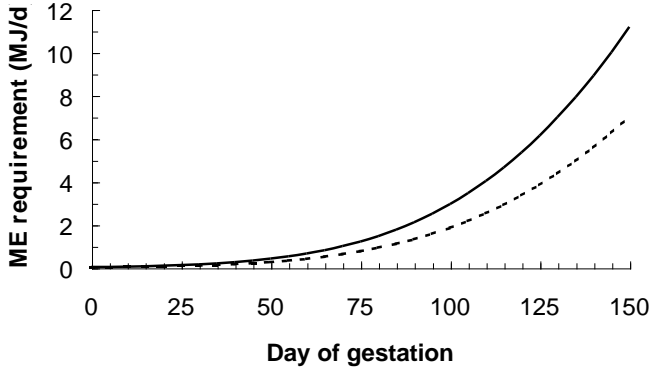


Fig. 9. Metabolizable energy requirement for pregnancy in relation to day of gestation for a ewe with standard reference weight of 50 kg, in average condition and carrying fetus(es) of normal weight: upper line, twin fetuses; lower line, single fetus.

Lactation requirements

The potential production of milk on a particular day of lactation, expressed as the ME value of the milk for the young, is predicted from equation 66 (Fig. 10), based on that of Wood (1969). Wood's equation has been rewritten to relate MP_{max} to stage of lactation expressed as a proportion of the time to peak lactation (equation 67). The predicted MP_{max} is scaled in two different ways, depending on whether the animal is suckling young. For animals with young it is scaled for the mother's SRW , relative size, and the number of young. For animals without young, usually dairy cows, the scaling factor is simpler as the peak weight of milk, WM_{peak} , is used as a parameter. In both cases, potential milk production is related to body condition at parturition, in accord with results from Broster and Thomas (1981) and Grainger *et al.* (1982).

Potential production is reduced if current milk production consistently fails to reach the potential after the time of peak lactation. In the GrazFeed DST, which holds no direct information on this, the adjustment LB , is estimated from the loss of live weight since parturition (equation 9). In the dynamic model, however, the adjustment is recalculated daily (equation 72) as a function of the maximum value of the lagged mean of the ratio of actual to potential milk production, DR , (equation 74). The same factor is used in adjusting the potential intake of feed (equation 6).

$$MP_{\max} = \begin{cases} C_{L0,Y} SRW^{0.75} Z BC_{part} LB M_m^{C_{L3}} \exp(C_{L3}(1-M_m)) & \text{suckling young} \\ C_{L5} C_{L6} WM_{peak} BC_{part} LB M_m^{C_{L4}} \exp(C_{L4}(1-M_m)) & \text{otherwise} \end{cases} \quad (66)$$

where

$$M_m = (A_y + C_{L1}) / C_{L2} \quad (67)$$

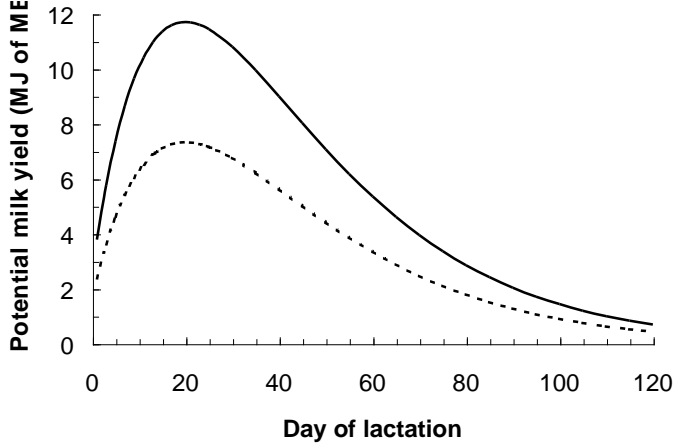


Fig. 10. Potential milk production by a mature Merino ewe with a standard reference weight of 50 kg and in average condition, expressed as the metabolizable energy value of the milk for the lambs: upper line, twin lambs; lower line, single lamb.

Milk production may fall below the potential either because the intake of ME is insufficient to sustain the potential (protein restriction will be considered later) or because production is limited by the young's ability to consume milk. For any amount of ME available, ME_{xs} (equations 68 and 69), as a proportion of MP_{\max} , equation 68 computes the level of milk production, MP_1 , which can be sustained. This logistic function reproduces a diminishing response to energy inputs at high levels of production (Jensen *et al.* 1942) while recognising that a relatively high level of milk production may be maintained even in severely underfed animals, typically beef cows, in early lactation (Fig. 11). The degree to which this is achieved is determined by the animal's current relative condition (Robinson *et al.*, 1999) We have followed the assumption of Hulme *et al.* (1986) that intake limitations will restrict milk production to not more than 85% (i.e. $100/C_{L7}$) of the asymptotic value of the function (equation 68).

$$MP_1 = \frac{C_{L7} MP_{\max}}{1.0 + \exp(-(-C_{L19} + C_{L20} MR + C_{L21} AD(MR - C_{L22} AD) - C_{L23} BC(MR - C_{L24} BC)))} \quad (68)$$

where

$$MR = ME_{xs} / MP_{\max} \quad (69)$$

$$ME_{xs} = (MEI_{total} - ME_m - ME_c) C_{L5} k_l \quad (69a)$$

$$AD = \max(A_y, MR / (2C_{L22})) \quad (70)$$

Where the mother is suckling young, the maximum consumption of milk by each of the offspring is predicted as a function of live weight and age (equation 71) from the results of Graham *et al.* (1976) and Dove (1988). With this ceiling included, MP_2 represents

the actual yield of milk (as ME for the young), unless later calculations show a deficiency of DPLS.

TABLE 7
Parameters used for prediction of lactation requirements: equations 66-77

Parameter	Description	Units	Sheep	Cattle
$C_{L0,Y}$	Peak yield scalar if suckling	MJ kg ^{-3/4}	1: 0.486 ¹ 2: 0.778 ¹ 3: 0.934 ¹	0.375 ²
	Lactation curve:			
C_{L1}	Offset	d	2	4
C_{L2}	Peak time	d	22	30
C_{L3}	Shape, with young	-	1.0	0.60
C_{L4}	Shape, not suckling	-	-	0.60 ³
C_{L5}	Milk: metabolizability	0-1	0.94	0.94
C_{L6}	energy content	MJ kg ⁻¹	4.7	3.1
C_{L7}	Energy deficit	-	1.17	1.17
C_{L8}			-	-
C_{L9}			-	-
C_{L10}			-	-
C_{L11}			-	-
C_{L12}	Milk consumption limit	kg kg ^{-3/4}	0.30	0.42
C_{L13}	"	kg kg ^{-3/4}	0.41	0.58
C_{L14}	"	d	0.071	0.036
C_{L15}	Protein content of milk	kg kg ⁻¹	0.045	0.032
C_{L16}	Adjustment of potential	-	0.7	0.7
C_{L17}	"	-	0.01	0.01
C_{L18}	"	-	0.1	0.1
C_{L19}	Energy deficit factors	-	1.6	1.6
C_{L20}			4.0	4.0
C_{L21}			0.008	0.004 ⁴
C_{L22}			0.012	0.006 ⁵
C_{L23}			3.0	3.0
C_{L24}			0.6	0.6

¹ In Merino types, $C_{L0,1} = 0.389$ and $C_{L0,2} = 0.746$

² In dairy type breeds, $C_{L0,1} = 0.50$

³ In dairy types, $C_{L4} = 0.105$

⁴ In dairy types, $C_{L21} = 0.0027$

⁵ In dairy types, $C_{L22} = 0.004$

$$MP_2 = \begin{cases} \min\left(MP_1, Y C_{L6} W_y^{0.75} \left(C_{L12} + C_{L13} \exp(-C_{L14} A_y)\right)\right) & \text{suckling young} \\ MP_1 & \text{otherwise} \end{cases} \quad (71)$$

$$LB \leftarrow \begin{cases} LB - C_{L17} (LR - DR) & A_y > C_{L16} C_{L2} \\ 1.0 & \text{otherwise} \end{cases} \quad (72)$$

$$\text{where } LR \leftarrow C_{L18} DR + (1 - C_{L18}) LR \quad (73)$$

$$DR = MP_2 / MP_{max} \quad (74)$$

The gross energy (GE) of the milk is obtained by dividing MP_2 by C_{L5} . GE is divided by k_l to calculate the ME used for lactation (equation 75) or by C_{L6} to calculate the weight of milk (expressed as 7% fat for ewes and 4% for cows). Protein requirements (equation 76) are calculated according to ARC (1990).

$$ME_l = \frac{MP_2}{C_{L5}k_l} \quad (75)$$

$$P_l = C_{L15} \frac{MP_2}{C_{L6}} \quad (76)$$

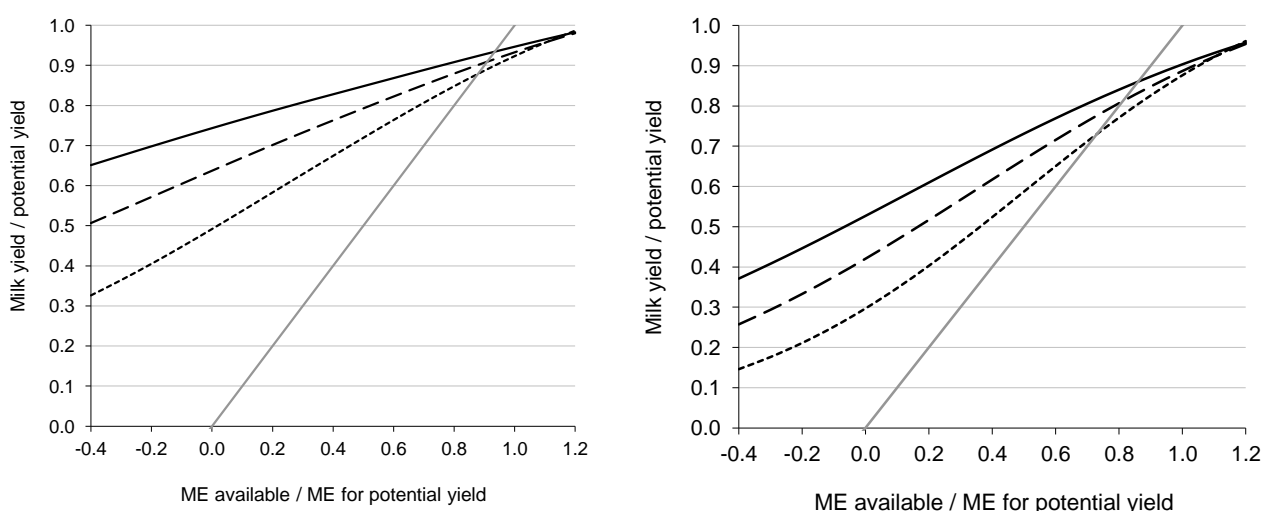


Fig. 11. Predicted milk yield as a proportion of potential yield, in relation to the available ME (after deductions for maintenance and pregnancy) on day 15 of lactation (on the left) and on day 90 (on the right) for ewes with relative condition (from top down) of 1.1, 1.0 and 0.9, compared with the 1:1 relationship (grey line).

Requirements for wool growth

Daily wool growth is estimated as a 25-day running mean (equation 77) to allow for the lag effect analysed by Nagorcka (1977). The daily increment to this function (equation 78) is predicted either from the DPLS available for wool production (equation 79), adapted from Hogan *et al.* (1979), or from the ME available for wool production (equation 80) if the ratio of $DPLS_w$ (g): ME_w (MJ) exceeds 12.0 (Kempton, 1979) (Fig. 12). The efficiency of conversion to wool is scaled for the specified fleece weight, SFW , as a proportion of mature weight of sheep, its age, AF based on the maturation of secondary follicles (Lyne, 1961) and daylength, DLF , an effect which is specific to the breed (Nagorcka, 1979). Greasy fleece weight is incremented daily after adjusting wool growth for percentage yield. The energy cost of daily wool growth is calculated (equation 81) after allowing for the basal rate of wool growth that is included in the standard function for basal metabolism.

$$P_w \leftarrow (1 - C_{W4})P_w + C_{W4} P_w^* \quad (77)$$

where

$$P_w^* = \min\left(C_{W7} \frac{SFW}{SRW} AF DLF DPLS_w, C_{W8} \frac{SFW}{SRW} AF DLF ME_w\right) \quad (78)$$

$$AF = C_{W5} + (1 - C_{W5})(1 - \exp(-C_{W12}A)) \quad (78a)$$

$$DLF = 1 + C_{W6}(DL - 12) \quad (78b)$$

$$DPLS_w = \max(0, DPLS - C_{W9}(P_c + P_l)) \quad (79)$$

$$ME_w = \max(0, MEI_{total} - (ME_c + ME_l)) \quad (80)$$

$$NE_w = C_{W1} \left(P_w - C_{W2}Z \right) / C_{W3} \quad (81)$$

TABLE 8

Parameters used for prediction of wool growth requirements: equations 77-87

Parameter	Description	Units	Sheep
C_{W1}	Energy content of clean wool	MJ kg ⁻¹	24.0
C_{W2}	Basal clean wool growth	kg	0.004
C_{W3}	Clean:greasy ratio	0-1	0.7
C_{W4}	Lag factor	0-1	0.04
C_{W5}	Wool growth: proportion at birth	d ⁻¹	0.25
C_{W6}	photoperiod	h ⁻¹	1
C_{W7}	DPLS limitation	kg kg ⁻¹	1.35
C_{W8}	MEI limitation	kg MJ ⁻¹	0.016
C_{W9}	Pregnancy and lactation adjustment	0-1	1.0
C_{W10}	Wool density	kg m ⁻³	1.35x10 ³
C_{W11}	Follicle density	m ⁻²	6x10 ⁷
C_{W12}	Age factor exponent		0.025
C_{W13}	Length/diameter exponent		0.18

¹. Values for C_{W6} are: Merinos 0.03; Southdown, Ryeland 0.09; Corriedale, Romney 0.06; Dorset, Suffolk, Border Leicester 0.11; Border Leicester x Merino 0.07.

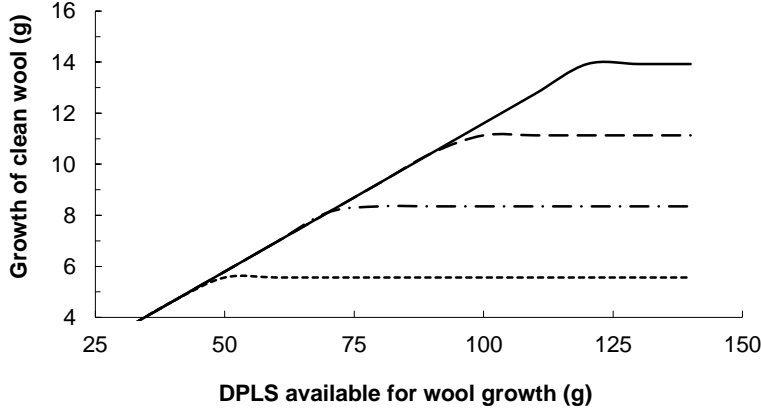


Fig. 12. Predicted growth of clean wool from a mature Merino ewe with a standard reference weight of 50 kg and a standard fleece weight of 5 kg, in relation to DPLS available for wool production, at four levels of ME available for wool production: from the top, 10, 8, 6 and 4 MJ/d

The diameter of the day's new growth, μ_δ , is estimated (equation 82) as a proportion of the mean diameter specified for the animal type, with the assumption that the ratio of the length, δF , of new wool to its diameter, increases slightly with growth rate (Reis *et al.* 1990) and that the exponent C_{W13} therefore has a value lower than $\frac{1}{3}$. Mean diameter of the whole fibre is adjusted (equation 84) and fibre length is incremented (equation 87).

$$\mu_\delta = \mu_{\text{mean}} \left(\frac{P_w}{\delta CFW_{\text{mean}}} \right)^{C_{W13}} \quad (82)$$

$$\text{where } \delta CFW_{\text{mean}} = C_{W3} SFW AF / 365 \quad (83)$$

$$\mu \leftarrow \frac{F \mu + \delta F \mu_\delta}{F + \delta F} \quad (84)$$

$$\text{where } \delta F = 100 \frac{4P_w}{\pi C_{W10} C_{W11} SA (10^{-6} \mu_\delta)^2} \quad (85)$$

$$SA = C_{C1} W^{2/3} \quad (86)$$

$$F \leftarrow F + \delta F \quad (87)$$

Energy cost of chilling

The energy retention that would be expected after the above deductions from MEI may be reduced if additional heat production results from chilling caused by cold wind or rain, i.e. if the lower critical temperature of the animal is above ambient temperature for any part of the day. The functions listed here have been recast from the results of Alexander (1974), Blaxter (1977) and Mount and Brown (1982). The effects of chilling are calculated for each 2-hour period of the day, using sinusoidally-varying temperature and windspeed functions (equations 88 and 89) and the contributions of each period to ME_{cold} are summed.

$$T_{a,h} = T_{mean} + \frac{T_{max} - T_{min}}{2} \sin\left(\frac{2\pi}{12}(h-3)\right) \quad (88)$$

$$v_h = v_{mean} \left(1 + 0.35 \sin\left(\frac{2\pi}{12}(h-3)\right)\right) \quad (89)$$

$$\phi_{clear} = 0.7 \exp(-0.25R) \quad (90)$$

The total insulation of the animal is provided by tissue insulation (equation 91) which is dependent on body condition, and by external insulation (equation 92) that is associated with the coat and the boundary layer of air. Both components are affected by windspeed, the radius of the animal and its coat depth (equations 93 to 95) and by the degree to which the coat is wet (equation 96).

$$IN_{tiss} = C_{C3} (C_{C4} + (1 - C_{C4}) BC) \quad (91)$$

$$IN_{ext,h} = WF (IN_{air,h} + IN_{coat,h}) \quad (92)$$

where

$$IN_{air,h} = \frac{r}{r+F} \frac{1}{C_{C7} + C_{C8} \sqrt{v_h}} \quad (93)$$

$$IN_{coat,h} = r \ln\left(\frac{r+F}{r}\right) (C_{C9} - C_{C10} \sqrt{v_h}) \quad (94)$$

$$r = C_{C2} W^{1/3} \quad (95)$$

$$WF = C_{C5} + (1 - C_{C5}) \exp\left(\frac{-C_{C6} R}{F}\right) \quad (96)$$

TABLE 9

Parameters used for prediction of the energy cost of chilling: equations 88-100

Parameter	Description	Units	Sheep	Cattle
C_{C1}	Surface area	$m^2 \text{ kg}^{-2/3}$	0.09	0.09
C_{C2}	Body radius	$\text{cm kg}^{-1/3}$	4.10	4.10
C_{C3}	Tissue insulation	$^\circ\text{C m}^2 \text{ d MJ}^{-1} \text{ cm}^{-1}$	1.3 ¹	1.6 ¹
C_{C4}	: body condition	-	0.5	0.5
C_{C5}	External insulation: wetting	0-1	0.7	0.7
C_{C6}	"	cm mm^{-1}	0.15	0.15
C_{C7}	air component		0.481	0.481
C_{C8}	"		0.619	0.619
C_{C9}	coat component	$^\circ\text{C m}^2 \text{ d MJ}^{-1} \text{ cm}^{-1}$	1.41	1.1
C_{C10}	"		0.322	0.322
C_{C11}	Body temperature	$^\circ\text{C}$	39	39
C_{C12}	Evaporative loss	$\text{MJ m}^{-2} \text{ d}^{-1}$	1.3	1.5
C_{C13}	Radiative effect on T_{lc}	$^\circ\text{C}$	5.0	5.0
C_{C14}	"	$^\circ\text{C}^{-2}$	0.15	0.15
C_{C15}	"	$^\circ\text{C}$	10.0	10.0
C_{C16}	Metabolic heat from conceptus	MJ kg^{-1}	0.38	0.38

¹ Up to the age of 1 month, $C_{C3} = C_{C3} * \text{MIN}(1.0, 0.4 * 0.02A)$

The lower critical temperature is calculated for each 2-hour period, h , (equation 97) in relation to insulation and the metabolic heat production per unit of surface area of the animal (equation 98), using k_g to estimate a provisional value of NE_g . During the night-time periods, the value of $T_{lc,h}$ is increased by up to 5°C for heat loss resulting from clear night skies. The adjustment, SKY , (equation 99) is predicted from night temperature and an estimate of the proportion of clear sky. Surface area, SA (m²), is estimated from equation 87.

$$T_{lc,h} = C_{C11} - HP IN_{tiss} + (C_{C12} - HP) IN_{ext,h} + SKY_h \quad (97)$$

where

$$HP = (MEI_{total} - NE_c - NE_l - NE_g + C_{C16} W_c) / SA \quad (98)$$

$$SKY_h = \begin{cases} \phi_{clear} C_{C13} \exp(-C_{C14} (\min(C_{C15} - T_{a,h}, 0.0))^2) & h = 7 \dots 11 \\ 0 & h = 1 \dots 6, 12 \end{cases} \quad (99)$$

If the atmospheric temperature is lower than the lower critical temperature in at least one 2-hour period, then the value of ME_{cold} (equation 100) is added to ME_m before the estimation of liveweight gain.

$$ME_{cold} = SA \frac{1}{12} \sum_{h=1}^{12} \frac{DIM(T_{lc,h}, T_{a,h})}{IN_{tiss} + IN_{ext,h}} \quad (100)$$

Weight change and protein balance

The first step is to compute the provisional net energy and protein available for weight change (equations 101 and 102). Efficiency of use of DPLS depends upon whether it was derived from milk or solid sources (equation 103).

$$NE_{g,1} = k_g (MEI_{total} - (ME_m + ME_c + ME_l)) - NE_w \quad (101)$$

$$P_{g,1} = k_{DPLS} \left(DPLS - \frac{P_m + P_c + P_l}{k_{DPLS}} - \frac{P_w}{C_{G1}} \right) \quad (102)$$

where

$$k_{DPLS} = \frac{C_{G2}}{1 + \left(\frac{C_{G2}}{C_{G3}} - 1 \right) \frac{DPLS_{milk}}{DPLS}} \quad (103)$$

The functions for the prediction of the energy (MJ/kg) and protein (kg/kg) in empty body weight change in growing animals (equations 104 and 105 and Figs 13 and 14) as used in SCA (1990), were developed with the aim of relating compositional changes to relative size rather than to weight. As SRW , and hence Z at any given W , varies with sex, no specific allowance is made for differences between females, castrates and entire males. The starting point was the analysis by Searle and Griffiths (1976) and the present functions (described by Corbett *et al.*, 1987) incorporate a wide range of data, including McClelland *et al.* (1976), Robelin and Daenicke (1980), Trigg and Topps (1981) and Geay (1984).

In mature animals, the composition of weight change depends on body condition (Wright and Russel 1984). Equations 104 and 105 generalize the SCA equation to allow for both growing and mature animals. The size-related factor ZF_1 decreases steadily as an animal matures; the factor ZF_2 is zero until near maturity and then increases to one.

The parameters C_{G8} , C_{G9} , C_{G12} and C_{G13} are altered for cattle of the Charolais type and *B. indicus* cattle to account for the lower fat and higher protein content of their weight gain, even at maturity. Intermediate values are used for crosses with British type cattle.

$$EVG = C_{G8} - ZF_1 \cdot (C_{G9} - C_{G10}(L-1)) + ZF_2 \cdot C_{G11}(BC-1) \quad (104)$$

$$PCG = C_{G12} + ZF_1 \cdot (C_{G13} - C_{G14}(L-1)) + ZF_2 \cdot C_{G15}(BC-1) \quad (105)$$

where

$$ZF_1 = \frac{1}{1 + \exp(-C_{G4}(Z' - C_{G5}))} \quad (106)$$

$$ZF_2 = \max\left(0, \min\left(\frac{Z' - C_{G6}}{C_{G7} - C_{G6}}, 1\right)\right) \quad (107)$$

and the relative size for weight gain purposes, Z' , is given by

$$Z' = \min\left(1.0 - \left(1.0 - \frac{W_{birth}}{SRW}\right) \cdot \exp\left(-\frac{C_{N1}}{SRW^{C_{N2}}} \cdot A\right), \frac{W_{max}}{SRW}\right) \quad (108)$$

The next step is to determine whether the available protein will support the weight change that would be predicted from the provisional NE_g . The surplus or shortage of protein, $P_{net,1}$, is calculated by equation 109. In lactating animals, some part of any deficiency in protein is relieved by reducing milk production (equation 110), thereby allowing a reallocation of net energy and protein for weight gain (equations 111 to 113). Equations 75 and 76 are then re-computed and, if protein is still limiting, NE_g is reduced (equation 111). Empty body gain, EBG , and the final protein requirement for gain, P_g , are then calculated and live weight incremented (equation 117).

$$P_{net,1} = P_{g,1} - PCG \frac{NE_{g,1}}{EVG} \quad (109)$$

$$MP = \left(1 + \min(0, P_{net,1}/P_l)\right) MP_2 \quad (110)$$

$$NE_{g,2} = NE_{g,1} + C_{L5}(MP_2 - MP) \quad (111)$$

$$P_{g,2} = P_{g,1} + (MP_2 - MP) \frac{C_{L15}}{C_{L6}} \quad (112)$$

$$P_{net,2} = P_{g,2} - PCG \frac{NE_{g,2}}{EVG} \quad (113)$$

$$NE_g = NE_{g,2} + C_{G12}EVG \frac{\min(0, P_{net,2})}{PCG} \quad (114)$$

$$EBG = \frac{NE_g}{EVG} \quad (115)$$

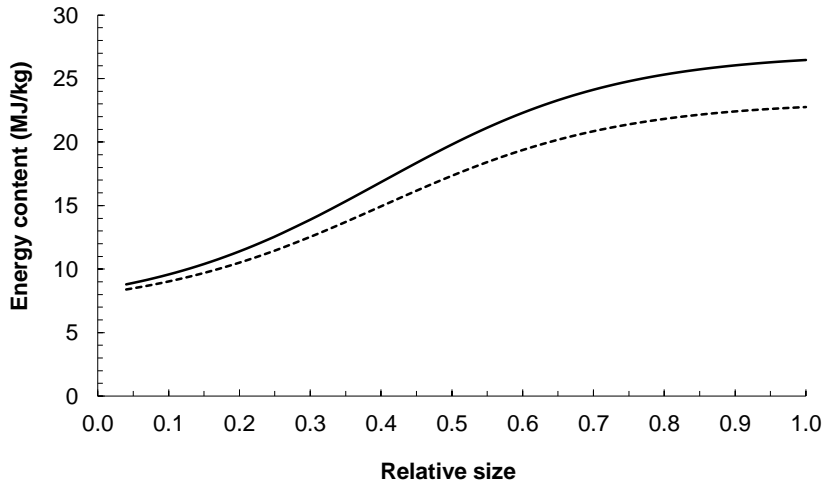


Fig.13. Energy content of empty weight gain at a feeding level of twice maintenance, in relation to the relative size of the animal: upper line, sheep and standard cattle; lower line, lean cattle types.

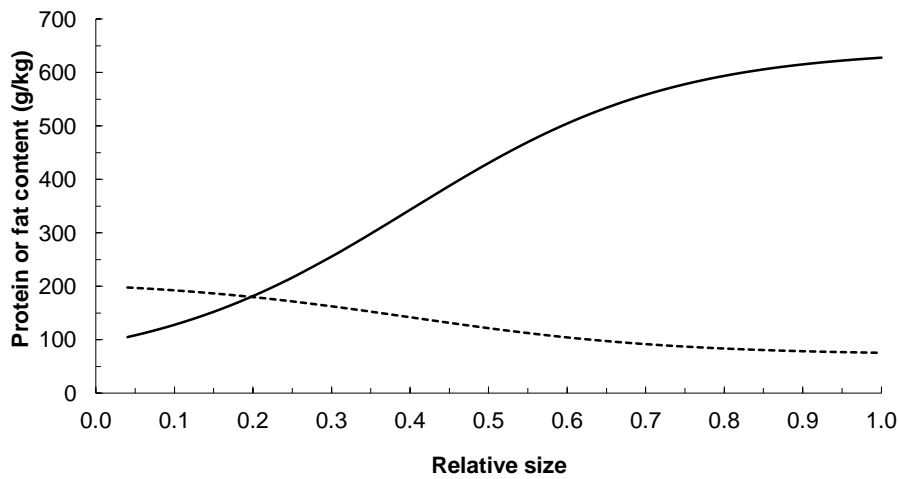


Fig. 14. Protein and fat content of empty weight gain in sheep or standard cattle types, at a feeding level of twice maintenance, in relation to the relative size of the animal: solid line, fat; dotted line, protein.

$$P_g = \min(P_{g,2}, PCG EBG) \quad (116)$$

$$W \leftarrow W + C_{G13} EBG \quad (117)$$

Finally, to compute the nitrogen mass balance the total faecal and urinary protein are computed, equations 118 and 119. Methane production, MT (MJ), is predicted (equation 120) after Blaxter and Clapperton (1965).

$$TFP = (1 - D_{udp})UDPI_{solid} + C_{A7}C_{A8}MCP + (1 - C_{A5})CPI_{milk} + EFP \quad (118)$$

$$TUP = CPI_{total} - (P_c + P_l + P_w + P_g) - TFP - DP \quad (119)$$

$$MT = C_{H1}(I_f + I_s)((C_{H2} + C_{H3}M/D_{solid}) + (L+1)(C_{H4} - C_{H5}M/D_{solid})) \quad (120)$$

TABLE 10

Parameters used for prediction of weight change and methane production: equations 102-120

Parameter	Description	Units	Sheep and cattle
	DPLS: efficiency of use		
C_{G1}	for wool (sheep only)	0-1	0.6
C_{G2}	for other purposes (from solid diet)	0-1	0.7
C_{G3}	" " " (from milk diet)	0-1	0.8
C_{G4}	EVG & PCG: effect of relative size on ZF_1	-	6.0
C_{G5}	EVG & PCG: relative size at which $ZF_1=0.5$	0-1	0.4
C_{G6}	EVG & PCG: relative size below which $ZF_2 = 0.0$	0-1	0.90
C_{G7}	EVG & PCG: relative size below which $ZF_2 = 1.0$	0-1	0.97
C_{G8}	EVG: reference value	MJ kg ⁻¹	27.0 ¹
C_{G9}	EVG: range with maturity at $L=1$ and $BC=1$	MJ kg ⁻¹	20.3 ¹
C_{G10}	EVG: effect of feeding level	MJ kg ⁻¹	2.0
C_{G11}	EVG: effect of body condition in near-mature animals	MJ kg ⁻¹	13.8
C_{G12}	PCG: reference value	kg kg ⁻¹	0.072 ¹
C_{G13}	PCG: range with maturity at $L=1$ and $BC=1$	kg kg ⁻¹	0.140 ¹
C_{G14}	PCG: effect of feeding level	kg kg ⁻¹	0.008
C_{G15}	PCG: effect of body condition in near-mature animals	kg kg ⁻¹	0.115
C_{G18}	Base weight:empty body weight		1.09
C_{H1}	Methane production	MJ kg ⁻¹	0.0184
C_{H2}	"	-	13.0
C_{H3}	"	kg MJ ⁻¹	7.52
C_{H4}	"	-	23.7
C_{H5}	"	kg MJ ⁻¹	3.36

¹ For *B. indicus* and Charolais type cattle, $C_{G8} = 23.2$, $C_{G9} = 16.5$, $C_{G12} = 0.092$ and $C_{G13} = 0.120$.

PREDICTION OF BIRTHS AND DEATHS

Conception and death rates are not required for the GrazFeed DST and are set by the user in the GrassGro DST, but are predicted in the AusFarm DST using the following logic.

Conception rates

The conception submodel is applied to eligible, empty females at the mid-point of each estrus cycle. Conception rates are modelled as a function of time of year and latitude (in the case of sheep) and of the relative size and body condition of the animals. In the present context, a predicted conception rate includes only those embryos that survive to the third trimester. The main equation (122) gives the probability of an animal conceiving at least a given number of young; the probabilities of conceiving specific numbers of young are then obtained by subtraction. The starting point for this equation was the sheep fertility model of

F.H.W.Morley (pers.comm.), developed further in White *et al.* (1983). In the present formulation, the model has been simplified to produce a general function applicable to sheep or cattle, using the relationships for cattle analysed by Morley *et al.* (1976). The parameter values for Merino and Border Leicester x Merino sheep (Table 11) result from analyses of published data from southern Australia amounting to a total of more than 14,000 ewe-years (Moore *et al.* 1995). Predicted lambing percentages for Merino ewes are shown in Fig. 15; predicted probability of conception in cows is shown in Fig.16.

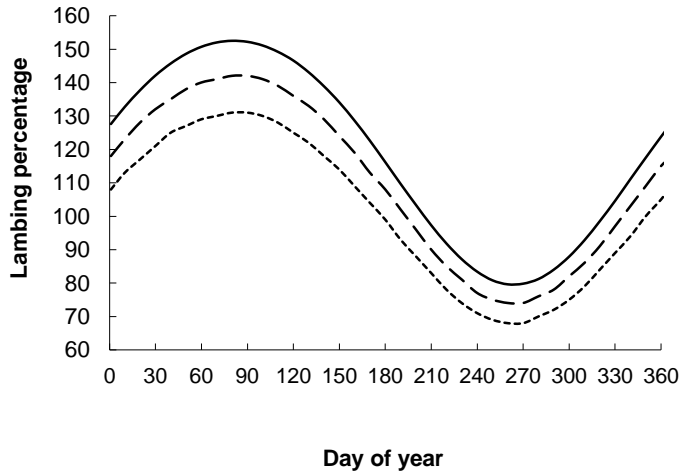


Fig. 15. Number of lambs reaching the third trimester of gestation per 100 mature Merino ewes mated, in relation to the date of the start of joining and the relative condition of the ewes at that time (assuming that the period of joining lasted for two estrus cycles): the three lines, from the top, represent relative conditions of 1.1, 1.0 and 0.9, respectively.

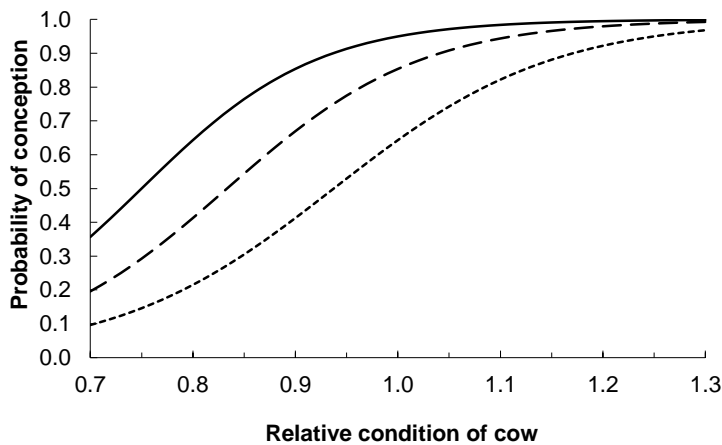


Fig. 16. Probability of conception in cows (*Bos taurus*), in relation to their relative size and relative condition: the three lines, from the top, represent relative sizes of 1.0, 0.9 and 0.8, respectively.

$$CR_{\geq n} = \left(1 - C_{F1,n} \left(1 - \sin \left(\frac{2\pi}{365} (DOY + 10) \right) \right) \frac{\sin \lambda}{-0.57} \right) SIG(ZBC, C_{F2,n}, C_{F3,n}) \quad (122)$$

with λ entered in radians and negative in S. Hemisphere

$$CR_n = CR_{\geq n} - CR_{\geq n+1} \quad (123)$$

where

$$SIG(x, a, b) = \frac{1}{1 + \exp \left(-\frac{5.891(x-a)}{b} \right)} \quad (124)$$

Mortality

The proportion of animals that die on each day is predicted (equation 125) from a basal rate, C_{D1} . There is an additional, condition-dependent component if body condition, and daily weight gain in the case of growing animals, are below nominated thresholds. It is also assumed that there is a greater risk of death in weaners under these conditions. The mean base weight of the surviving animals is increased, on the assumption that the animals that died were 10% lighter (C_{D12}) than the mean of the group.

$$MR = \begin{cases} C_{D1} + (C_{D13} - C_{D1}) RAMP(A, C_{D15}, C_{D14}) + C_{D2} \max(0, C_{D3} - BC) & C_{G13} EBG < 0.2 \frac{dN}{dA} \\ C_{D1} & \text{otherwise} \end{cases} \quad (125)$$

$$\text{where } RAMP(x, a, b) = \begin{cases} 1.0 & x < b \\ (x-b)/(a-b) & b < x \leq a \\ 0.0 & x > a \end{cases}$$

During late pregnancy and around parturition, ewes or lambs, or both, may die from pregnancy toxaemia, dystocia or exposure. The proportion of twin-bearing ewes (with their lambs) that die in the last 6 weeks of gestation is predicted (equation 126) from the loss of maternal weight over this period, in a sigmoid relationship, with 5% and 95% losses set by nominated parameters. The prediction of the proportion of lambs lost from dystocia (equation 127) is a similar function, depending on foetal weight at term in relation to expected birth weight and greater than average condition of the mother.

$$TR = SIG \left(\frac{W_p - W}{N}, C_{D4}, C_{D5} \right) \quad (126)$$

$$DR = SIG \left(\frac{W_{foetus}}{BW} \max(BC, 1), C_{D6}, C_{D7} \right) \quad (127)$$

The proportion of young that die soon after birth from exposure (equation 128) is predicted from the logistic function of Donnelly (1984) (equation 129). This uses the chill index of Nixon-Smith (1972) (equation 130) which predicts potential heat loss ($\text{kJ m}^{-2}\text{h}^{-1}$) as a function of mean daily wind velocity, v (m s^{-1}), mean daily temperature, T_{mean} ($^{\circ}\text{C}$), and total daily rainfall, R (mm). For twins, XO is incremented by CD_{11} . Predictions from equation 128 are discussed more fully in the description of the LambAlive DST (Donnelly *et al.*, 1997)

$$XR = \frac{\exp(XO)}{1 + \exp(XO)} \quad (128)$$

where

$$XO = C_{D8} - C_{D9}BC + C_{D10}CH + C_{D11}Y \quad (129)$$

$$CH = 481 + (11.7 + 3.1v^{1/2})(40 - T_{mean}) + 418(1 - \exp(-0.04R)) \quad (130)$$

TABLE 11
Parameters used for prediction of conception and death rates: equations 121-129

Parameter	Description	Units	Sheep	Cattle
$C_{F1,Y}$	Time of year: 1 young		0.23 ¹	0.0
	2 young	-	0.39	-
	3 young		0.39	
$C_{F2,Y}$	Size and condition: 5% conception: 1 young	-	0.64	0.5
	2 young		1.315	-
	3 young		5	
$C_{F3,Y}$	95% conception: 1 young	-	2.34	1.0
	2 young		2.69	-
	3 young		2.69	
C_{F4}	Length of estrus cycle	d	17	21
C_{D1}	Mortality: basal rate	0-1	5.53x10 ⁻⁵	5.53x10 ⁻⁵
C_{D2}	body condition		0.30	0.30
C_{D3}	"		0.60	0.60
C_{D4}	Pregnancy toxaemia: 5% loss		0.2	0
C_{D5}	95% loss		29.44	0
C_{D6}	Dystocia: condition for 5% loss		1.4	0
C_{D7}	condition for 95% loss		9.815	0
C_{D8}	Exposure: basal		-9.95 ²	-40
C_{D9}	body condition		1.71	0
C_{D10}	chilling		0.0098	0
C_{D11}	effect of multiple lambs		1.1	
C_{D12}	Relative difference in weight of dying animals		0.1	0.1
C_{D13}	Upper limit for mortality in weaners	0-1	³	³
C_{D14}	Lower age for reduction of mortality in weaners	d	300	300
C_{D15}	Upper age for reduction of mortality in weaners	d	365	365

¹ These conception parameters are for Merino ewes; for Crossbred ewes the values are 0.34, 0.64, 0.64, 0.75, 0.94, 5, 5.12, 7.1 and 7.1, respectively.

² These exposure parameters are for Merino sheep; for Crossbred sheep the values are -8.90, 1.49, 0.0081, 0.0 and 0.82, respectively.

³ The value for the upper limit for mortality of weaners is provided by the user.

THE GRAZFEED APPLICATION OF THE ANIMAL BIOLOGY MODEL

GrazFeed is a program designed to run on personal computers. The user interface (Fig. 17) follows the other DST in the GRAZPLAN project (Donnelly *et al.*, 1997), being based on menus and dialogue boxes.

As the main purpose of GrazFeed is to help the user to assess a specific pasture for a specified class of animals at one point in time, many of the values required to drive the

functions in the animal biology model must be supplied by the user rather than being generated on a daily basis as they are in the GrassGro and AusFarm DST. This applies particularly to the description of the pasture but also to some attributes of the animals that depend on their weight, condition etc. at an earlier date. In addition, the GrazFeed program offers special options for the user, providing estimates of the amount of supplementary feed required for a desired level of production and comments on the main factors limiting production in the specified situation. To operate GrazFeed, the user proceeds through the main menu, supplying the appropriate information under each heading: Pasture 1, Pasture 2, Weather, Supplement, Breed, Animals, Females and Feeding.

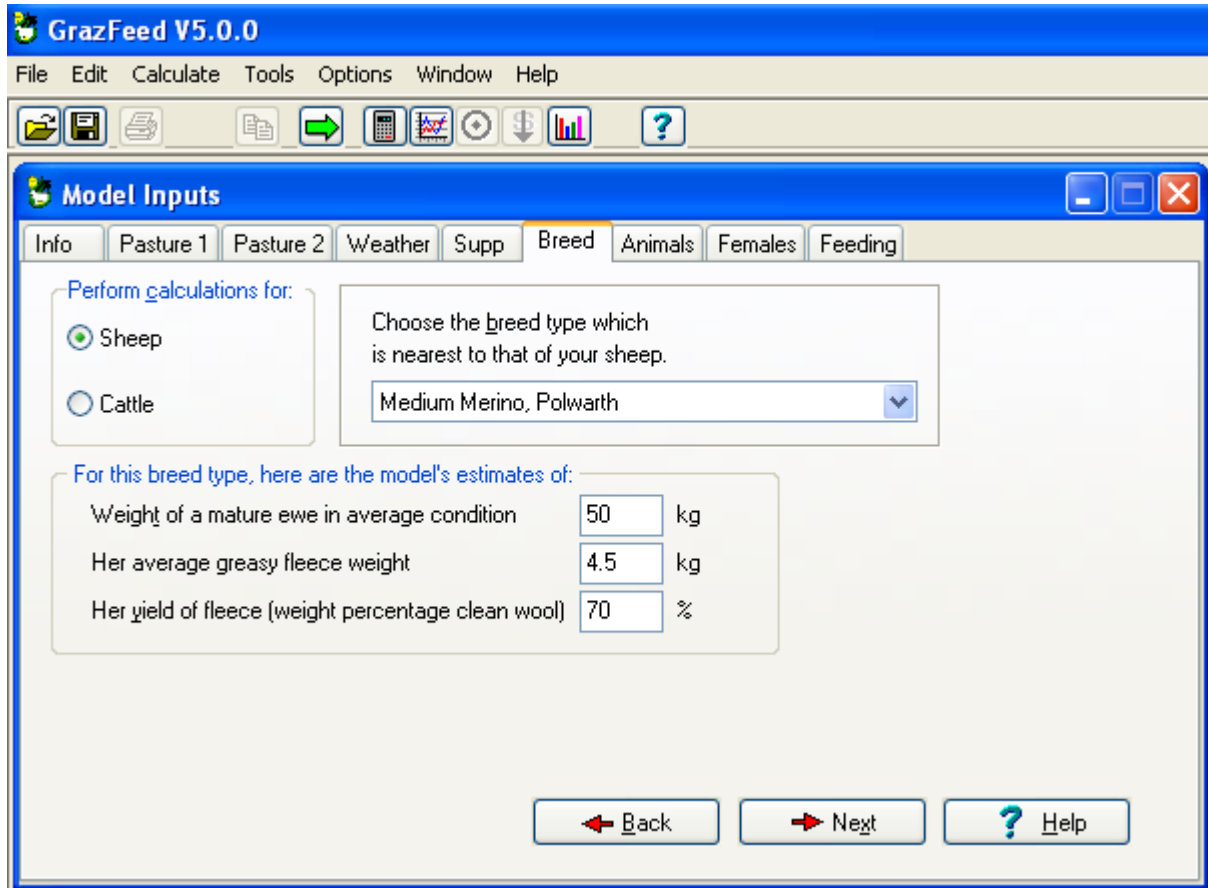


Fig. 17. Screen interface for GrazFeed DST

Pasture 1 & Pasture 2

On the Pasture 1 screen, the user is required to provide a simple quantitative description of the pasture: weights of green and dead material, B_{green} and B_{dead} (t DM ha⁻¹), mean digestibilities of green and dead, DMD_{green} and DMD_{dead} , and the proportion of legumes in the pasture, ϕ_{legume} . From the nominated mean digestibilities, the program then computes, and displays on the Pasture 2 screen, a default distribution of B_{green} between herbage classes (d) 1-4 (as defined earlier), and B_{dead} between classes 2-6 (equation 131 and Figs 18 and 19) according to the proportions, $\phi_{green,d}$ and $\phi_{dead,d}$.

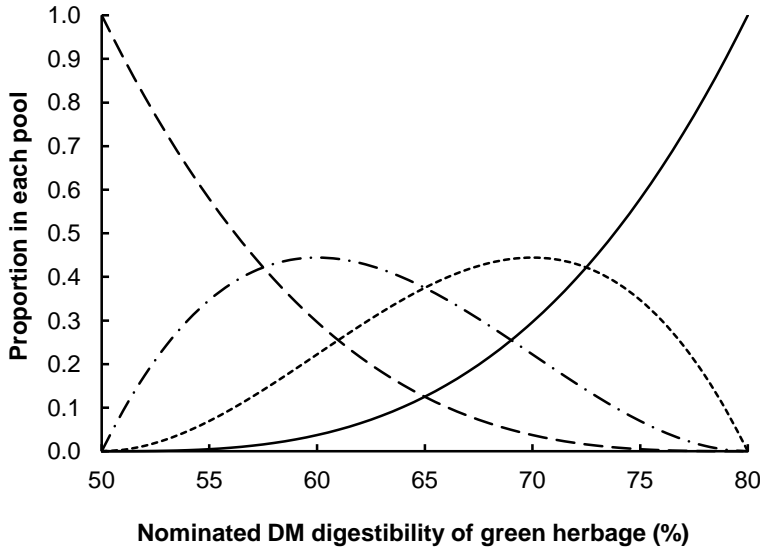
$$B_{herb,d} = \phi_{green,d} B_{green} + \phi_{dead,d} B_{dead} \quad (131)$$

The proportions $\phi_{green,d}$ and $\phi_{dead,d}$ are given by the following functions:

	$d = 1$	2	3	4	5	6
$\phi_{green,d}$	x^3	$3x^2(1-x)$	$3x(1-x)^2$	$(1-x)^3$	0	0
$\phi_{dead,d}$	0	y^4	$4y^3(1-y)$	$6y^2(1-y)^2$	$4y(1-y)^3$	$(1-y)^4$

where

$$x = \frac{DMD_{green} - 0.5}{0.8 - 0.5} \quad (132)$$



$$y = \frac{DMD_{dead} - 0.3}{0.7 - 0.3} \quad (133)$$

Fig.18. The proportion of green herbage allocated to each of the four digestibility pools, in relation to the nominated mean dry matter digestibility (DMD) of the herbage: solid line, pool 1, DMD = 0.8; short dashes, pool 2, DMD = 0.7; dashes and dots, pool 3, DMD = 0.6; long dashes, pool 4, DMD = 0.5.

If the user has selected tropical rather than temperate as the predominant type of grass, the functions in equation 128 are modified to span only 3 herbage pools for both green and dead herbage. However, the user is warned that there is wide variation between tropical grass species in the likely distribution and the default values should not be accepted uncritically.

The array of herbage weights by class is presented to the user so that it can be adjusted if better information is available. The estimated protein content of material in each class is presented similarly, after adjustment for ϕ_{legume} . If the user inserts zero values for green and dead herbage, the animals are treated as being housed or yard-fed, with no additional energy requirements for grazing.

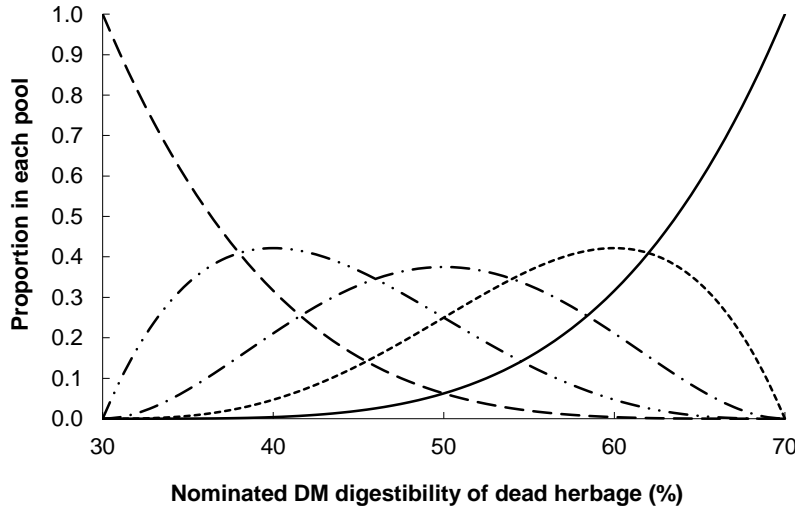


Fig.19. The proportion of dead herbage allocated to each of the five digestibility pools, in relation to the nominated mean dry matter digestibility (DMD) of the herbage: solid line, pool 2, DMD = 0.7; short dashes, pool 3, DMD = 0.6; double dashes and dots, pool 4, DMD = 0.5; dashes and dots, pool 5, DMD = 0.4; long dashes, pool 6, DMD = 0.3.

The program also estimates the mean heights of the green and dead fractions, on the assumption that complete cover by one fraction represents $3 \text{ cm (tonne DM ha}^{-1}\text{)}^{-1}$. The probable non-linearity of the height:weight relationship as height increases is ignored, as heights above about 9 cm have little effect on the prediction of intake. Where green and dead fractions are both present, the height of a fraction per unit weight will increase as the proportion of that fraction decreases. The default values are calculated on the assumption that the proportion of the ground covered by a fraction is the same as its proportion by weight (equations 134 and 135). If the specified pasture includes a significant proportion of bare ground or is exceptionally dense, the mean heights of the pasture fractions, as assessed by the user, will be greater or less, respectively, than these estimates and default values should be adjusted. From the adjusted values, the program estimates a herbage height for each class, depending on the proportions of green and dead in each class. The ratio of this height to the implied default value for the class is used in equation 16 as HR_d . The user also provides information in Pasture 1 on the type of grass in the pasture (see equation 19), the average steepness of the land, the month of the year and the latitude.

$$Height_{green} = 3 \cdot 10^{-3} \frac{(B_{green} + B_{dead})^2}{B_{green}^2 + B_{dead}^2} B_{green} \quad (134)$$

$$Height_{dead} = 3 \cdot 10^{-3} \frac{(B_{green} + B_{dead})^2}{B_{green}^2 + B_{dead}^2} B_{dead} \quad (135)$$

Weather

This option is selected only if the specified animals are likely to suffer from chilling, *viz.* young or recently shorn animals, or if feed intake is likely to be affected by very high or very low ambient temperatures. In these cases, the values entered would usually be the expected maximum and minimum temperatures, mean wind speed and rainfall for the next 24 hours.

Supplement

If the user of GrazFeed elects to supplement animals, the options are roughage alone, which may be offered *ad libitum*, or 'concentrate': a mixture of feeds, which may include a roughage offered in limited quantities. This avoids the problem of predicting the 2-way substitution that might occur between pasture, roughage and concentrate feeds if both a concentrate feed and unlimited roughage were available. If the roughage option is selected, the user enters its composition in a simple table. If the concentrate option is selected, the user composes a mixture from a short menu of feeds, which may be changed to suit requirements. The user also adjusts the default values for the price of the selected feeds and for their composition, if necessary. Any change that is made to the estimate of *DMD* automatically adjusts *ME/DM* (and *vice versa*), according to equation 32; ether extract values are implicit for standard feeds. To change the short menu, the user either selects items from a longer standard list of some 40 common feeds or enters a new feed with details of its composition. Some grains are included in the list in both a crushed and a whole condition, e.g. 'wheat, crushed' and also 'wheat, whole'. If a whole grain is selected by a user feeding cattle, the program corrects the intake for the amount of grain predicted to pass through to the faeces.

The level(s) at which the supplement is to be offered are entered later, in the Feeding option. If the user has already indicated zero levels of herbage, then the 'supplement' specified will make up the whole diet of the animals. Their performance will then be predicted with the assumption that they are penned and, therefore, not using additional energy for grazing.

Breed

For sheep or cattle, the user selects from a menu of major breed types grouped by size and productive characteristics. Selection of a prime lamb sheep or dairy cattle type automatically increases potential milk yield of a female relative to that of a type classified as wool or beef producing. Similarly, selection of a Brahman cattle type adjusts parameters for energy and protein maintenance requirements and heat tolerance, whereas selection of a lean cattle type, e.g. Charolais, adjusts the body composition parameters in equations 104 and 105. Selection of a cross-bred type averages the parameters of the parents. Having selected the type, the user adjusts default values for its mature size, using the *SRW* of a female as the index for the type, and, for a sheep, its average fleece weight, an index used for scaling wool growth.

Animals

The user selects a class of animal by sex, age and physiological status, and specifies its weight, age and coat depth. If entire males or castrates have been selected, the program computes *SRW* by multiplying the mature weight of the selected type by 1.4 or 1.2, respectively. For immature animals, the user is asked whether the animals are now lighter than they were at a younger age. This information enables the normal weight to be estimated. If the user's test conditions include a system of rotational grazing that is intensive enough for the mass of herbage to decrease noticeably during the day's grazing, then the number of

animals and the area available to them must be specified. The program will respond by indicating the implied herbage allowance (kg DM per animal).

Females

If female animals of reproductive age are specified, this screen becomes active and the stage of pregnancy or lactation, or both, are entered. For lactating animals, the user enters the values needed for scaling potential milk production (see equations 66-71); loss of weight during lactation is estimated from the specified condition of the female at parturition. Unweaned young are not entered as a separate class but their performance, from a specified initial base weight, is calculated as a consequence of their mother's milk production.

Feeding

If a supplement has been selected, the user must specify what levels of feeding are to be tested, how the tests are to be made and how the supplement is to be offered. The alternative to specifying a number of discrete levels of supplement, which will usually include a zero level, is to set a target for daily weight gain by the animal or by the young it is suckling, or for milk production (by dairy cows). The program searches for a supplement level that meets this target by an iterative process. In the case of mothers with young, this search may be quite extended because sharing of supplement between mothers and young, and the effect of maternal milk production on the intake limit of the young (equation 4) have to be taken into account. The output shows the closest point reached and, if the target is not achieved, will state the reason, e.g. the intake limit of the animal may have been reached.

If a supplement is offered to the animals in a stall or bail before they graze, then this must be indicated as it will change the method for predicting the substitution rate. In this case, the supplement becomes the first member of the selection hierarchy (i.e. $d^* = 0$ in equation 21), and its effect on relative intake will be accounted for before the effects of grazed herbage, regardless of supplement digestibility. If the supplement is of low quality, this can have a significant effect on the substitution rate but, in the more usual situation, bail-fed supplements are of high quality and the time of feeding may have little effect.

Output

Before the Calculate or Run button is pressed, the user may elect to see only a brief summary of the results, showing predicted intakes of pasture and supplement, weight gain and production of wool or milk. Otherwise, the full output consists of the brief results, a record of the input values and of a set of tables detailing predicted diet composition, partitioning of energy and protein intakes, animal production, chilling response (if weather data were included) and a table which shows nitrogen excretion, microbial protein synthesis and methane production.

As the main limits to animal production that are indicated by these results may not be clear to all users, the tables are followed by an optional set of interpretative comments, appropriate to the type of animal under test. These highlight crucial results, indicate their significance with respect to limiting animal production and suggest, in broad terms, remedial measures that might be taken. A final comment attempts to guide the user towards a stocking rate that would be sustainable in the short term, in relation to the expected growth rate of the pasture. The necessary calculations are made for the user if the Stocking Rate Calculator tool is activated. This tool also allows those practising rotational grazing to estimate either the number of animals that could be carried for a specified period or the duration of grazing by a

specified number of animals, on a fixed area and with a specified weight of residual herbage. All of these estimates are to be treated with caution as they take no account of changes in the quality of the herbage during the grazing period.

Three plotting options are available for the user to test animal response to different feeding conditions. If the fixed levels option is active on the Feeding screen, various animal responses to a range of levels may be tested, with the option for including a second variable, such as the ME/DM value of the supplement or the weight of green herbage. If the target gain option is active, the Supplement Target tool enables the user to test various attributes of the supplement on the weight required to meet the target. The third plotting tool, available with either feeding option, is labelled General Responses and allows the user to examine the response of any selected animal output variable to a wide range of feed characteristics in the supplement or the pasture.

An additional facility allows the user to seek the least-cost supplement mixture that will achieve a nominated target. On the Supplements/Concentrates screen, the user includes those feeds that are available for the ration; some of these feeds may initially be set at 0% of the mixture. With a Target set on the Feeding screen and the Least Cost icon selected from the tool bar, the program will estimate the least-cost mixture from the included feeds. The effect of changing the target, the number of included feeds or their cost can be tested by editing these values on the Least Cost Ration screen.

EXAMPLES OF THE USE OF GRAZFEED

Validation of the animal biology model has been carried out with the model running within the GrassGro DST as it is usually difficult to relate, in a satisfactory way, the point estimates from the GrazFeed DST to field measurements made over extended time intervals. The validation exercises will be covered fully in later papers but comparisons between predictions and observations have been reported by Donnelly *et al.* (1995), Stuth *et al.* (1999), Clark *et al.* (2000) and Cohen *et al.* (2003). The following examples are intended merely to illustrate practical situations where GrazFeed may be, and has been, useful in improving nutritional management.

TABLE 12

Predicted response in maternal weight gain by Merino ewes, 110 days pregnant with either single or twin fetuses, and grazing sparse pasture (0.5 t DM/ha; mean DM digestibility 72%), to supplementation with oats

Weight gains			
Supplement (g)	Pasture intake (g DM)	Single fetus (g/d)	Twin fetuses (g/d)
0	930	-18	-62
200	830	9	-21
400	780	35	14

Table 12 shows an example where Merino ewes in late pregnancy are grazing sparse, but good quality, winter pasture. The predicted losses of maternal weight by ewes with 1 or 2 foetuses at 110 days gestation indicate that, without supplementation, the twin-bearing ewes and their lambs would be at risk from pregnancy toxemia or poor milk production, respectively. The predictions indicate no shortage of protein in the diet and cereal grain is quite adequate as a supplement. By setting target maternal weight gains of -40 g d^{-1} or -20 g d^{-1} for ewes with one or two foetuses, respectively, and running GrazFeed for each of the last

six weeks of pregnancy, we have estimated the total supplement required to maintain these rates of weight loss as 6 kg and 23 kg for the two classes of ewes, respectively.

With so much less need for supplementation in ewes with one foetus, it may be more efficient to separate these animals before feeding begins, a policy that has become more practicable with the use of ultrasonic scanning in early pregnancy. If oats cost \$0.15 kg⁻¹, then the GrazFeed predictions show that the saving in supplementary feeding costs from scanning would be about \$0.15 x (23-6) = \$2.50 per ewe with one foetus, as compared with feeding all the ewes at the higher level.

In the example summarised in Table 13, weaned beef cattle graze a lucerne pasture in one sub-division of a rotation. The first results are for early in the grazing of the plot, when abundant leaf is available, whereas the other results are for some days later, when, with the loss of leaf, the assessed mean digestibility is much lower. The comparison illustrates the point that despite the presence of 1.5 t ha⁻¹ of easily accessible and apparently green dry matter on the latter occasion, the removal of leaf has reduced its quality quite severely in terms of liveweight gain by the weaners. It might be a better policy to move the weaners on more rapidly, at a point determined by the use of GrazFeed, and remove the remaining material with older animals.

TABLE 13

Predicted liveweight gains by weaned steers of Hereford type, 8 months old, 220 kg, grazing lucerne, either soon after entering a fresh sub-division or later in the grazing period

	Early in grazing	Later in grazing
Weight of green herbage (t DM/ha)	2.5	1.5
Digestibility of green herbage (%)	70	60
Intake (kg DM)	7.93	5.89
Digestibility of diet (%)	77	65
Efficiency of use of ME for gain (k _g)	0.48	0.33
Liveweight gain (kg)	1.53	0.30

In the third example, Table 14, Merino ewe weaners graze abundant but dead summer pasture with a low concentration of crude protein. In the absence of a supplement, intake of herbage was restricted by a deficiency of rumen degradable protein and liveweight loss was severe. Supplementation with oats alone (10% crude protein) does little to rectify the protein deficiency; herbage intake is further depressed and the effect on weight change was only moderate. On the other hand, as little as 100g of a 60:40 mixture of oats and lupins (18.5% crude protein) corrects the protein deficiency, maintains the intake of herbage and brings the weaners close to the point of weight maintenance. If a target weight gain of 50 g/d is set, then the program predicts that 420 g of the mixture would be required. To achieve the same target with oats alone would require 560 g, an amount that would be quite likely to lead to feeding problems in animals of this size. Larger gains, of the order required for finishing weaners as prime lambs, would be impossible to achieve with this supplement. These predictions are very similar to the experimental results of Freer *et al.* (1985).

TABLE 14

Predicted response by 7 month, 24 kg ewe weaners of medium Merino type, grazing abundant dead pasture (1.5 t/ha DM, DM digestibility 45%, CP 4% of DM), to supplementation with either oats alone (CP 10% of DM) or a 60:40 mixture of oats and lupins (CP 32% of DM).

Supplement intake (g)	Oats alone			Oats and lupins (60:40)		
	Pasture intake (g DM)	CP in diet (%)	Weight gain (g/d)	Pasture intake (g DM)	CP in diet (%)	Weight Gain (g/d)
0	570	7	-66			
100	510	7	-33	600	8	-4
200	440	8	-3	570	10	12
400	310	9	24	490	12	47

To date, more than 1500 copies of the GrazFeed software have been distributed. Most of the early users were professional agricultural advisors, either in the public or private sector. For many of these users, GrazFeed has become a routine advisory tool in consultations about requirements for supplementary feeding. The program can quickly show the least-cost combination of the feeds available to the grazer for any specific situation, taking into account the costs and composition of the supplements and the value of the animal production that may be achieved.

The major limitation to the accuracy of GrazFeed is, in many situations, the ability of the user to supply correct estimates of green and dead pasture weights and digestibilities. Inadequate estimates of herbage weight may result from inexperience or from a failure to use the appropriate cutting technique for the calibration of estimates. Functions in the intake model have been scaled to pasture weights obtained by running a shearing hand-piece over the pasture at ground level. Recognising these problems, NSW Agriculture ran a program - the Pasture and Animal Assessment Project (Archer *et al.*, 1990) - to train advisors in the assessment of pastures, using a modified form of the calibrated visual assessment procedure of Morley *et al.* (1964). This program was then extended in the PROGRAZE Project (Allan and Bell, 1996; Bell and Allan, 2000) which, up to 1997 had trained nearly 4000 graziers over a 3-year period (C. Allan, pers. comm) and has the aim of training a further 5000 graziers in its second stage. Up to the start of PROGRAZE, 13% of purchasers of GrazFeed were graziers; since then, this proportion has risen to 57%.

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APPENDIX

User-supplied inputs*Physical variables*

<i>Name</i>	<i>Units</i>	<i>Description</i>
<i>DL</i>	h	Day length
<i>DOY</i>	-	Day of year; 1 January = 1
λ	°	Latitude; south is negative
<i>T_{max}</i>	°C	Maximum daily temperature
<i>T_{min}</i>	°C	Minimum daily temperature
<i>R</i>	mm	Daily precipitation
<i>S</i>	1-2	Steepness score for grazing area
<i>v</i>	m s ⁻¹	Mean daily wind speed

Pasture variables

<i>Name</i>	<i>Units</i>	<i>Description</i>
<i>B_{green}</i>	kg DM ha ⁻¹	Weight of green herbage
<i>B_{dead}</i>	kg DM ha ⁻¹	Weight of dead herbage
<i>DMD_{green}</i>	0-1	Mean apparent dry matter digestibility of green herbage
<i>DMD_{dead}</i>	0-1	Mean apparent dry matter digestibility of dead herbage
ϕ_{legume}	0-1	Proportion of legume in the herbage
<i>SF</i>	-	Species factor for intake: C3 grasses=0.00; C4 grasses =0.16

Supplement variables

<i>Name</i>	<i>Units</i>	<i>Description</i>
<i>DMS</i>	kg	Weight of supplement DM offered per head per day
<i>DMD_s</i>	0-1	Apparent dry matter digestibility of supplement
<i>CP_s</i>	0-1	Crude protein concentration
<i>dg_s</i>	0-1	Rumen degradability of crude protein in supplement
<i>M/D_s</i>	MJ kg ⁻¹	Ratio of metabolizable energy to dry matter in supplement

Animal variables

All animals (cattle and/or sheep, where appropriate)

<i>Name</i>	<i>Units</i>	<i>Description</i>
<i>A</i>	d	Age
<i>F</i>	cm	Coat depth
<i>LW</i>	kg	Live weight (excludes fleece weight)
μ_{mean}	µm	Mean fibre diameter
<i>SFW</i>	kg	Standard fleece weight; i.e. average weight of fleece
<i>SRW</i>	kg	Standard reference weight, base weight of a mature female, <i>BC</i> =1
<i>W</i>	kg	Base weight; equals live weight in non-pregnant animals
<i>W_{birth}</i>	kg	Base weight at birth
<i>W_{high}</i>	kg	Highest base weight previously attained in a growing animal

Pregnant and lactating animals

<i>Name</i>	<i>Units</i>	<i>Description</i>
<i>A_{foetus}</i>	d	Days since conception in pregnant animals
<i>A_y</i>	d	Days since birth of young in lactating animals

BC_{part}	-	Body condition at parturition
W_y	kg	Base weight of young in lactating animals
WM_{peak}	kg	Expected peak milk yield in current lactation
Y		Number of young

Model-generated variables needed to define state of pasture or of animal groups

Pasture variables

Name	Units	Description
$B_{herb,d}$	kg ha ⁻¹	Weight of herbage DM, summed over all species; for d = 1...6
$B_{seed,k}$	kg ha ⁻¹	Weight of seed DM for each species (k= ripe, unripe; j = species)
CP_d	0-1	Crude protein content of herbage class d (d = 1...6)
dg_d	0-1	Rumen degradability of protein in herbage class d (d = 1...6)
DMD_d	0-1	Dry matter digestibility of herbage class d (d= 1...6)
QS_{kj}	1-7	Class occupied by seeds of type k and species j

Animal variables

Name	Units	Description
GFW	kg	Weight of greasy wool
δGFW	kg d ⁻¹	Growth rate of greasy wool
μ	μm	Wool fibre diameter
MEI_{milk}	MJ	ME intake from milk
MP	MJ	Milk production of mother as ME for the young
CPI_{milk}	kg	Protein intake from milk
W	kg	Base weight of pregnant animal; live weight less conceptus
W_{foetus}	kg	Weight of foetus in pregnant animals

Other variables

These variables are not necessary to define the state of an animal group, but are used in more than one section of the model.

Name	Units	Description
BC	-	Relative body condition: W/N
CPI_{total}	kg	Crude protein intake
DMD_f	0-1	Dry matter digestibility of herbage+seed intake
DP	kg	Dermal protein loss
$DPLS$	kg	Truly digestible protein leaving the stomach
$DPLS_{milk}$	kg	$DPLS$ derived from milk
EFP	kg	Endogenous faecal protein
EUP	kg	Endogenous urinary protein
$\phi_{milk} \phi_s \phi_f$	0-1	Proportions of the diet as milk, supplement and herbage+seed
$I_f I_s$	kg DM	Intakes of herbage+seed and of supplement
I_{max}	kg DM	Potential intake
k_m, k_l, k_c, k_g	0-1	Efficiencies of use of ME for maintenance, lactation, conceptus growth and weight gain
L	-	Relative feeding level: $MEI/ME_m - 1$
LB	-	Lactation adjustment for weight loss
M/D_{solid}	MJ kg ⁻¹	ME:DM for solid intake
MCP	kg	Microbial crude protein

MEI_f , MEI_s	MJ	ME intakes from herbage+seed and supplement
MEI_{total}	MJ	Total ME intake
ME_m	MJ	ME requirements for maintenance
ME_c , ME_l	MJ	ME requirements for conceptus growth and lactation
ME_{cold}	MJ	Additional requirement for maintenance in chilling conditions
N	kg	Normal weight
NE_w , NE_g	MJ	Net energy requirement for wool growth and weight gain
P_m , P_c , P_l	kg	Protein requirements for maintenance, conceptus and lactation
P_w	kg	Protein requirement for wool growth
$RDPI$	kg	Intake of rumen degradable protein
$RDPI_f$, $RDPI_s$	kg	$RDPI$ from herbage+seed and from supplement
SA	m ²	Surface area of animal
W_c	kg	Weight of conceptus
Z	-	Relative size of animal: N/SRW