MODEL COMPONENTS OF FORAGE-FED CATTLE SYSTEMS: ENERGY EXPENDITURE OF GRAZING CATTLE AND PREDICTION OF INTAKE IN DAIRY COWS

By

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CHAPTERS

List of Abreviations

ADF	Acid detergent fiber
AFRC	Agricultural and Food Research Council
ARC	Agricultural Research Council
BW	Body weight
BWC	Body weight change
CF	Crude fiber
CP	Crude protein
CSIRO	Commonwealth Scientific and Industrial Research Organization
CV	Coefficient of variation
DE	Digestible energy
DIM	Days in milk
DM	Dry matter
DMD	Dry matter digestibility
DMI	Dry matter intake
DOM	Digestible organic matter
EB	Energy balance
FADF	Forage acid detergent fiber
FCM	Fat corrected milk
FCP	Forage crude protein
FDM	Forage dry matter
FME	Forage metabolic energy
FNDF	Forage neutral detergent fiber
GE	Gross energy
GT	Grazing time
HM	Herbage mass
HP	Heat production
IB	Intake per bite

INRA	Institut National de la Recherche Agronomique
K	Efficiency of utiliztion of ME
K_m	Efficiency of utilization of ME for maintenance
K_g	Efficiency of utilization of ME for weight gain
K_l	Efficiency of utilization of ME for lactation
LactN	Lactation number
ME	Metabolizable energy
MFP	Milk fat percent
MILK4	4% fat corrected milk
MPE	Mean prediction error
MSE	Mean square error
MSPE	Mean square prediction error
MY	Milk yield
NDF	Neutral detergent fiber
NE	Net energy
NE_g	Net energy for gain
NE_l	Net energy for lactation.
NE_m	Net energy for maintenance
NRC	National Research Council
PDMI	Predicted dry matter intake
Q_m	Metabolizability quotient
RB	Rate of biting
RMSE	Root mean square error
RPE	Relative prediction error
RQ	Respiratory quotient
SEM	Standard error of the mean
SNF	Solids-non -fat
SSE	Error sum of squares
TDI	Total dry matter intake
TDN	Total digestible nutrients

TMR	Total mixed ration
TNDF	Total Diet NDF
UFL	Milk feed unit
UFV	Beef feed unit
VFA	Volatile fatty acids
VIF	Variance inflation factors

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The maintenance energy requirements of cattle should include the activity component when cattle are grazing. The prediction of the voluntary dry matter intake (DMI) is also a factor of importance for feed management of cattle. The objectives were to develop a procedure to account for energy maintenance requirement of grazing cattle, and to develop predictive equations for voluntary DMI by dairy cattle fed high-forage diets.

A literature review of factors affecting maintenance energy requirements was conducted. It is concluded that the principal factors affecting the additional requirements for maintenance of grazing cattle are the activities of walking and eating. Paddock size is an important factor affecting walking distance and a quadratic equation to calculate walking distance from paddock size is proposed. Adjustments for activity of grazing cattle, walking, ascent, and eating ranged from 15% for cattle grazing small paddocks of high quality forage, and high forage availability, to 70% for cattle grazing large paddocks of low quality forage, with limited forage availability.

Data from published experiments with dairy cows fed high-forage diets were used to generate and evaluate equations for the prediction of voluntary DMI. Equations were developed by multiple regression and variable selection procedures. Three equations were evaluated together with three published equations. The equations including only the linear terms of the selected variables resulted in a better sensitivity of the model. The models generated had a mean square prediction error from 4.24 to 4.56 kg^2, lower than that obtained with the published equations. The model selected for voluntary DMI prediction includes body weight, days in milk, production of 4% fat corrected milk, forage

dry matter, and diet neutral detergent fiber as independent variables.

CHAPTER 1
INTRODUCTION

Ruminants have evolved with a comparative advantage over other herbivores in terms of a highly efficient cellulose utilization. The fermentation of fibrous compounds in the rumen involves a symbiosis of microorganisms such as bacteria, protozoa and fungi, and the host animal. The fermentation of fiber results in formation of volatile fatty acids (VFA) that are utilized by the host animal to fulfill energy requirements for maintenance and production. The particularity that ruminants have, in comparison to non-ruminants, is that this process occurs prior to passage of the feed through their true stomach, the abomasum, and the intestines. As a result, ruminants have the advantage of being able to use ruminal microorganisms and their products as a source of high quality nutrients subject to the digestion processes of the lower tract. This makes ruminants relatively free from requirements for external sources of B vitamins and essential amino acids (Van Soest, 1994).

This unique characteristic of ruminants makes them animals of choice when production of high-quality animal products is attempted with low-quality feeds. Forages and agricultural by-products have been historically the main component of ruminant diets. This continues to be so in most of the extensive production systems where grazing is involved or where utilization is made of by-products such as straw. A different situation can be observed in the developed countries, where grain is available to be fed to ruminants. Under these conditions, production systems were developed that make intensive use of concentrates. This is the case for some stages of the production cycle such as the finishing cycle of beef cattle in feed-lots, or milk production with cows kept under confinement conditions. But, even in the U.S.A., grasslands are the main nutritional source for beef cow-calf operations and backgrounding and growing enterprises, activities that involve the major part of total cattle population.

The general tendency towards utilization of more sustainable production systems also is leading to changes in feeding systems, as there is a sense that in the future animal production will serve both to produce food and to maintain the environment (Van der Zijpp, 1993). Grazing has been revisited for dairy production as a tool for a more efficient nutrient recycling and effluent management. In other cases where land cannot be used for cropping due to soil limitations, climate, and erosion risks, utilization of the forage biomass by grazing becomes the only sustainable production feasible.

The fact that an important part of the worldwide cattle population acquires the majority of its feed by grazing, makes it necessary to address the effect that activities related to grazing have on the energy maintenance requirement of animals. Compared to hand-fed cattle, extra energy is necessary to obtain a bite of feed from the standing forage and to explore the grazing area in order to obtain the needed amount of feed. A correct estimation of the requirement of energy necessary to meet these needs will allow the producer to have a better prediction of the expected animal performance and also to design grazing systems that will allow the minimization of the energy requirements for maintenance.

Another critical determinant of animal production potential is related to the amount of feed an animal is capable of eating, the voluntary dry matter intake (DMI). Different mechanisms are involved in the regulation of DMI, which can be classified as metabolic, fill or ingestive behavior. Metabolic(chemostatic) regulation has been involved primarily when high concentrate diets are fed. Fill(distention) regulation has been associated with high roughage diets. The behavior mechanism has been associated with grazing situations. The different mechanisms act simultaneously in many situations and Fisher et al. (1989) proposed that the effect of the chemostatic feedback on intake must be interpreted in relation to the level of ruminal distention. The complexity of the interaction involved in the regulation of intake is not fully understood and, as concluded by Fisher et al. (1989), the adoption of empirical methods is an undesirable but necessary means of interpreting data and developing models to predict voluntary DMI when forage is available *ad libitum*. In conditions where grazing is involved, ingestive behavior as affected by forage availability and canopy structure should be considered as interacting with the other mechanisms.

The objectives of this dissertation are: a) to develop a procedure to account for energy requirement for activity in the energy maintenance requirement in simulation models, and b) to develop a predictive equation for voluntary DMI by dairy cattle fed high-forage diets in a non-grazing situation. For both objectives, extensive literature reviews were conducted.

CHAPTER 2
QUANTIFICATION OF ENERGY REQUIREMENTS IN CATTLE

Partition of the Energy of Feeds

The total energy concentration of a feed can be determined by the heat produced after the combustion of a sample in a bomb calorimeter. This value is termed gross energy (GE). It rarely, if ever, happens that all GE is utilized by the animal. In practically every case a proportion of the GE of the feed escapes unutilized (Armsby and Fries, 1915). The GE of the feed minus the energy lost in the feces constitutes the digestible energy (DE). Digestible energy as a proportion of GE may vary from 0.3 for a very mature, weathered forage to nearly 0.9 for processed, high-quality cereal grain (NRC, 1996). Metabolizable energy (ME) can be defined as the DE minus the urinary energy and the gaseous energy losses. For most forages and mixtures of forages and cereal grains the ratio of ME to DE varies between 0.81 to 0.86 (AFRC, 1993). Net energy (NE) is the energy available for animal maintenance and production. It results from subtracting the heat increment (or calorigenic effect of food) from ME (Kleiber, 1961). In theory, NE expresses the amount of energy utilized for maintenance and production by the animal. The NE values for production (body accretion, milk synthesis, wool, etc,) can be obtained by direct measurement. The NE values for maintenance instead rely on estimation, because the proportion of heat produced for maintenance cannot be separated from that pertaining to the heat increment. The partial efficiency of the utilization of ME varies for different physiological functions and is termed as K where:

$$K = NE / ME,$$

$$\text{thus: } NE = ME \times K$$

Values of K will range theoretically from 0, if ME is totally used for heat increment, to 1, if ME is used only for maintenance and production. In practice, K values have a range from 0.20 for roughages used for growth to 0.70 for concentrates used for maintenance.

Methods of Estimating Energy Balance

Heat Production

The requirement of energy for maintenance in cattle has been defined as the amount of feed energy intake that will result in no loss or gain of energy from the tissues of the animal body (NRC, 1996). It has long been realized that if an animal is given no food and certain other conditions are met, a measurement of heat production (HP) represents that animal's minimal energy demand (Blaxter, 1962). Measurements of this type are called "basal metabolism" determinations, and the conditions for the measurements are, firstly, that the animal should be in a postabsorptive state, secondly, that it should be in a state of muscular repose though not asleep and, lastly, that the environment in which the measurement is made is thermoneutral (that is, neither so cold nor so hot as to cause an increase in the metabolism)(Blaxter, 1962). The term basal metabolism applies particularly to man.

When HP is measured with farm animals, the second condition of repose cannot be ensured, and the measurement of the metabolism is made over a long period of time irrespective of whether the animal is standing, lying or asleep within the confines of the apparatus. This measurement is called “fasting metabolism” (Blaxter, 1962). The measurement of fasting metabolism can be made using different methods consisting of direct calorimetry, which is the measurement of the heat loss by radiation, convection, conduction, and as latent heat arising from the vaporization of water. Such measurements can be performed using two main types of calorimeters: heat sink calorimeters, and gradient layer calorimeters (Blaxter, 1989). In the former, the chamber accommodating the subject is heavily insulated to prevent heat loss and the heat produced is collected by liquid-cooled exchangers. Non-evaporative heat loss is calculated as the rate of flow of coolant multiplied by its temperature rise and the specific heat of the coolant. Evaporative heat loss is measured as the product of the mass flow of air, the increase in its humidity and the latent heat of vaporization. In gradient layer calorimeters the chamber confining the animal is lined with a thin layer of material of constant thickness and thermal conductivity and the whole chamber is surrounded by a jacket maintained at constant temperature.

Another method used to estimate the HP is referred to as indirect calorimetry, and consists of methods which are based on determinations of gaseous exchange. The equipment used can be classified in two types. In the first type the whole animal is confined in a respiration chamber for the quantitative measurement of the gaseous exchange. In the second type, masks, hoods or tracheal cannulas are employed to measure the gaseous exchange from the lungs alone (Blaxter, 1989). The measurement of the air exchange of the animal with the environment can be made through two methods, in the closed circuit method the animal is cut off from the outside air and the oxygen consumption can be measured as the decrease in the volume of oxygen in the closed chamber. In the open circuit method the animal breathes air from the outside while its exhaled air volume is measured. The exhaled air is analyzed for its oxygen and carbon dioxide concentration and, by comparing those values to the concentration of the entering air, the volume of oxygen consumed and carbon dioxide produced is calculated. In ruminants methane production is also measured.

Heat production can be calculated by applying a specific equation (Brouwer, 1965), based on the volumes expressed in liters of oxygen consumption, carbon dioxide production, methane production, and of the urinary nitrogen excretion expressed in grams:

$$HP(kcal) = (3.866 \times O_2) + (1.200 \times CO_2) - (0.518 \times CH_4) - (1.431 \times N)$$

A less precise estimation can be made if only oxygen consumption is measured. McLean (1972) describes calculation of HP from oxygen consumption as:

$$HP\ (kcal) = 4.89 \times O_2\ (Liters)$$

When heat production is measured based only on the measurement of one gas, it is necessary to adjust the calculation for the respiratory quotient (RQ), obtained by dividing the volume of CO_2 produced by the volume of O_2 consumed. Respiratory quotients vary according to the feed that is being utilized, ranging from 0.71 with fats to 1.0 with carbohydrates (Blaxter, 1989). Synthesis of fat can have a higher RQ, up to 1.3. The McLean (1972) equation reflects a RQ value that roughly represents a mean between fats and carbohydrates.

Portable equipment for the measurement of gaseous exchange has been developed (Young and Webster, 1963; Ochiai et al., 1985) and successfully utilized in field studies. Indirect calorimetry is inexpensive and convenient, as the equipment for an open-circuit system can be used in the field and in the laboratory for experimenting on resting animals or working animals (Yousef, 1985). These advantages, coupled with an accuracy similar to that of a direct calorimeter, make indirect calorimetry the procedure of choice in the measurement of HP (Yousef, 1985).

Using another indirect calorimetry approach, energy expenditure is estimated by reference to the rate of formation of carbon dioxide within the body (the CO_2 entry rate), in relation to the infusion of radioactive $NaH^{14}CO_3$ (Corbett et al., 1971; Whitelaw, 1974). The entry rate of metabolic CO_2 into the body is given by the relationship:

CO_2 entry rate (mmol/min) = rate of infusion of activity (mCi/min)/specific activity of CO_2(mCi/mmol)

Heat production is calculated then from the CO_2 production. Sahlu et al.(1988) describe a relationship of HP and CO_2

production as:

$$HP(kcal/kg\ BW^{0.75}/day) = 13.91 + 4.39\ CO_2(L/kg\ BW^{0.75})$$

A multichannel pump has been used for continuous injection of $NaH^{14}CO_3$ and sampling of saliva to determine the specific activity of CO_2 (Sanchez and Morris, 1984; Sahlu et al., 1988; Mendez et al., 1996).

Comparative Slaughter

Other, even more indirect techniques have been used to measure HP in animals. Comparative slaughter was a technique used in early research (Lawes and Gilbert, 1860) to measure the changes in energy content of growing animals. Heat production can be estimated as the difference between the ME intake and the energy balance (EB) of the animal. The technique is based on the determination of the energy content of the animal. A sample of the animals is slaughtered at the beginning of the trial. The carcasses are ground and a representative sample is obtained. Measurements of the energy concentration of the sample are made in a bomb calorimeter, which allows estimation of initial energy content. At the end of the trial a similar procedure is carried out to determine the energy content. The homogeneity of the animals used in the trial is very important in order to obtain a representative initial sample. The difference between both measurements constitutes the energy balance (it can be positive or negative).

Lofgreen (1965) described a modification of the comparative slaughter technique where the energy determinations were made indirectly, through determination of the specific gravity of the carcass. This measurement allows the estimation of water and fat concentration using the relationships developed by Kraybill et al.(1952) and protein concentration based on equations from Reid et al. (1955). The energy retained is determined by assuming the caloric values of fat and protein to be 9.367 Mcal/kg of fat and 5.686 Mcal/kg of protein. Criticism of this approach has arisen from the fact that the equation of Kraybill et al. (1952) was derived primarily to predict body water concentration from specific gravity, using the antipyrine dilution technique. The accuracy of such technique is considered inadequate (Knox and Handley, 1973). Garrett and Hinman (1969) studied the relationship between specific gravity and the components of the carcass determined by chemical analysis. The correlation coefficients were 0.99 between carcass and empty body weight, percent of water and fat. Nitrogen percent had a slightly lower correlation coefficient of 0.96.

Heart rate monitoring has been proposed as an alternative technique to measure HP (Brockway, 1978; Gibney and Leahy, 1996). Yamamoto et al. (1979) did simultaneous measurement of the heart rate and the HP with a calorimetric chamber. The relationship between HP and heart rate for each animal was described by linear regression, but differences between animals made necessary separate calibration equations for each animal, limiting its practical use.

Estimation of Energy Requirements in Ruminant Feeding Systems

The use of digested energy or metabolizable energy as an index of the animal needs for food, and for the various productive functions of animals, assumes that the digested energy of different foods is utilized with the same efficiency (Blaxter, 1962). The imperfections of the total digestible nutrients (TDN) systems are not very apparent, if rations given to stock are “standard”, and the animal response to them is known. Morrison (1956) proposed different feeding standards for dairy cattle, growing and finishing beef cattle, and dry or lactating beef cows. Within the range of the type of animal and feed formulation used with them, the system worked. Blaxter (1962) stated that any feeding system can be made to work for a very restricted range of rations. Problems with the TDN system arise as non-standard rations are used, such as all-roughage rations, high-concentrate rations, rations containing by-products, and high-protein diets. The recognition of the limitations of systems of feed evaluation based on TDN or DE led to the proposal of several NE systems (Moe and Tyrrell, 1973).

The determination of the partial efficiency of ME use or NE values requires more than one level of feeding. Because the relationship between energy intake and energy balance is curvilinear over the entire range of food intake, NE values and partial efficiencies are not constant but are influenced by the intakes over which measurements are made (Garrett and Johnson, 1983).

The NRC System for Beef Cattle

The NRC (1996) system for beef cattle is based on the California net energy system (Lofgreen and Garrett, 1968; Garrett, 1980). It relies on the concept that energy is utilized with different efficiency for maintenance and gain. The curvilinear relationship between recovered energy and ME intake was thus approximated by two linear relationships (Garrett and Johnson, 1983).

The net energy for maintenance (NE_m) requirement is calculated from the estimation of the HP of the fasting animal. It is possible to indirectly measure HP at zero feed intake by deducting EB from ME intake thus

$$HP(Mcal/d) = ME\ intake(Mcal/d) - EB(Mcal/d)$$

Metabolizable energy is determined by deducting from the GE the energy of feces, urine and methane, and energy retained is determined by the comparative slaughter method (Lofgreen and Garrett, 1968). In fed animals, HP is made up of basal metabolism, heat increment and heat produced by activity. At zero feed intake, however, heat increment is zero and the components of HP can be considered to be equal to the net energy required for maintenance. Five studies comprising 208 feeder cattle were conducted (Lofgreen and Garrett, 1968). The trials differed in the percentage of roughage of the ration, which were 2, 20, 25, 40 and 100%. Within each trial two or three feeding levels were used which allowed the expression of different energy balances. The relationship between HP and ME intake was described by a logarithmic equation (Lofgreen and Garrett, 1968) as:

$$\text{Log HP} = 1.8851 + 0.00166 \text{ ME intake}$$

$$s_{y.x} = 0.0293$$

The log of heat produced by the fasting animal therefore is equal to 1.8851 ± 0.0293. The antilog of these limits are 72 and 82, indicating that the HP of fasting beef cattle probably lies between 0.072 and 0.082 Mcal/kg $BW^{0.75}$. The average NE_m requirement for these cattle therefore can be considered to be equal to 0.077 Mcal/kg $BW^{0.75}$ (Lofgreen and Garrett, 1968). This expression was derived using data from primarily growing steers and heifers of British ancestry that were penned in generally nonstressful environments.

The NE for gain (NE_g) requirement for weight gain is simply the energy deposited in the gain. The calculation of the NE_g of the ration was determined by feeding the experimental diet at two levels and measuring the energy deposition brought about by the increase in feed intake between the two levels (Lofgreen and Garrett, 1968).

Garrett (1980) studied the relationship between the ME concentration of the feed and the NE_m or NE_g. Digestion trials were conducted on most diets at about 1.1 times the maintenance level. Metabolizable energy was estimated from DE by the factor 0.82. The relationship for converting ME values to NE_m and NE_g were:

$$NE_m = 1.37\ ME - 0.138\ ME^2 + 0.0105\ ME^3 - 1.12$$

$$NE_g = 1.42\ ME - 0.174\ ME^2 + 0.0122\ ME^3 - 1.65$$

As the equations were developed from data on a limited range of ME concentrations, the application of these formulas can not be extended without validation for feeds outside the range of 2 to 3 Mcal ME/kg. These equations were validated using seven different bermudagrass hays ranging from 1.66 to 2.13 Mcal ME/kg DM (Moore et al., 1991).

The requirements exhibit considerable variation due to different factors (NRC, 1996). Variation exists in maintenance requirement among cattle germplasm resources. *Bos indicus* breeds require 10% less energy for maintenance than beef breeds of *Bos taurus* cattle, and maintenance requirements of cross breds are intermediate. Conversely dairy dual purpose *Bos taurus* breeds require about 20% more energy than beef breeds with crosses being intermediate (NRC, 1996). Bulls have requirements 15% higher than steers or heifers.

The NRC System for Dairy Cattle

The NRC (1989) system for dairy cattle approaches growing cattle in the same way as the NRC (1996) does in the case of beef cattle. Some differences can be found in the way that ME is calculated from DE. In the dairy system the ME increases linearly as digestibility increases, as:

$$\text{ME (Mcal/kg DM)} = -0.45 + 1.01 \text{ DE (Mcal/kg DM)}$$

For lactating cows, the system is based on the proposal made by Moe et al. (1972). They considered that lactating animals use energy with the same efficiency for milk production and for maintenance, so for this case the calculation of diets requires a single NE value, the NE of lactation (NE_l). The calculation of NE_l for different feeds was made from TDN concentration as:

$$NE_l \text{ (Mcal/kg DM)} = 0.0245 \text{ X TDN (\% of DM)} - 0.12$$

This equation takes into account the reduction of the digestibility observed when animals are fed above maintenance, and is adjusted for an intake three times that of maintenance. The equation was, however, developed with TDN values above 56%, and its application to moderate to low quality forages (50% TDN or lower) in lactating cattle was not evaluated.

Moe et al.(1972) conducted studies in respiration chambers and reported a maintenance requirement of 0.073 Mcal NE_l /kg $BW^{0.75}$/day for lactating cows. An extra allowance of 10% was included to account for additional activity that occurs when cows are managed in a confined system which results in 0.080 Mcal NE_l /kg $BW^{0.75}$/day (NRC, 1989). Additional adjustments should be made if more activity occurs, such as grazing.

The British System

The British system (ARC, 1980; AFRC, 1990; AFRC, 1993) is based on the original proposal of Blaxter (1962) for a feed system aimed to replace the starch equivalent system being used in Britain at that time.

The system is based on the ME concentration of the feeds. The concentration of the ME is the result of applying the metabolizability quotient (Q_m) of the feed to its GE concentration. Metabolizability quotient is determined as:

Q_m = Concentration of ME / Concentration of GE

then: Concentration of ME = Concentration of GE X Q_m

The ME is utilized with different efficiencies for maintenance (K_m), lactation (K_l), growth for growing ruminants (K_f) and growth of lactating ruminants (K_g), being:

$K_m = 0.35\ Q_m + 0.503$

$K_l = 0.35\ Q_m + 0.420$

$K_f = 0.78\ Q_m + 0.006$

$K_g = 0.95\ K_l$

The NE concentration is calculated then as:

$$NE = ME * K$$

The system, because of the use of efficiency factors to partition ME, is really a NE system.

The maintenance ME requirement for cattle is given by the equation:

$$\text{Maintenance ME (MJ/day)} = (F + A)/K_m$$

Where F= fasting metabolism

A= activity allowance

The fasting metabolism requirements of cattle are given (ARC, 1980) by:

$$F\ (\text{MJ/day}) = C1\{0.53(BW/1.08)^{0.67}\}$$

where C1 = 1.15 for bulls and 1.0 for other cattle.

The INRA System

Jarrige (1989) presented the system proposed by the INRA in France. The system recognizes that each feedstuff has two different NE values, one for milk production and the other for beef production. The system uses a reference feed, the standard barley, from which two units are derived. The beef feed unit (UFV) corresponds to the net energy content of one kg of barley for meat production (1820 kcal NE) and the milk feed unit (UFL) corresponds to the NE content of one kg of barley for milk production (1700 kcal NE). The energy requirements and allowances are also expressed in feed units and are additive.

The NE values of feedstuffs for ruminants are calculated in a similar way to the British system. Digestible energy was measured directly on a large number of feedstuffs using wether sheep. Later digestibility was estimated using prediction equations derived from sheep studies, and DE was calculated multiplying the GE concentration of the feed by its estimated digestibility. The relation ME/DE was used to calculate the ME concentration and was calculated as:

$$ME/DE = 0.8417 - (9.9 \times 10^{-5}\ CF) - (1.96 \times 10^{-4}\ CP) + 0.221 \times L$$

Where CF = Crude Fiber (g/kg DM)

CP = Crude Protein (g/kg DM)

L = Feeding Level (L=1 at maintenance)

The efficiency of utilization of the ME for maintenance and production are calculated as K values, which are, using the same nomenclature as the AFRC (1993):

$K_m = 0.287\ Q_m + 0.554$

$K_l = 0.60 + 0.24(Q_m - 0.57)$

$K_f = 0.78\ Q_m + 0.006$

The expression of the energy concentration of the feedstuffs in feed units is obtained by multiplying the concentration of ME by the corresponding K value and dividing it by 1700 in the case of UFL or by 1820 in the case of UFV.

The proposed energy requirements for maintenance varied depending on the type of production analyzed. Balance feeding trials of fast-growing animals from dairy breeds resulted in an energy requirement for maintenance of 0.088 Mcal NE_m/ kg $BW^{0.75}$ /day. The requirement is higher by 15% for large-sized cattle (bulls, steers) and/or late maturing breeds which have a high protein content at the beginning of the fattening period because of the higher energy cost of protein turnover.

The energy requirement for maintenance of dairy and beef cows has been established at 0.070 Mcal NE_m/kg $BW^{0.75}$/day. Data obtained in respiration chambers which were checked in feeding trials were used to obtain this value.

The Australian System

The Australian system (CSIRO, 1990) calculates the maintenance requirements of ruminants as:

$$ME_m\ (\text{Mcal/day}) = \{[K*S*M*(0.28\ BW^{0.75}\ \exp(-0.03A))]/K_m + 0.09MEI\}\ /4.184$$

Where:

K = 1.0 for sheep and goat, or 1.2 for *Bos indicus,* or 1.4 for *Bos taurus,* and intermediate between 1.2 and 1.4 for crosses.

S = 1.0 for females and castrates or 1.15 for intact males.

M = 1 + (0.23 x % of diet DE from milk), or =1 +(0.26 - B*a) with B = 0.015 for suckled lambs and kid goats or 0.01 for suckled calves, and a = weeks of life. Minimum value of M is 1.0.

BW = body weight (kg)

A = age in years with a maximum value of 6.0, when $\exp(-0.03A) = 0.84$.

K_m = net efficiency of use of ME for maintenance. Calculated as $K_m = 0.02\ M/D + 0.5$, where M/D are the Megajoules of ME per kg of feed DM measured at the maintenance level.

MEI = total ME intake.

The Australian system also takes into consideration the additional requirements needed to support grazing and the relative effect of climate.

The systems analyzed present some differences in the mechanics to calculate the energy value of the feedstuffs and the energy requirements for maintenance but in essence they all constitute NE systems and, as was pointed by Moe and Tyrrell (1973), the difference is one of application rather than of principle.

Estimation of the Energy Requirements for Grazing Activity

The NRC (1935) defines two different maintenance requirements for energy. The physiologic maintenance requirement is the quantity of energy necessary to maintain an energy equilibrium under ideal conditions as are found in the respiration calorimeter or chamber. The economic maintenance requirement includes an additional quota of net energy sufficient to cover the energy expenditure in muscular activity under the particular conditions prevailing. The report included the recommendation that the net energy requirements of "economic" maintenance be further investigated, especially by the analysis of muscular activities incident to maintenance, as affected by individuality, age, sex, breed and species, and by method of confinement in barn, feedlot and pasture.

Two approaches have been utilized to measure the energy expenditure of the grazing animal. The first one was the direct measurement or estimation of the HP. This was derived from the activity developed by the animal under a set of situations which are compared to the requirement estimated under the conditions in the conventional situation (in the calorimeter, dry lot, etc.). The second approach utilized has been defined as a factorial approach, under which the energy requirement of each particular activity is measured, and these values are used to build up an additive model. In this model activity requirements are calculated after knowing the energetic cost of each particular component and the amount of activity exercised by the animal in a period of time, generally a day.

Direct Measurement of Activity Requirements

The development of techniques that allowed the estimation of dry matter intake and of digestibility of the ingested forage by grazing animals resulted in estimations of digestible organic matter intake needed for maintenance of grazing animals (Wallace, 1956; Lambourne and Reardon, 1963). Those studies were done by using chromic oxide doses to estimate the fecal output and using nitrogen as a fecal index to estimate digestibility. Wallace (1956) studied a total of 217 lactations of dairy cows between the years 1948 and 1955. The requirements of digestible organic matter (DOM) were estimated by multiple regression with 4% fat corrected milk (FCM), body weight $^{0.73}$ ($BW^{0.73}$) and body weight change (BWC). The resulting equation was:

$$DOM(lb/d) = 0.35\ FCM(lb/d) + 0.08\ BW(lb)^{0.73} + \\ + 3\ BWC(lb/d)$$

The comparison of the results obtained with those in use by the current feeding systems at that time gave similar values for the energy required to produce a liter of milk (0.36 kg TDN/kg FCM vs 0.324 kg TDN calculated by Morrison, 1936). Larger differences were obtained for the maintenance requirements of energy, where the calculated requirement for a 454 kg cow was 5.64 kg of DOM/day, equivalent to 5.86 kg of TDN, while Morrison (1936) proposed a value of 3.63 kg TDN/day for cows under a stall-fed system. The increase in the requirements due to the effect of grazing was then estimated to be 60%. A higher increase in the requirements, of 90%, was also obtained performing a similar comparison with the Starch Equivalent system used in Britain at that time (Woodman, 1954).

Coop and Hill (1962) realized four experiments using grazing sheep to determine the intake of DOM required for maintenance. Digestible organic matter intake was determined from the calculated fecal output using Chromic oxide as an indigestible marker and the estimation of the herbage digestibility using nitrogen as a fecal index. The number of animals used in the different experiments were: experiment 1, twelve wether sheep, thirteen thin ewes, and thirteen fat ewes were used; experiment 2 thirty-six weaned lambs were used; experiment 3, forty ewes; and experiment 4, fifteen ewes. The authors found a 50 to 70% increase in the intake of DOM in order to maintain body weight in grazing sheep, compared to the intake of DOM required by pen fed animals (Coop, 1962). The authors suggested that the cause of this difference derives from the energy cost of walking and harvesting the pasture together with climatic factors of wind, cold and rain. The amounts of activity and the climatic conditions prevailing in the trial were not reported, so the incidence of each one on the results obtained can not be analyzed.

Lambourne and Reardon (1963) studied the effect of grazing and the outdoor environment in sheep (wethers), selected at random from a flock, with an initial BW range of 39 to 41 kg. They were managed in a way to maintain three different groups of seven sheep each, which differed in mean BW: high with 45 kg BW, medium with 36 kg BW and low with 27 kg BW. Two sheep from each group were maintained in metabolism pens and the remaining five from each group were maintained on separate 1 to 2 acre pastures, adding extra animals if necessary to prevent weight gains in the medium and low weight group. Intake on pasture was measured by the chromic oxide calculated fecal output and digestibility estimated with the nitrogen as a fecal index. They observed an increased maintenance requirement due to differences in the environment and to the activity of grazing (Table 1).

The increase in the maintenance requirements due to location and activity was higher in the low BW sheep. Maintenance requirements of the low BW sheep were 45% greater when fed outdoors in pens compared to those housed indoors. Sheep given unlimited time for grazing were maintained with the target BW by adjusting the stocking rate of the paddocks with the addition of extra sheep when necessary. Herbage mass was the variable used to regulate BW in this group.

Unlimited grazing time resulted in a maintenance increase of 33% in the high BW sheep while it was 160% in the medium BW sheep and 275% for the low BW sheep compared to sheep penned indoors. These values were higher than those observed with sheep given limited grazing time, a situation in which the BW was regulated by adjusting the grazing time in the same high quality pasture. Low and medium BW sheep were allowed to graze for 1 to 3 hours in a good quality

Table 1. Mean maintenance intake(g DOM/sheep/day) of sheep maintained at high, medium and low body weight in different environments.

		Mean Body Weight Group		
		45 kg	36 kg	27 kg
Pens	Indoors	420	300	200
	Outdoors	480	340	290
Grazing	Limit time	490	480	420
	Unlimited time	560	780	750

From Lambourne and Reardon (1963)

pasture. With limit grazing, there was a 16% increase in maintenance requirement for the high BW group, 60% for the medium BW, and 110% for the low BW group compared to sheep penned indoors. An interaction of activity of grazing and climate also was observed.

The validity of the maintenance requirements obtained utilizing chromic oxide to estimate fecal output and nitrogen as a fecal index to estimate digestibility has been questioned (Corbett, 1960, Corbett and Farrell, 1970, Young and Corbett, 1972b). Reasons for the discrepancies can arise from the use of generalized equations to calculate the digestibility of the diet with the nitrogen fecal index (Coop and Hill, 1962). Factors such as type of herbage can affect the application of the equations (Corbett, 1960). The development of specific equations for each trial was recommended (Raymond et al., 1956). The comparison of the digestibility values determined in forage samples obtained with oesophageally fistulated sheep with the *in vitro* technique, and those obtained using the fecal nitrogen index showed that the digestibility calculated with fecal index was 20 units higher than the corresponding *in vitro* values (Corbett and Farrell, 1970). The ingestion of soil by sheep grazing a sparse pasture can increase the concentration of ash in the feces up to 72% and can explain the discrepancy between methods used to determine digestibility(Young and Corbett, 1972b).

Young and Corbett (1972a) studied the energy balance of grazing sheep, measuring the respiratory gaseous exchange of tracheostomized sheep and simultaneously by the CO_2 entry rate technique. They studied three groups of ten Merino wethers weighing an average of 25, 35 or 45 kg. The weight difference resulted from imposing differential grazing regimes to wethers with an initial BW of 44.4 ± 1.9 kg. During the experiment, BW was confounded with grazing conditions as heavier sheep grazed on pasture with abundant herbage and those with lower BW grazed sparse herbage, thus creating greater activity for the lighter animals. The experimental paddocks were 0.78, 0.58, and 0.39 ha for the high, medium and low BW groups. The measurement of the respiratory gaseous exchange was realized in two tracheostomized sheep from each group and the energy expenditure was measured with the CO_2 entry rate in three to five sheep from each group. The energy requirement was proportional to BW, and the energy requirements of grazing sheep were between 52 and 75% higher than those of housed sheep. The increase was the result of both the activity expenditure as well as the effect of the exposure of the sheep to the outdoor weather conditions because these effects cannot be separated.

Havstad and Malechek (1982) calculated the energy expenditure of four yearling Angus heifers grazing on a 28-ha pasture with the use of the CO_2 entry rate technique. They found an energy expenditure 46% higher than the one estimated using stall-fed heifers consuming similar forage. The energy expenditure was not affected by a decrease of the herbage mass from 880 kg/ha to 284 kg/ha. Ochiai et al. (1985) studied HP on two tracheostomized animals, a Japanese Black cow and a Holstein steer, grazing a 0.5 ha-orchardgrass pasture, by measuring the oxygen consumption rate. They found an increase of 56% for the steer and of 37% for the cow, compared to the values obtained while the animals were housed.

Energy Requirement of Components of the Activity of Grazing Ruminants

The relative importance of different components of daily energy expenditure, in relation to the energy budget of animal has been subject to debate. In domestic animals the costs associated with basal metabolism plus heat increment of feeding usually dominate the daily budget, but research on wild species, particularly the moose, suggest that activity costs can dominate (White, 1993). In domestic animals subjected to extensive production systems, the activity component also has greater importance.

Activity, for the grazing ruminant, comprises the acts of standing, walking, eating and ruminating.

Walking

Walking consists of successive lifting of the body. The energy cost of walking should vary with the weight of the animal and with the speed of walking (Brody, 1945). The higher the speed the less the overhead charge per unit of ground covered and, therefore, the less the overall cost. Brody (1945) considered two components in the energy requirement of the animal while it was walking: the "rest maintenance" and the energy used for work. If, however, the "rest maintenance" item is not included in the total cost, the cost of walking was independent of the speed and was only related to the distance walked. Their studies were made with a motorized treadmill, and fitting the animals with a respiratory mask connected to an open circuit respiratory apparatus. Using seven cattle with a BW range between 383 and 930 kg, Brody (1945) calculated an energetic cost of 0.452 cal/kg BW/m; data from seven horses ranging from 91 to 688 kg BW gave a mean value of 0.385 cal/kg BW/m.

Clapperton (1964) studied the energy metabolism of two sheep of 40 kg BW, which walked on a treadmill at level and on gradients. They were housed in a respiration chamber, where carbon dioxide and methane production, and oxygen consumption were measured daily in two periods, day and night. He measured the energy cost at two walking speeds and at two levels of feeding of a pelleted, ground dried grass with a crude protein concentration of 15.1 g/100 g DM. Feeding more DM allowed the animal to retain energy even when working at the highest rate while the restricted diet resulted in loss of energy even at rest (Table 2).

The apparent energy cost of walking on the horizontal was greater at higher speed for both sheep. The mean apparent cost of horizontal walking was .59 ± .03 cal/kg/m. The high variability between sheep resulted in no significant difference being detected between the energy

Table 2. Energy cost (cal/kg BW/m) of walking on the horizontal by sheep fed two amounts of dry matter.

	Low feed intake		High feed intake		
Walking Speed	Sheep H	Sheep J	Sheep H	Sheep J	Mean ± SE
1.46 Km/h	.577	.649	.328	.513	.517± .037
2.91 Km/h	.673	.698	.584	.695	.663± .037
Mean	.649 ± .037		.530 ± .037		

From Clapperton (1964).

cost of walking at different speeds and between nutrition levels. The application of the feeding levels resulted in one sheep that was gaining tissue and the other that was maintaining or losing tissue. This difference in condition may explain the variation of the results for the energy cost of walking under the different feeding regimes.

Farrell et al.(1972) studied the effect of body condition on the energy expenditure of sheep. Sheep of similar body weight were adjusted to their diets in order to produce weight differences that were maintained during the experiment (Table 3). The measurements of HP were obtained in respiration chambers fitted with a treadmill. Two walking speeds (1.1 and 1.5 km/h) were used with two sheep per treatment. No differences were found among the three different body conditions and, also, no difference was observed for sheep walking at the two speeds.

Ribeiro et al. (1977) measured the energy cost to cattle of walking on the level and on gradients, and the influence on the energy cost of body weight and plane of nutrition (Table 4). The studies were made using four steers (two British Friesian and two British Friesian X Hereford). They were fed a diet with a ME concentration of 2.63 Mcal/kg

Table 3. Energy expenditure in horizontal locomotion by adult sheep varying in body condition.

Body Condition	Fleece-free BW(kg)	Energy expenditure (cal/kg BW/m)
High	46.9 ± 4.6	.71 ± .10
Mean	32.5 ± 1.2	.63 ± .12
Low	27.4 ± 1.6	.64 ± .11

From Farrell et al. (1972).

Table 4. The energy cost for cattle of walking at two speeds, low (2.42 km/h) and high (4.84 km/h) on the horizontal level and at a gradient of 6 ° and the resulting cost of vertical ascent.

	British Friesian		Friesian X Hereford		
	Steer 1	Steer 2	Steer 3	Steer 4	Mean
	-----------------cal/kg BW/m-----------------				
Horizontal					
Low speed	0.42	0.45	0.38	0.58	0.46
High speed	0.50	0.44	0.50	0.55	0.54
Gradient					
Low speed	1.31	1.12	1.12	1.38	1.23
High speed	1.16	0.97	1.01	1.22	1.09
Vertical ascent					
Low speed	8.5	6.4	7.1	7.6	7.4
High speed	6.3	5.0	4.9	4.9	5.3

From Ribeiro et al. (1977).

DM at a level of maintenance or 1.6 times maintenance (maintenance was assumed to be 119 Kcal ME/kg $BW^{.75}$/day). They did not find differences due to nutritional level. An interaction between animal and speed was observed as the cost of walking increased with speed in two animals while decreased in two.

The energy cost of horizontal walking observed for cattle (Ribeiro et al., 1977) is in agreement with those reported by Brody (1945) and also with the ones reported for sheep (Clapperton, 1964, Farrell et al., 1972). Lawrence and Stibbards (1990) measured the cost of walking in three zebu cattle and in two swamp buffalo (*Bubalus bubalis*). The energy consumption of all animals was measured by open circuit calorimetry. The animals were fitted with a face hood. The O_2 consumption, CO_2 production, and air flow were measured. At comfortable walking speeds (from 2.16 to 3.6 km/h) the energy expenditure was 0.46 cal/kg BW/m. Energy expenditure obtained with a wider range of walking speeds (1.45 to 5.75 km/h) was 0.50 cal/kg BW/m.

Lachica et al. (1997a) studied the energy cost of locomotion of Granadina goat (*Capra hircus*). They measured the HP on six goats walking on positive and negative slopes on a treadmill located inside a respiration chamber. The energetic costs of walking were 0.46, 0.56, 0.83, 1.12, and 1.54 cal/kg BW/m for -10, -5, 0, 5, 10% incline respectively. The energy cost of horizontal walking for goats in this study was higher than the values observed in other studies for sheep and cattle.

Recent studies reported lower estimations of the energetic cost of walking. With the use of the CO_2 entry rate technique, Mendez et al. (1996) estimated the energy requirement of walking for Angus steers that were led by a rope outdoors for 1 or 2 hours at a speed of 3 km/h. Three steers were assigned to each treatment. The estimated energy requirement for walking varied between .11 to .14 cal/kg BW/m. The authors attribute this low value to differences that may arise from conducting the measurements outdoors compared to those obtained with treadmills installed inside the calorimetric chambers. Nicholson (1987) studied the effect of walking and night enclosure on the productivity of Zebu cattle. Two hundred Boran Zebu cows were allotted to four treatments: 1) no walking, no night enclosure; 2) walking 40 km every third day to the water supply; 3) enclosure at night, and 4) both walking and night enclosure.

The treatments did not affect calving percentage, calf birth weight, or weaning weights. Considering the differences in body weight, the animals that walked lost 20 kg BW, giving an estimated cost of walking of 0.14 cal/kg BW/m. Studies with similar type of cattle, Boran Zebu and Boran Zebu X Hereford steers, studied the feed intake required to maintain BW when animals were subjected to a walking exercise (Ledger, 1977). The animals were kept in pens and exercised on an oval track constructed on flat land, and walked 0, 5, 10 or 15 km daily. The animals ate 34% more DM if they walked 5 km/d, 69% if they walked 10 km/d and 97% if they walked 15 km/d compared to no walking. Calculation of the energetic cost of walking gave a value of 1 cal ME/kg BW/m.

The energy requirement for vertical movements in cattle has been estimated to be between 5.3 and 7.4 cal/kg BW/vertical meter (Ribeiro et al. 1977, Table 4), with the higher value occurring when the walking speed was lower. In goats Lachica et al. (1997a) found a similar value, 7.58 cal/kg BW/ vertical meter. The AFRC (1993) proposes an intermediate value of 6.7 cal/kg/m for the adjustment of the maintenance requirement due to activity for vertical movement. The measurements of the cost of walking in negative slopes are scarce. Lachica et al. (1997a) estimated the energy recovery of vertical descent as 3.15 cal/kg BW/ meter of vertical descent. The total cost of locomotion could be estimated in goats (Lachica et al., 1997b) as:

$$\text{Energy for locomotion(cal/animal/day)} = BW \times \{(H \times 0.8) + (A \times 7.43) - (D \times 3.15)\}$$

Where:

H = Horizontal walking m/24h.

A = Ascending m/24h.

D = descending m/24h.

Most studies of walking and running have been developed under laboratory conditions where the terrain is the smooth surface of the belt of a treadmill or running track. The energy cost is considerably greater if the surface is rough or uneven (Blaxter, 1989). Also the energy cost of transport is much higher when animals move across spongy or soft surfaces, such as bogs, mires, sand, or snow (Fancy and White, 1985). In man, the energy cost above that of standing, of walking a ploughed field is about 50% greater than that for walking on a smooth surface. It may be that the effect of the type of terrain on energy cost of locomotion is somewhat greater in man with their bipedal gait than in quadrupeds (Blaxter, 1989).

Studies conducted on reindeer (White and Youssef, 1978) reported that the animals expended 13% more energy when walking on dry tundra compared to walking on hard packed roads, and 30% more energy when walking on wet tundra (sinking depth, 6 to 10 cm).

Dijkman and Lawrence (1997) studied the energy expenditure of cattle (mainly *Bos indicus*) and buffalo (*Bubalus bubalis)* working on different soil conditions. Six animals, two Brahman steers, two water buffalo and two Brahman X Friesian steers were used in an experiment to measure the energy expenditure walking on concrete and on mud, on an artificial setting. The gaseous exchange was measured using an open circuit gas analysis system. The consumption of O_2 , and the production of CO_2 were used to calculate the energy expenditure. The energy expenditure walking on concrete was 0.40 cal/kg BW/m, and the same animals spent 0.80 cal/kg BW/m when walking on mud. Measurements were conducted under field conditions in

Nigeria with eight Bunaji bulls(*Bos indicus*) fitted with a portable O_2 metering system. The animals walked on different types of soils, fadama, which is a flat terrain with a high proportion of clay or very fine sand, or uplands which have a better structure, and under conditions wet or dry, and ploughed or unploughed conditions (Table 5). An increment of up to 480% of the requirements can be found for the case of ploughed wet fadama soil.

Even though data are scarce and were obtained with a limited number of animals, the value of 0.6 cal/kg BW/m for horizontal walking and 6.7 cal/kg BW/vertical meter proposed by the AFRC (1993) can be regarded as an approximation to measure the energy expenditure for horizontal walking and vertical ascent. A component for energy gain due to the lower cost of descending compared to horizontal walking should be made, and the use of the value obtained by Lachica et al. (1997a), 3.15 cal/kg BW/vertical descended m, could be reasonable even though it was obtained with goats. In conditions where the animals travel on soft terrain such as mud, additional requirements should be considered.

Table 5. The energy cost and the speed of walking of Zebu bulls on ploughed or unploughed soils of different consistency in the sub-humid zone of Nigeria.

Soil type	Walking speed (km/h)	Energy for walking (cal/kg BW/m)
Unploughed upland	3.49	0.35
Ploughed upland	2.99	0.69
Unploughed dry fadama	3.13	0.42
Ploughed dry fadama	2.66	0.90
Unploughed wet fadama	2.88	0.78
Ploughed wet fadama	2.34	2.05

From Dijkman and Lawrence (1997)

Eating

The ARC (1965) considered that the energy expenditure associated with the activity of eating could be assumed as negligible. The heat increment associated with feeding was considered to be primarily a function of the quantity and quality of the food ingested. But if the muscular and secretory activity of prehension and mastication are major items in the energy cost of feeding, then the properties of the ration would be expected to influence the energy expended (Young, 1966).

Graham (1964) studied the effect of grazing on the energy expenditure of sheep within the environment of a closed circuit respiration chamber. Three wether sheep with 30, 40, and 50 kg, and a ram of 110 kg were used in the grazing measurements. Four 40 kg wethers were used to determine the cost of eating prepared meals of fresh herbage and hay. The feeds offered were a prepared feed of either fresh herbage or hay, and areas of turf that were dug out from the field and relaid on the floor of the chamber. The energy cost of eating over that of standing was 0.54 kcal/kg BW/h and no differences were observed between grazing or eating a prepared food.

The type of feed and the processing to which the feed is subjected, can influence the ingestion rate of the feed and so the energetics of the feeding act. Graham (1964) found that sheep of 40 kg BW consumed 60 to 120 g DM/h when grazing and 300 to 400 g DM/h when fed cut fresh herbage. The consumption of hay was 400 to 800 g DM/h, and assuming a DM concentration of 90%, the rate of eating hay DM was higher than that for fresh herbage. The energy required for eating can be calculated as 6 kcal/kg DM/kg BW for grazed forage, 1.5 kcal/kg DM/kg BW for fresh cut forage and 1.0 kcal/kg DM/kg BW for hay.

Young (1966) measured the energy expenditure of sheep eating chaffed alfalfa or wheaten hay, and a concentrate ration. He used five tracheostomized Merino wethers, where the energy expenditure was measured by an open circuit calorimetric technique. He found no differences in the energy cost per unit of time between rations or between sheep and the values observed had a range from 0.32 to 0.74 kcal/kg BW/h. The energy cost of eating a unit of DM was lower for the concentrate diet than for the chaffed rations, and these were not different. The energy expenditure ranged from 0.3 to 0.6 kcal/kg DM/kg BW for the concentrate ration, and from 1.2 to 1.9 kcal/kg DM/kg BW for the chaffed rations.

Osuji et al. (1975) studied the effect of different physical forms of feeds on the energy exchange associated with eating and rumination in sheep. In an experiment where a fixed amount of DM was offered for one hour to four adult wether sheep with 57 kg BW, they found that the energy cost of eating was lower for pelleted than for chopped dry grass or fresh grass. Eating chopped dry grass resulted in a higher energy requirement per kg of food as fed, but eating fresh grass had a higher requirement when on a dry matter basis. The time spent to eat equivalent amounts of dry matter was higher in the case of fresh grass (Table 6). In a second experiment, four adult wether sheep weighing 51 kg BW were fed at an estimated maintenance level and at two times maintenance, with dried grass either chopped or pelleted. The energy expenditure was 1.43 kcal/kg DM/kg BW for the chopped dried grass at maintenance and 1.08 kcal/kg DM/kg BW at two times maintenance. In the case of pelleted dried grass the requirements were lower, 0.12 kcal/kg DM/kg BW and no difference was observed between sheep eating the two amounts of DM. A comparison of the same grass either dried

Table 6. The apparent energy cost of eating for four sheep given access to chopped dried grass, pelleted dried grass or fresh grass for 1 hour daily.

	Chopped	Pelleted	Fresh
Intake as fed (g)	790	951	1221
Dry matter intake (g)	671	828	233
Time spent eating (min)	58	29	49
Increase in heat production (kcal/h)	23	6	12
Cost of eating			
Kcal/kg as fed	22	3	8
Kcal/kg DM	26	2	42
Kcal/kg DM/kg BW	.45	.03	.73

From Osuji et al. (1975)

or fresh, made in a third experiment using four 57 kg wether sheep, resulted in an energy expenditure of 0.87 kcal/kg DM/kg BW for the dried grass and 1.45 kcal/kg DM/kg BW for the fresh grass.

Holmes et al. (1978) measured energy expenditure using two calves. The measurements of oxygen consumption were made with the animal's head restrained in a ventilated box. The animals while grazing had a higher HP than when they ate the same forage cut, dry or fresh. For grazed forage, the expenditure was 117 kcal/kg DM ingested and for cut forage, either fresh or dry, the value was 60 kcal/kg DM.

Adam et al. (1984) used five steers with 298 to 407 kg BW in a 5 X 5 Latin square design to study five different foods. They calculated the energy cost of eating measuring the rate of O_2 consumption using a ventilated hood attached to a respiratory-gas analysis system in the animals during the period of eating activity, and compared it to the rate of O_2 consumption in the pre- and post-feeding period. They found a higher energy cost of eating hay compared to pellets. Turnips, which had a higher water concentration, had a higher cost of ingestion per dry matter unit, despite the fact that the rate of ingestion of turnips as fed was the highest and no difference was found among the energy cost of ingestion in unit of time (Table 7). Because cattle generally ingest food more rapidly than sheep, the cost of feeding activity, when expressed on a DM intake basis, is less for cattle.

The experiments analyzed by Lofgreen and Garrett (1968) resulted in an estimation of a mean maintenance energy requirement of 0.077 Mcal/kg $BW^{0.75}$. An independent analysis of the data within each type of ration provide an estimation of 0.074 Mcal/kg $BW^{0.75}$ for a diet with 2% roughage. The estimate increased to 0.082 Mcal/kg $BW^{0.75}$ with a 100% roughage diet, an increment of 11% in the maintenance requirement due, perhaps, to the increased cost of eating.

The energy cost of eating for the grazing animal can be affected by the type of forage and the structure of the canopy (Di Marco et al., 1996). In a study conducted with Angus steers using the CO_2 entry rate technique, they compared the energy expenditure for grazing, in two separate experiments. The animals grazed small areas restrained by a rope to avoid the effect of walking. In experiment 1, six Angus steers, weighing an average 259 kg were used on a ryegrass pasture, and in experiment 2, seven Angus steers,

Table 7. Rate of energy costs of ingestion of diets by cattle.

	Rate of ingestion (g/min)		Energy cost of ingestion per kg BW	
Diet	As fed	DM	kcal/h spent eating	kcal/kg DM ingested
Concentrate pellets	149.3^a	129.7^a	.396	.057^a
Lucerne pellets	149.9^a	137.9^a	.414	.052^a
Lucerne hay	42.8^b	36.8^b	.510	.246^b
Dried grass, chopped	39.1^b	38.8^b	.396	.185^b
Turnips, chopped	196.2^a	29.8^b	.498	.341^c
SEM	15.0	10.1	.048	.027

^{abc} Superscripts that differ within columns indicate means that are different ($P<.05$)

From Adam et al.(1984).

three small (258 kg) and four medium size (327 kg), were used on an oats pasture. The two types of pasture included a ryegrass pasture with a herbage mass of 1420 kg/ha, 10.5 cm high, and 61% DM digestibility, and an oat pasture with a herbage mass of 2280 kg/ha, 26.9 cm high and 76% DM digestibility. The animals exhibited a differential grazing behavior, as the bite rate increased from 28 bites/min when grazing the oat pasture to 59 bites/min when grazing the ryegrass pasture. The increase in HP, compared to that obtained when the animals were fed in a corral at a submaintenance level, was 1.84 kcal/kg $BW^{0.75}$/h for the ryegrass pasture and 0.55 kcal/kg $BW^{0.75}$/h for the higher quality oat pasture; these values represent 52 and 16% increases over the maintenance levels, respectively. The value of the grazing energy expenditure over the total energy budget was calculated and, considering 10 hours of grazing/day, resulted in a 19% increase for the animals grazing the low-quality pasture and 6% increase for the ones grazing the high-quality pasture.

The measurement of the basal maintenance requirements has been made using regular feed-lot rations that were not pelleted (Lofgreen and Garrett, 1968). The low energy requirement that pelleted rations have for their ingestion may require a discount in the maintenance requirements. Calculating according to the data of Adam et al. (1984), a 400 kg-steer consuming 8 kg DM/d of a pelleted diet will require between 6 to 9% less energy for maintenance than a similar steer eating a chopped diet.

Standing

The energetic cost of standing over that required when the animal is lying has been estimated as 0.06 kcal/kg BW/h (Osuji, 1971, cited by Osuji, 1974), 0.15 kcal/kg BW/h (Forbes et al., 1927), and up to 0.24 to 0.28 kcal/kg BW/h (Toutain et al., 1977). The latter authors also found that energy expenditure was not constant in time as it decreased in an exponential form with the length of time spent standing. During the first 2 min after standing the additional heat produced was calculated as 0.31 kcal/kg BW/h, while after 40 min it was 0.16 kcal/kg BW/h, a value close to that obtained by Forbes et al. (1927). Toutain et al. (1977) could not separate the energy cost of rising to a standing position from other activities, but calculating it from the differences in HP observed during the first minutes after rising with those measured afterwards, they calculated that the extra energy cost for the first 5 min after rising was 0.011 kcal/kg BW. The AFRC (1993) uses a value of 0.062 kcal/kg BW to estimate the energy cost of the double movement of lying and standing up again. The energy requirement of standing has been proposed as 0.10 kcal/kg BW/h (AFRC, 1993). This activity is already included in the Lofgreen and Garret (1968) maintenance energy requirements estimation.

Rumination

The energy requirement for rumination has been estimated as 0.03 kcal/kg BW/h (Osuji, 1974), 0.08 kcal/kg BW/h (Toutain et al., 1977) and 0.24 kcal/kg BW/h (Graham, 1964). The values are small when compared to the estimated cost of eating of 0.62 kcal/kg BW/h (Osuji, 1974). They can be considered included in the NE_m requirement estimation calculated by Lofgreen and Garrett (1968).

Summary

The study of the maintenance energy requirements for activity in grazing cattle has been conducted generally using a factorial approach. The components responsible for the largest requirements include the ones for bodily movement, both horizontal and vertical, and those related to eating. An adjustment of 0.6 cal/m/kg BW and 6.7 cal/m/kg BW for horizontal and vertical movement can be considered. The energy cost of eating is more difficult to estimate, as it will depend on animal and feed characteristics. The energy cost of eating a pelleted diet is less than for eating a ration with chopped forage, and an adjustment reducing the requirements for maintenance by 10% should be made. Grazing by cattle increases the maintenance requirements over 50% when grazing a low quality pasture, and the actual adjustment will require knowledge of grazing time.

CHAPTER 3
ADJUSTMENT OF THE ENERGY REQUIREMENT FOR MAINTENANCE DUE TO GRAZING ACTIVITY

Introduction

The factorial approach to estimate the energy requirements for maintenance of grazing cattle requires knowledge of the factors involved, the energy cost of each factor, and the amount of time spent on each. Eating and walking are the main factors to consider in the calculation of the additional energy requirements for maintenance of grazing animals. Different environmental and animal factors will affect the magnitude of these activities for an animal on a particular condition. Modifying factors that should be considered include herbage mass and herbage quality, stocking rate, paddock size, availability of water and location of the water supply, breed of the animal, and climate.

Level of Activity Developed by Grazing Cattle

Eating

The gathering of food is the central objective of ruminants on pasture, and one of obvious importance to animal nutrition and vegetation response (Ungar, 1966). The time spent grazing reflects part of the animal's response to its nutritional needs (Arnold and Dudzinski, 1978).

Hodgson (1982) states that the daily consumption of herbage by grazing animals will be determined by:

$I = GT \times RB \times IB$

where I = herbage intake (g)

GT = grazing time (min) ✓

RB = rate of biting during grazing (bites/min)

IB = herbage intake per bite (g/bite)

Allden and Wittaker (1970) studied the factors that affect intake of forage by sheep. They found that grazing time increased from 6 h 40 min to 12 h 30 min, as the herbage mass decreased from 4000 kg DM/ha to 500 kg DM/ha. The herbage mass was not solely responsible for that type of response, as results obtained in a second experiment indicated that structure of the pasture also affected the grazing behavior of lambs. The rate of DM intake increased from 2 to 4 g DM/min by lambs, and from 2 to 6 g DM/min by yearling sheep as the average tiller length increased from 10 to 25 cm.

The comparison of the grazing activities of horses, cattle and sheep grazing together was made by Arnold (1984). He observed that the grazing time for the horse was longer, intermediate for cattle and shorter for sheep. Horses grazed 4.1 to 16.0 h/d, cattle 2.3 to 12.7 h/d and sheep 4.4 to 10.6 h/d. Pasture availability in winter-spring negatively influenced the grazing time in horses and cattle but not in sheep.

The principal source of variation affecting the grazing time in cows grazing a ryegrass-white clover pasture in England was day of the year, a variable highly correlated with day length (Rook and Huckle, 1996).

The amount of walking that an animal performs also affects grazing behavior. Nicholson (1987) found that the combination of walking 40 km every third day and night enclosure reduced the grazing time 38%, while DM intake declined only by 10% compared to animals that grazed without walking or being subjected to night enclosure. Animals enclosed at night only, reduced their grazing time by 9%. El Aich and Rittenhouse (1988) studied the effect of herding on sheep. They found that animals herded to walk up to 11.4 km/day did not exhibit any change in grazing time. In another study with sheep repeated at two locations, El Aich et al. (1991) found that sheep that walked more on watering days reduced their grazing time and feed intake, without altering the rate of biting and the mass per bite.

The group size also affects the grazing time in sheep (Penning et al., 1993). They observed an asymptotic relationship between grazing time and group size, studying groups with size from 1 to 15 sheep. The equation calculated was:

$$\text{GT (min/24 h)} = 629 - (311 \times \exp[-0.46 \times \text{group size}])$$

Supplementation of the grazing animals can affect forage intake. Moore and Kunkle (1995) analyzed the change in forage intake when forages are supplemented with energy and/or protein. The analysis of 135 observations where the intake of forage with and without supplement was known, showed that in some cases the supplementation increased forage intake, in some cases decreased forage intake, and in some cases had no effect on forage intake. The change in voluntary intake of forage expressed as percentage of BW had a range of -1.5 to 1%. There was a relationship between the change in forage intake and the digestible organic matter (DOM) : crude protein (CP) ratio of forage. When CP protein was not deficient (< 7 DOM:CP), the changes in forage intake were negative with few exceptions. When crude protein was deficient relative to DOM (>7 DOM:CP), however, the changes in forage intake were positive or negative (Moore and Kunkle, 1995). Probably the mechanism operating in the response to supplementation of forage intake in grazing animals will be a variation of the grazing time.

Sarker and Holmes (1974) studied the effect of concentrate supplementation on the organic matter (OM) intake and on the grazing time of nonlactating cows. The total OM intake increased as the level of supplement increased, from 11.5 kg/d with 2 kg concentrate/d to 13.6 kg/d with 8 kg concentrate/d. Forage intake decreased from 9.5 to 5.6 kg/d. The time spent grazing decreased from 8 h 15 min/d to 6 h/d with the greater supplementation rate.

Combellas et al. (1979) studied the effect of concentrate supplementation on herbage intake and grazing behavior of Friesian heifers. The heifers were supplemented with 0, 3 or 6 kg/day of concentrate with an *in vivo* OM digestibility of 78% and 22% CP. Herbage intake decreased from 25.7 to 17.8 g OM/kg BW/d and also the grazing time, from 7.7 to 6.6 h/d in heifers supplemented with 6 kg/day of concentrate compared to the unsupplemented heifers.

In another study, no differences were detected on the components of grazing behavior (GT, IB, and RB) in steers (335 kg BW) supplemented with 0, 1.5, 3.0, or 4.5 kg of corn (Dougherty et al., 1988). In this case grazing was restricted to two 2-h periods, one in the morning and the other in the afternoon, and probably no treatment was allowed to express the grazing potential of the animals.

Walking

Reports on the distances that cattle walk are summarized in Table 8. The range of walking distance was from 0.9 to 12.6 km/day. As stated by Arnold and Dudzinski (1978), these values may not represent the maximal walking distance that cattle can walk in a particular day. Nicholson

Table 8. Daily walking activity realized by cattle in different environments.

Location	Size of paddock (ha)	n	Distance walked (km/day)	Reference
North Dakota	12	1[a]	2.7	Shepperd (1921)
	41	1[a]	5.0	
	260	1[a]	8.9	
Reading, UK	0.4	4	2.8	Castle et al. (1950)
Ayr, UK	0.5	6	1.2-2.0	Waite et al. (1951)
Kansas	338	6	4.4	Moorefield and Hopkins (1951)
Hurley, UK	0.2	3	2.1	Hughes and Reid (1952)
Montana	41	10	3.2	Peterson and Woolfolk (1955)
Oklahoma	610	20	5.0	Dwyer (1961)
California	62	9	4.4	Wagnon (1963)
	93	8	5.1	
Texas	691	20	6.6	Box et al. (1965)
New Mexico	1464	36	12.6	Herbel and Nelson (1966)
Colorado	20	5	2.4	Quinn and Harvey (1970)
Oregon	813	5	9.7	Sneva(1970)
Utah	2000	15	6.3	Malechek and Smith (1976)
Wyoming	12	4	2.4	Hepworth et al. (1991)
	9	4	2.7	
Wyoming	24	6	3.2	Hart et al. (1993)
	207	6	6.1	

[a] Observations made on the whole herd.

(1987) describes a management system in Africa where cattle were herded every 3 d to the water supply, walking on that particular day 40 km. Bonsma and Le Roux (1953) reported that as a result of drought conditions some groups of cattle covered 26 km/day or more, walking to the watering points and back to the grazing areas.

Other factors also have an influence on the distance walked by freely grazing animals. In conditions of the range in the western USA, Sneva (1970) observed that Brahman x Hereford steers walked 9.7 km/d, a longer distance than the 7.4 km/d walked by Hereford steers while grazing the same paddock. Herbel and Nelson (1966) also found that Santa Gertrudis cows walked 12.6 km/day while Hereford cows walked 7.9 km/day, when kept under the same conditions. Arnold and Dudzinski (1978) suggested that, even though these studies represented the only evidence available, it is generally accepted that Brahman, Santa Gertrudis, and Africander cattle will range further than British breeds of cattle in hot climates. In the experiments where paddock size was compared (Shepperd, 1921; Hart et al., 1993), the distance that animals walked increased as the size of the paddock increased.

A limit to the distance that an animal can walk can be affected by factors other than the paddock size. Compton and Brundage (1971) observed the behavior of a herd, composed mostly of Holstein-Friesian heifers and a few steers, in an unfenced range of the subalpine zone of Alaska. The animals walked a mean distance of 4.2 km/d with a range of 2.6 to 6.9 km/d.

The location of the water sources and supplement feeders can affect the distance that an animal walks. Squires and Wilson (1971) studied the effect of placing the ration feeders 2.4, 3.2, 4.0, 4.8 or 5.6 km from the water, in a setting where no other feed was available to the animals. They used Merino and Border Leicester sheep. Distance walked reached a maximum of 13.6 km/d for Merino sheep when food was 4.0 km away from water, and 17.6 km/d for Border Leicester sheep when food was 4.8 km away from water. Sheep regulated the distance walked by reducing the drinking frequency. The strategical placement of mineral feeders within a paddock has been used to improve the grazing of under-grazed areas of the pasture (Heady, 1975).

The winter supplementation of a protein supplement can reduce the distance that cattle walk. Box et al. (1965)

observed a reduction in the distance walked by Hereford heifers supplemented with 680 g/d of 41% CP cottonseed meal. The supplemented heifers walked 3.1 km/d while the unsupplemented heifers walked 6.6 km/d grazing paddocks of similar size (691 ha). Grazing time was not affected by the supplementation.

Schmidt (1969, cited by Lynch and Alexander, 1973) studied the cattle movements in a hot dry climate in Australia. The area was unfenced and 800 head of cattle used each watering point that served 18,000 ha. He observed that the cattle herd divided itself into two groups. Forty percent of the cattle set off from the water in the early morning and walked 6 to 7 km in single file before stopping to graze. The remaining 60% slowly moved to a maximum of 4 km from the water.

Studies conducted in Wyoming (Pinchak et al., 1991) observed cattle dispersion in animals fitted with radio telemetry collars, which were located with a receiver and a two elements directional antenna. Cattle dispersion was constrained by the spatial distribution of water and slope. Seventy-seven percent of the grassland's use was within 366 m from the water, while 65% of the land, which was beyond

723 m sustained only 12% of use. The dispersion away from the water increases as the grazing season advances, presumably as available forage gets depleted. We can assume that the increase of cattle dispersion can be associated with a higher walking distance. Cattle also avoided grazing when the slope was more than 10% (Pinchak et al., 1991; Bailey et al., 1996).

Animals move more slowly through areas with more abundant nutrients, because they spend more time eating than moving (Laca et al., 1994, cited by Bailey et al., 1996). Another study did not find any correlation between the distance traveled by Corriedale sheep on the Peruvian Puna and forage availability (Fierro and Bryant, 1990). Selectivity of palatable plants can affect the grazing pattern of herbivores, as they tend to move slower when they are grazing areas with a high density of palatable plants (Bailey et al., 1996). In pastures that are not homogeneous, the distribution of the patches can be a factor that will interact with location of water, supplement feeders, or terrain, as the animals will select the better patches for grazing and the walking will be related to their location.

Quinn and Harvey (1970) studied the effect of three stocking rates on the distance walked by yearling steers. The stocking rates used in ha/steer were 0.80, 0.44, and 0.28, respectively for the light-, moderate-, and heavy-use pastures. The distance walked by the steers in the light-use pasture was 2.4 km/d, a lower distance than the 3.2 km/d walked by the steers in the moderate- and heavy-use pasture.

Shape of the paddock can also affect the spatial distribution of cattle in a paddock. Hart et al. (1993) found that in a "U" shaped 207 ha paddock, where the water supply was located in one end, use of the pasture declined beyond 3 km from the water (maximal distance = 5 km). A similar size paddock, but square in shape will have a maximal distance of 2 km to the water, so it can be expected that the distance walked by the animals can be lower in the square paddock.

Estimation of the amount of activity by grazing animals should then consider various factors and the way they interact. Often this will be unique to a particular situation. The use of generalizations for the estimations will not always provide accurate values, and in some circumstances will result in misleading calculations of energy requirements. A detailed knowledge of the behavior exhibited by animals will improve the results of the calculations.

Estimation of Energy Requirements for Activity by Different Feeding Systems

The feeding systems in use have utilized some corrections to their maintenance energy requirement estimations to account for the activity requirements.

The AFRC (1993) based its recommendations on the original proposition of the ARC(1980), which is a factorial approach. The activities considered and their estimated energy requirements were:

Horizontal movement	0.62 cal/kg BW/m
Vertical movement	6.7 cal/kg BW/m
Standing for 24 hours	2.4 kcal/kg BW/d
Body position change	62 cal/kg BW

The adjustments were made knowing the amount of activity done by the animals. ARC (1980) proposed a base activity allowance of 1.03 kcal/kg BW in cattle, to account for standing and walking when no estimation of activity level was possible. AFRC (1990) recommends the inclusion of an activity allowance for beef cattle of 1.69 kcal/kg BW. The estimation is based on a horizontal movement of 200 m, 12 h standing and 6 position changes. In the case of dairy cattle the adjustment is 2.26 kcal/kg BW, assuming a 500 m walk, 14 h standing, and 9 position changes. No adjustment is made for the form in which the ration is given or for grazing activity.

The INRA (Jarrige, 1989) considers that the energy requirement for maintenance of a stall-fed cow is the same as that obtained from the respiration chamber calculations and an increment of 10% over that should be made for loosely-housed cows and 20% for cows at pasture. In the case of beef cows the same criteria are followed, considering also that the adjustment will consider some climatic components. No consideration is made in the case of growing steers.

The NRC (1984) considered that the maintenance requirements estimated by the Lofgreen and Garrett (1968) equation were most applicable for penned animals in nonstressful environments with minimal activity. No adjustment was proposed for conditions different to that where the estimation was made.

George (1984) proposed to adjust the base maintenance requirements to consider activity by a multiplicative effect:

$$AE = 1.05 + (0.0741 \times GU)$$

where AE is activity effect, the multiplicative effect of activity, and GU is the grazing land area unit required to sustain a 500-kg nonlactating mature cow for the grazing season in hectares. The equation assumes a maintenance increase of 5% because the animal is grazing even though the area is no larger than the area occupied by a housed animal consuming the same forage fed clipped. Furthermore, maintenance increases 7.41% per hectare per grazing unit. The AE nearly doubles the NRC(1996) energy maintenance requirement (0.077 Mcal/kg $BW^{0.75}$) when the grazing unit exceeds 12 ha. For areas where GU equals 0.5 to 2, it increases 7 to 20%. This approach was used by the developers of the Cornell Net Carbohydrate and Protein System to adjust the maintenance requirements (Fox et al., 1992). This approach does not consider, however, paddock size, or the type of terrain which can affect the estimation of the energy requirements.

CSIRO (1990) also established the estimates of activity according to the ones proposed by the ARC (1980). It includes also the energetic cost of eating as 0.6 Kcal/kg BW/hour and the energetic cost of ruminating of 0.48 Kcal/kg BW/hour. Considering that the energy requirement increases in animals under grazing from 10 - 20% in the best grazing conditions up to about 50% for animals on extensive hilly pastures, the CSIRO (1990) proposed an adjustment for the energy expenditure at pasture: EGRAZE.

$$\text{EGRAZE (MJ NE/d)} = [(C*DMI(.9-D))+(.05T/(GF+3))]* BW$$

where:

C = 0.05 (sheep, goats) or 0.006 (cattle)

DMI = dry matter intake from pasture, kg/d, excluding supplementary DM

D = digestibility of the dry matter (decimal)

T = 1.0 or 1.5 or 2.0 for level, undulating or hilly terrain respectively.

GF = Availability of green forage, tons DM/ha (quantity when cut to ground level). If GF is so low that, in effect, dead forage only is available to the animal it is suggested that total forage (t DM/ha) be used in place of GF.

BW = Bodyweight (kg)

NRC (1996) uses the same CSIRO (1990) equation to adjust for activity, corrected so it is expressed in Mcal net energy/day.

The first term of the CSIRO equation defines the additional net energy expenditure for eating incurred by grazing compared with housed animals. The difficulty of estimating DMI of the animal under grazing is an important factor to be considered. Associative effects on the digestion of the supplement and the forage also must be considered, in the digestibility term included in the equation. The second term of the equation defines the energy expenditure due to walking. It assumes that the animals will select only green forage in the diet, but when green forage disappears completely, the term can be replaced with total herbage mass. The structure of the canopy, and the percentage of green forage with respect to the total forage available, are factors that will introduce variation in the activity necessary to obtain the feed. Also there is a limit to grazing time. Even though grazing time increases as the forage availability decreases, there is an upper limit of 12-14 h/d, that occurs at a limiting herbage mass, a value well above zero. The type of terrain is an important factor to consider and the definition of the different situations is not well defined (level of undulations, etc). No considerations are made for paddock size or grazing system, which affect the walking distance and the selectivity exhibited by the animals.

Proposed Adjustment for Activity of Maintenance Energy Requirements

Utilizing information compiled in this review, adjustments to the maintenance requirements for animals in the grazing situation will be proposed. The main factors associated with activity of the grazing animal will be walking, which considers the horizontal and vertical components, and eating, the actual gathering of forage.

Using the information compiled in Table 8, a regression model analysis using PROC REG (SAS, 1988b) was performed with the model:

$$Y = a + bx + bx^2 + e$$

where

y = walking distance in km/d

x = paddock size in ha

e = error term

The equation obtained was:

$$Y = 2.90 + 0.0111\, x - 0.00000441\, x^2$$

The equation was significant ($P<0.0001$) with an R-square of 0.6992 and a root-MSE of 1.65. The prediction equation could not be evaluated because no independent data set was available. This equation can be used to obtain a first approximation of the expected walking distance in paddocks of different sizes. Results obtained for different paddock sizes are presented in Table 9. According to the walking distances calculated in Table 9, the energy cost of the activity can be calculated. In Table 10 calculations of the energy cost of walking of cattle of different BW, placed in paddocks of different sizes are presented. The energy maintenance requirements were calculated according to the expression of 0.077 Mcal/kg $BW^{0.75}$ (NRC, 1996), and the energy requirements for walking using the (AFRC, 1993) estimates of .62 cal/kg BW/m.

Table 9. Estimated daily walking distance in paddocks varying in size.

Paddock size (ha)	Distance walked (m)[a]
1	2,911
10	3,010
50	3,444
100	3,967
200	4,946
500	7,354
1000	9,609

[a] Distance walked, m = $[2.90 + (0.0111 * ha) - (0.00000441 * ha^2)] * 1000$

Table 10. Estimation of the energy cost of horizontal walking in cattle of different BW as Mcal/day and as a percentage of the NRC (1996) maintenance requirements.

Bodyweight (kg)	Maintenance Requirement (Mcal/d)	Paddock size (ha)		
		10	100	1000
300	5.550	0.560[a] (10.1%)[b]	0.738 (13.3%)	1.787 (32.2%)
400	6.887	0.746 (10.8%)	0.984 (14.3%)	2.383 (34.6%)
500	8.142	0.933 (11.5%)	1.228 (15.1%)	2.987 (36.7%)

[a] Mcal/d, calculated from walking distance (table 9) and 0.62 cal/kg BW/m of horizontal walking.

[b] Percentage increase over maintenance.

Estimations of vertical displacement done by cattle were not found in the literature reviewed. Lachica et al. (1997b) reported that goats exhibited a range of vertical ascent from 139 m in the autumn to 197 m in the spring, while grazing a 130-ha paddock with a rugged topography and an altitude range from 735 to 1025 m above sea level. Estimations of the energy spent on vertical ascent for an hypothetical ascent of 100 m, 200 m, and 300 m are presented in Table 11. The AFRC (1993) estimate of 6.7 cal/kg BW/m was used, but an adjustment to account for the lower requirements generated while walking downhill was made. The adjustment was based on the proposal of Lachica et al. (1997a) of a discount of -3 cal/kg BW/m descent. The resulting value to account for vertical ascent was then 3.7 cal/kg BW/m. The adjustment in percentage over the NRC (1996) energy maintenance requirement is presented.

The adjustments required for horizontal walking and vertical ascent when expressed as percentage of the basic energy maintenance requirement increased with higher BW. As the NRC (1996) maintenance energy requirements calculation is based on metabolic weight ($BW^{0.75}$) and the adjustments are based on BW, that trend could be expected.

Table 11. Estimation of the energy cost of vertical displacement in cattle of different BW as Mcal/day and as a percentage of the NRC (1996) maintenance requirements.

Bodyweight (kg)	Maintenance Requirement (Mcal/d)	Vertical ascent (m)		
		100	200	300
300	5.550	0.111[a] (2.0%)[b]	0.222 (4.0%)	0.333 (6.0)
400	6.887	0.147 (2.1%)	0.294 (4.3%)	0.441 (6.4)
500	8.142	0.184 (2.3%)	0.368 (4.5%)	0.553 (6.8%)

[a] Mcal/day, calculated from 3.7 cal/kg BW/m vertical ascent

[b] Percentage increase over maintenance.

Heavier animals will require a higher adjustment of their energy maintenance requirements, when done on a percentage base.

In the case of eating, the estimates made by Di Marco et al. (1996) were used. For a regular pasture condition, defined as a ryegrass pasture with a herbage mass of 1480 kg/ha, a height of 10.5 cm, DM digestibility of 61% and a CP concentration of 15 g/100g DM, the HP measured/h of grazing was 1.85 kcal/$BW^{0.75}$. In the case of a good pasture condition, an oat pasture with a herbage mass of 2280 kg/ha, 26.9 cm height, a digestibility of 76%, and a CP concentration of 19.4 g/100 g DM, HP measured/h of grazing was 0.55 kcal/$BW^{0.75}$. The adjustment for the maintenance energy requirements due to grazing time, is presented in Table 12. No values are assigned for 3-hours grazing time in the regular pasture condition and for 12-hours grazing in the good pasture condition, as it is unreasonable to expect such grazing time with those forage qualities. The data available represent a limited range of temperate pasture conditions, but in the case of regular pasture condition the biting rate observed was 59 bites/min, a value that approach the upper biting rate limit for cattle (Minson, 1990), and

Table 12. Estimated energy requirements for grazing activity of cattle grazing pastures of different conditions, as kcal/kg $BW^{0.75}$ and as a percentage of the maintenance requirements.

Grazing Time (h)	Pasture Condition	
	Regular[a]	Good[b]
3	-	1.65[d] (2.1%)
6	11.1[c] (14.4%)[e]	3.30 (4.2%)
9	16.1 (21.6%)	4.95 (6.4%)
12	22.2 (28.8%)	-

[a] Ryegrass pasture, 1480 kg DM/ha HM, 61% DMD, 10.5 cm height, and 15 g CP/ 100g DM.

[b] Oats pasture, 2280 kg DM/ha HM, 76% DMD, 26.7 cm height, and 19.4 g CP. 100 g DM.

[c] 1.85 Kcal/Kg $BW^{0.75}$/h.

[d] 0.55 Kcal/Kg $BW^{0.75}$/h.

[e] Percentage of maintenance requirement.

probably the energy expenditure recorded for the regular pasture condition (1.85 kcal/h) is close to the upper limit of energy requirement for grazing. In mature tropical pastures with low nutritive value, there may be also an added energy requirement to cut the bitten forage from the standing plant, but such information was not found in the literature reviewed.

The combination of the additional adjustments of the energy maintenance requirements and integrating them to solve for particular situations is a task that animal managers should perform, knowing the particular situation of the operation where the adjustment will apply.

Calculation of the adjustment for activity of the energy requirements for maintenance of grazing cattle can be made knowing the size of the paddock where the animals are grazing or the daily walking distance, the daily vertical ascent, grazing time, and pasture condition. The equation is:

Activity Requirements(Mcal/d) = [(walking distance (m) * 0.62 (cal/m/ kg BW) * BW (kg)) + (vertical ascent (m) * 3.7 (cal/m/ kg BW) * BW (kg)) + (grazing time * eating energy expenditure (cal/h/kg $BW^{0.75}$))]/ 10^6

Where walking distance is a known value or was calculated from paddock size. Eating energy expenditure has a mean value of 1200 cal/h/kg $BW^{0.75}$, with a range from 550 cal/h/kg $BW^{0.75}$ in a lush pasture without a limiting herbage availability, to 1850 cal/h/kg $BW^{0.75}$ in a regular pasture condition where the availability of forage is limited.

As a summary and in order to give examples for some scenarios, correction factors to be applied to the requirements of energy for maintenance, due to activity for a 400-kg steer are presented in Table 13. The grazing energy expenditure used to calculate the adjustment was 1200 cal/h/kg $BW^{0.75,}$ the mean value reported by Di Marco et al. (1996). An adjustment should be made to the percentages reported in Table 13 if the pastures are lush or sparse. In the case of lush pastures 5% should be discounted from the adjustment percentage, in animals grazing 6 h/d, and in the case of animals grazing sparse pastures 12 h/d , an additional 10 % should be added to the adjustment percentage. Lighter animals than the 400-kg cow selected for this example will require a lower adjustment while heavier animals will require a greater adjustment. The knowledge of the amount of activity developed by grazing animals will allow a better adjustment for a particular situation.

Table 13. Estimated adjustment of the energy maintenance requirements for the combined effect of walking and eating, for a 400 kg cow under grazing in paddocks with different sizes, vertical ascent distances, and grazing time.

Paddock Size (ha)	Vertical Ascent (m)	Grazing Time h/d		
		6	9	12
1	0	1.366[a] (19.8%)[b]	1.688 (24.5%)	2.010 (29.2%)
10	0	1.391 (20.2%)	1.713 (24.9%)	2.035 (29.5%)
100	0	1.628 (23.6%)	1.950 (28.3%)	2.272 (33.0%)
100	200	1.924 (27.9%)	2.246 (32.6%)	2.568 (37.3%)
1000	0	3.027 (44.0%)	3.349 (48.6%)	3.671 (53.3%)
1000	200	3.323 (48.3%)	3.645 (52.9%)	3.967 (57.6%)

[a] Mcal/d, calculated as Activity requirements = [(walking distance (m) * 0.62 * BW (kg)) + (vertical ascent (m) * 3.7 * BW (kg)) + (grazing time * 1200 * kg $BW^{0.75}$)]/10^6.

[b] Percentage of the NRC (1996) maintenance requirement (0.077 Mcal/kg $BW^{0.75}$)

Summary

The review of the adjustment for activity of grazing cattle proposed by actual feeding systems reveals a lack of uniform criteria for making the adjustments. In many range conditions the size of the paddock may play an important role in determining the walking activity of grazing cattle. A regression equation generated from published data where walking distance and paddock size was developed as:

$$\text{Walking (km/d)} = 2.90 + 0.0111 * \text{ha} - 0.00000441 * \text{ha}^2$$

It can be used as a primary approach to the estimation of the walking distance, and from that the energy requirements for walking, considering the energy expenditure of horizontal walking, 0.62 cal/kg BW/m.

Information on the energy requirements of the eating component of grazing is scarce, but the adjustment should be based on the pasture condition, a subjective measurement that combines nutritive value of the forage on offer, and aspects of herbage mass and canopy structure, and on the grazing time of the animals in the pasture.

The energy requirement for vertical ascent also must be included in the adjustment, but corrected for the energy spent during the descent, which gives a value of 3.7 cal/kg BW/m.

There are additional factors that may affect the energy maintenance requirement for grazing. However there is inadequate information in the literature to model all adjustments.

CHAPTER 4

PREDICTION OF INTAKE BY LACTATING COWS ON FORAGE DIETS

Introduction

The recognition of the importance of food intake in animal production can be traced back to ancient times. Flatt (1987, cited by Poppi, 1996) commented that the Egyptians force-fed cattle around 2500 BC, one of the first records of recognition that food intake was limiting animal performance. Farm animals producing under extensive or intensive systems are fed generally *ad libitum*, and the knowledge of the factors which control and influence intake are relevant for agriculturists around the world (Forbes, 1995). The development of a feeding management system for high producing dairy herds needs to attain as its first step a high dry matter intake (DMI) (Chase, 1993).

Prediction of intake in ruminants is relevant for the day to day management in the care of grazing stock, in the planning of rations, and in the long term programming of feed production, acquisition and storage (Kahn and Spedding, 1984). The task is often difficult because of the interactions between animal and diet and is particularly so under conditions where few reliable data are available on which to base equations, as for grazing cattle (Forbes, 1995).

Lactation generates a large increase in nutrient demands, especially in dairy cows which have been bred for high milk production. Lactating cows fed diets where protein is not a limiting factor, can consume to 2 to 3.8 times the amount of energy required for maintenance including a minimal activity, and can exceed 4 times maintenance when the diet is based on grain due to an increase of milk production (NRC, 1987).

The objective of this work was to develop DMI prediction equations from information collected from published trials for further use in production models.

Literature Review

The study of the mechanisms controlling intake regulation has been described as comprising short- and long-term mechanisms of control (Mertens, 1987). Short-term regulation of intake is related to within-day events that affect frequency, size and pattern of meals. The study of the factors that affect the short-term regulation of intake has focused on the specific chemicals and endocrine regulators that, together with nervous stimuli, control the mechanisms of hunger and satiety. Long-term regulation of intake refers to average daily intake over periods of time during which animal nutrient requirements for maintenance and production are stable (Mertens, 1987). The development of applied models for prediction of intake relies for its development on the utilization of inputs that characterize the long-term intake regulation, as the complexity of the factors responsible for the short term regulation require elaborate dynamic models (Mertens, 1987).

Intake Prediction Models

Before the 1960's several prediction equations had been derived, all based on the idea that ruminants ate until they were 'full' (Forbes, 1995). Lehmann (1941, cited by Conrad et al., 1964) observed in Germany that feed intake was such that the amount of undigested organic matter excreted daily in the feces was the same for all feeds used. Conrad et al. (1964) studied the regulation of feed intake in Holstein and Jersey cows fed *ad libitum*. The digestibilities of the diets ranged from 52 to 80%. They observed that the mechanisms regulating intake were not the same through the whole range of digestibilities studied. Intake of diets with a digestibility lower than 67% was regulated by physical control mechanisms, related to the fill capacity of the animal and the digestibility of the feed. When the digestibility of the diet was higher than 67%, metabolic control mechanisms were implicated in the intake regulation, which was related to the energy required for production. Two different relationships were found applying regression analysis. For diets with less than 67% digestibility the equation was:

$$\log \mathrm{DMI}(\mathrm{lb/d}) = -5.296 + 1.53 \log D(\%) + 1.01 \log F(\mathrm{lb/d}) + 0.99 \log BW\ (\mathrm{lb})$$

where: DMI = dry matter intake

D = dry matter digestibility

F = fecal dry matter output

BW = body weight

Dry matter intake increased as digestibility of the feed increased.

For diets with digestibility above 67%, the equation that was the best fit for the data was:

$$\log \mathrm{DMI}(\mathrm{kg}) = 1.48 - 1.19 \log D(\%) + 0.62 \log BW(\mathrm{kg}) + + 0.27 \log E(\mathrm{kcal/d})$$

where: E = production energy requirement, the sum of the energy content of milk and energy from the protein balance. In this case DMI decreased as digestibility increased. The models included variables that characterized the diet and the animal, and the animal and feed components had different relative importance according to the mechanism controlling intake. If the fill mechanism was involved, the feed characteristics were relatively important, while if the metabolic mechanism was controlling intake, animal characteristics were relatively more important (Conrad, 1966).

Lactation generates a large increase in demand of nutrients, especially in dairy cows which have been bred for high milk production. Correlations between milk production and DMI have varied from less than 0.2 to 0.8 (Forbes, 1995). Ruiz (1993) considered that the prevalent approach to relate milk production to DMI was that the amount of milk production is the factor that drives DMI. Simple systems have been proposed to predict DMI based on development of multiple regression equations. MAFF (1975) proposed the use of the following equations:

$$\text{DMI (kg/d)} = 0.025\ \text{BW (kg)} + 0.1\ \text{MY (kg/d)}$$

or for the case of high producing cows:

$$\text{DMI (kg/d)} = 0.022\ \text{BW (kg)} + 0.2\ \text{MY (kg/d)}$$

where DMI is the voluntary dry matter intake and MY is the milk yield.

Similar types of equations have been proposed in the USA. Rayburn and Fox (1993) converted into a mathematical function the NRC (1989) table of DMI requirements, which included the production of 4% fat-corrected milk (FCM) and the metabolic body weight ($BW^{0.75}$). The resulting equation was:

$$\text{DMI (kg/d)} = -0.293 + (0.372\ \text{FCM (kg/d)}) + (0.0968\ BW^{0.75}\text{(kg)})$$

Kertz et al. (1991) used the data obtained in 18 experiments over a period of six years to develop a series of equations using least square procedures. Two data sets were evaluated, one with data from 469 cows in the period covering from parturition to 63 days postpartum. Cows were fed diets containing 37 to 45% of its DM from forage. A second data set with data from 247 cows with 70 to 147 days postpartum was also used. Cows were fed diets of 43 to 56% forage DM. The equation developed including all parities and both data sets that best predicted DMI was:

$$\mathrm{DMI(kg/d)} = 0.008037\ \mathrm{BW(kg)} + 0.3134\ \mathrm{FCM(kg/d)} + 0.2286\ \mathrm{DIM} - 0.002176\ \mathrm{DIM}^2 + 0.00000705\ \mathrm{DIM}^3$$

$$R^2 = 0.64 \qquad CV = 0.111$$

Vadiveloo and Holmes (1979) compiled data on cows at least eight weeks postpartum provided by several experimental farms in England to develop equations using multiple regression. The data included the following variables: DMI, concentrate intake (C), BW, week of lactation (WL), milk yield (MY), milk fat percentage (MFP), solids-not-fat percentage (SNF), forage ME concentration (FME) and lactation number(L). Two equations selected from four models evaluated were the following:

$$\mathrm{DMI(kg/d)} = 0.076 + 0.404\ \mathrm{C(kg/d)} + 0.013\ \mathrm{BW(kg)} - 0.129\ \mathrm{WL} + 4.12\ \log \mathrm{WL} + 0.140\ \mathrm{MY(kg/d)}$$

$$R^2 = 0.730$$

$$\mathrm{DMI(kg/d)} = -4.140 + 0.430\ \mathrm{C(kg/d)} + 0.015\ \mathrm{BW(kg)} - 0.095\ \mathrm{WL} + 4.040\ \log \mathrm{WL} + 0.208\ \mathrm{MY(kg/d)}$$

$$R^2 = 0.719$$

AFRC (1990) selected the second equation from Vadiveloo and Holmes (1979) as a general predictor of DMI in the British feed system.

Roseler et al. (1993) proposed four equations to predict DMI for primiparous or multiparous cows, including a comprehensive and a simplified version for each one. The comprehensive equations were:

$$\text{Primiparous DMI(kg/d)} = 3.7 + 0.012\ \text{BW(kg)} + 0.12\ \text{BW change(kg/wk)} + 12.2\ \text{MP(kg/d)} - 0.007\ \text{days pregnant*early LAG}$$

$$\text{Multiparous DMI(kg/d)} = 0.6 + 0.005\ \text{BW(kg)} + 0.12\ \text{BW change(kg/wk)} + 10.4\ \text{MP (kg/d)} - 0.13\ \text{days pregnant} - 0.17\ \text{Lactation wk} + 4.59\ \ln\ \text{Lactation wk}$$

where MP is milk protein yield and LAG is an adjustment for time where the peak of milk production is reached. An $R^2 = 0.87$ was obtained with these equations.

The simplified equations included only BW at calving and milk protein yield corrected by LAG for peak of milk production, and resulted in an $R^2 = 0.79$.

Production systems based on the utilization of feed with medium to high concentration of fiber should also take into account variables from the feed to predict DMI. Mertens (1987) proposed the use of 'conceptual' equations to develop theoretical models to estimate DMI. From data obtained in several experiments he concluded that the intake of NDF was constant at a value of 1.2% of BW by cows that produced a maximum of FCM. Intake can be calculated by the equation:

$$DMI(kg/d) = (0.012*BW(kg))/NDF(\%, \text{decimal fraction})$$

Not all research supports the concept that forage intake is limited by an animal's capacity to consume NDF. For forage diets, Beauchemin (1996) observed that NDF intake varied among sheep fed a particular forage, and among various forages. Sheep ate 12.9 g NDF/kg $BW^{0.75}$ when fed Cicer milkvetch but ate up to 32.9 g NDF/kg $BW^{0.75}$ when fed orchardgrass. She concluded that although digestible fiber limits intake of forage diets, the reliability of predicting

DMI solely from NDF is poor. Ruiz (1993) concluded that for diets containing traditional sources of forages (corn silage or alfalfa), predictions of DMI based on equations using NDF or undigested NDF achieved similar accuracy. The use of indigestible NDF may be recommended when nontraditional fiber sources (sorghum silage, bermudagrass silage, dwarf elephantgrass silage) with a wide range in fiber quality are fed to cattle.

Other fiber-related variables have been used to develop predictive equations of DMI. Brown et al. (1977) found that the inclusion of crude fiber, in linear and quadratic terms, improved the prediction of DMI with a model including DIM, ln DIM, ln milk production, milk fat production, and BW. Yungblut et al. (1981a) developed predictive equations for DMI with the use of two independent data sets. The inclusion of feed ADF was significant. With a data set from cows fed total mixed rations (TMR), with rations containing 40 to 100% forage, the resulting equation was:

$$\begin{aligned} \mathrm{DMI(kg/d)} = {} & 3.3676 + 0.3395\ \mathrm{LactN} + 0.3362\ \mathrm{MY(kg/d)} + \\ & + 0.5282\ \mathrm{MFP}\ (\%) - 0.1061\ \mathrm{ADF}(\%) + \\ & 0.0096\ \mathrm{BW(kg)} \end{aligned}$$

where LactN is the lactation number. In this case the R^2 was 0.78, and the inclusion of ADF increased the R^2 by 0.002.

Another equation was developed with an independent data set where cows were fed the forage ad libitum with a fixed amount of concentrate:

$$\mathrm{DMI(kg/d)} = -5.5231 + 0.3155\ \mathrm{LactN} + 0.4209\ \mathrm{MY(kg/d)} + \\ + 0.7836\ \mathrm{MFP(\%)} + 0.3786\ \mathrm{ADF(\%)} + \\ 0.0013\ \mathrm{BW(kg)}$$

In this case $R^2 = 0.77$, and the inclusion of ADF represented an increase in R^2 of 0.177, the second most important variable after MY.

Rayburn and Fox (1993) found the need for different equations, according to DIM, to predict DMI. If DIM was lower or equal to 84, the equation was:

$$\mathrm{DMI(kg/d)} = 0.0117\ \mathrm{BW(kg)} + 0.281\ \mathrm{FCM(kg/d)} + \\ 0.0749\ \mathrm{DIM}$$

When the postpartum period was longer than 84 d, the equation included also the concentration of NDF in the ration:

$$\mathrm{DMI(kg/d)} = 0.023\ \mathrm{BW(kg)} + 0.286\ \mathrm{FCM(kg/d)} + 0.0201\ \mathrm{DIM} - 0.0979\ \mathrm{NDF(\%)}$$

Degradation characteristics of the feed have been proposed as variables to develop prediction equations for DMI. Orskov et al. (1988) studied the degradability characteristics of barley straw applying an exponential equation to the data obtained by the nylon bag technique, where P is the disappearance of substrate at time t, and a, b, and c are constants:

$$P = a + b\ (1 - e^{ct})$$

An equation including the three factors, a, b, and c was obtained, which had an R^2 of 0.79.

Prediction of DMI for animals fed silage diets has been studied. Richards and Wolton(1975) proposed a prediction equation for silage, which was developed using data from beef and dairy cattle, either growing or lactating. The equation was:

$$\text{DMI(kg/d)} = -3.54 + 0.133 \text{ silage DM} - 0.282 \text{ silage pH}$$
$$-0.364 \text{ supplement intake(kg/d)} + \text{BW}^{0.73}\text{(kg)}.$$
$$R^2 = 0.963$$

AFRC(1991) proposed the use of the following equation to predict DMI in lactating cows fed with silage:

$$\text{DMI(kg/d)} = -3.74 - 0.387 \text{ supplement intake(kg/d)}$$
$$+ 1.486 \text{ yield protein + fat(kg/d)}$$
$$+ 0.0066 \text{ BW(kg)} + 0.0136 \text{ DOMD(g/kg DM)}$$

Where: DOMD = digestible organic matter

Evaluation of prediction models

Evaluation of different equations using independent data sets has been conducted (Yungblut, 1981b; Neal et al., 1984; AFRC, 1991; Kabuga, 1992; Rayburn and Fox, 1993; Roseler et al.,1993; Fuentes-Pila et al., 1996). In some cases the evaluation was made on the data collected on individual farms (Yungblut et al., 1981b), or with different data set to evaluate the robustness of the equations under different conditions (Fuentes-Pila et al., 1996). In the other cases a data set was obtained by merging data obtained from the literature, or compiling extensive data from research results of different experiments.

Neal et al. (1984) compared the equations developed by Vadiveloo and Holmes (1979), MAFF (1975), ARC (1980), Bines et al. (1977), and by Lewis (1981, cited by Neal et al., 1984). The actual and predicted weekly intakes were compared by calculating the mean square prediction error (MSPE). From MSPE, MPE can be calculated as the square root (Theil, 1966; Bibby and Toutenburg, 1977). The equations that presented the lowest values for MSPE were those of Vadiveloo and Holmes (1979) and the equation developed by Lewis (1981, cited by Neal et al., 1984). These equations were developed with data from feeding regimes similar to the ones used in the evaluation data set. The evaluation data set had a mean DMI of 14.8 kg DM/d, and the lowest MPE was 1.45 kg DM/d for the second equation developed by Vadiveloo and Holmes(1979). The same equation was considered the best in the evaluation done by Kabuga (1992), with a data set of dairy cows producing in Ghana, but the MSPE ranged from 1.32 kg DM/d for cows in middle lactation to 2.13 for cows in late lactation.

Yungblut et al. (1981b) evaluated the equations developed by Yungblut et al. (1981a), the equation of Brown et al. (1977) and an equation described by McCullough (1973, cited by Yungblut el al., 1981b). They collected data from 20 farms and evaluated each equation separately with each farm's data. The best fitted equation predicted the mean DMI ± 10% in 12 of the 20 cases. Fuentes-Pila et al. (1996) evaluated equations that included only animal factors; none of the equations that they evaluated predicted DMI satisfactorily in individual cows. AFRC (1991) suggested that the predictions would be more accurate for groups of cattle than for individuals. The emphasis in future model development should be allocated to the collection of more appropriate data rather than to the improvement of the structural forms of the model. The construction of models from data sets for specific diets and animal classes rather than a continued search for global models might also yield benefits (AFRC, 1991).

Materials and Methods

As a general approach, the strategies for building a regression model as proposed by Neter et al.(1996) were followed.

The strategies involved four phases:

1. Data collection and preparation.
2. Reduction of the number of independent variables.
3. Model refinement and selection.
4. Model evaluation.

Data collection and preparation

A search of published literature was conducted, using Agricola and Commonwealth Agricultural Bureau databases. The scope of the search included articles published after 1970.

Requirements for an experiment to be included in the database were:

a) Animals should be lactating dairy cows.

b) Total dry matter intake should be reported for each treatment.

c) Forage intake should be reported, or could be calculated from the ingredient composition of the total mixed ration.

d) Milk production should be reported.

e) If the cow was nursing a calf, the amount of milk drunk by the calf should be known and added to milk production.

f) A forage only control treatment was recorded but not required for inclusion in the database.

g) The forage when fed alone or the total mixed ration should be fed *ad libitum*.

The resulting compiled database included results from 54 experiments, containing a total of 327 observations. The source and the number of observations obtained from each publication are summarized in Table 14.

A spreadsheet, Quattro Pro, was used to create the database, and all further analysis and data management was done with the use of SAS System (SAS, 1988a; SAS, 1988b). Variables included in the database are presented in Table 15. Some variables were created from the existing information. MILK4, milk corrected to 4% fat, was calculated from the MILK and MFP using the NRC(1989) formula:

$$\text{MILK4} = (0.4 * \text{kg of milk}) + (15 * \text{kg of fat})$$

Table 14. Summary of references, number of observations from each reference and origin of data included in the complete working data set.

Reference	Observations	Origin
Adams et al. (1995)	12	Florida, USA
Arieli and Adin (1994)	2	Israel
Beauchemin et al. (1994)	12	Canada
Beauchemin and Rode (1994)	2	Canada
Blauwiekel et al. (1990)	4	W.Virginia, USA
Broderick (1992)	14	Wisconsin, USA
Broderick (1985)	7	Wisconsin, USA
Broderick et al. (1990)	12	Wisconsin, USA
Broderick et al. (1993a)	8	Wisconsin, USA
Broderick et al. (1993b)	6	Wisconsin, USA
Burgess et al. (1973)	6	Canada
Cadorniga and Satter (1993)	4	Wisconsin, USA
Cameron et al. (1991)	4	Illinois, USA
Canale et al. (1988)	2	Pennsylvania, USA
Chamberlain et al. (1992)	12	Great Britain
Charmley et al. (1993)	3	Canada
Christensen et al. (1993)	4	Illinois, USA
Cody et al. (1990)	4	Ireland
Cunningham et al. (1993)	5	Indiana, USA
Cushnahan and Mayne (1995)	3	Ireland
Dado and Allen (1996)	2	Michigan, USA
Deetz et al. (1989)	2	Washington, USA
DePeters and Smith (1986)	8	California, USA
Eastridge et al. (1988)	3	Indiana, USA
Fisher et al.(1972)	4	Canada
Glenn et al. (1986)	30	Maryland, USA
Khalili et al. (1992)	6	Ethiopia
Khorasani et al. (1996)	3	Canada
Khorasani et al. (1993)	8	Canada
Laird et al. (1981)	4	Great Britain
Lubis et al. (1990)	5	Florida, USA
MacLeod et al. (1983)	4	Canada
McKnight and McLeod (1977)	2	Canada
Mcqueen and Fillmore (1991)	3	Canada
Mitzner et al. (1994)	8	Nebraska, USA

Table 14. Continued

Reference	Observations	Origin
Muinga et al. (1993)	4	Kenya
Nelson and Satter (1990)	15	Wisconsin, USA
Nocek et al. (1986)	2	New York, USA
Petit and Tremblay (1995)	4	Canada
Petit and Veira (1991)	3	Canada
Petit et al. (1993)	4	Canada
Phipps et al. (1988)	10	Great Britain
Phipps et al. (1990)	6	Great Britain
Poore et al. (1993b)	2	Arizona, USA
Poore et al. (1993a)	4	Arizona, USA
Robinson and McQueen (1992)	4	Canada
Robinson and Burgess (1990)	6	Canada
Robinson et al. (1991)	6	Canada
Strahan et al. (1987)	4	Kentucky, USA
Weiss and Shockey (1991)	4	Ohio, USA
Willcox et al.(1994)	4	Wisconsin, USA
Wilman et al. (1995)	2	Great Britain
Wing et al. (1988)	10	Florida, USA
Woodford et al. (1986)	8	Wisconsin, USA

Table 15. Name and description of variables included in the database.

Variable name	Description
ADG	Average daily gain (g/d)
ADGC	Average daily gain (control) (g/d)
BAS	Basis of measurement of intake
BCSF	Final body condition score
BCSFC	Final body condition score (control)
BCSI	Initial body condition score
BCSIC	Initial body condition score (control)
BRD	Breed
BW	Initial bodyweight (kg)
BWC	Initial bodyweight (control) (kg)
CADF	Concentrate ADF (% DM)
CCP	Concentrate crude protein (% DM)
CDE	Concentrate DE (Mcal/kg DM)
CDM	Concentrate DM (% as fed)
CNDF	Concentrate NDF (% DM)
CNEL	Concentrate NE_1 (Mcal/kg DM)
COM	Concentrate organic matter (% DM)
DIM	Days in milk at the beginning of the experiment
DS	Dry supplement intake (kg/d)
EXP	Experiment number
FADF	Forage ADF (% DM)
FCP	Forage crude protein (% DM)
FCPD	Forage crude protein digestibility (%)
FDE	Forage DE (Mcal/kg DM)
FDM	Forage dry matter (% as fed)
FDMD	Forage DM digestibility (%)
FEED	Feed type
FFA	Forage fed alone (kg/d)
FFW	Forage fed with supplement (kg/d)
FIVOMD	Forage *in vitro* organic matter digestibility (%)
FNDF	Forage NDF (% DM)

Table 15. Continued.

Variable name	Description
FNDFD	Forage NDF digestibility (%)
FNEL	Forage NE_l (Mcal/kg DM)
FOM	Forage organic matter (% DM)
FT1	Forage origin and type number1
FT2	Forage origin and type number2
FT3	Forage origin and type number3
LS	Liquid supplement intake (kg DM/d)
MFP	Milk fat percent (%)
MFPC	Milk fat percent (control) (%)
MILK	Milk production (kg/d)
MILKC	Milk production (control) (kg/d)
MPP	Milk protein percent (%)
MPPC	Milk protein percent(control) (%)
PAR	Parity
PF1	Percent of forage 1 in total diet (%)
PF2	Percent of forage 2 in total diet (%)
PF3	Percent of forage 3 in total diet (%)
REF	Reference number of publication
SPER	Supplemental period (days)
STG	Stage of lactation
TADF	Total diet ADF (% DM)
TCP	Total diet crude protein (% DM)
TCPD	Total diet crude protein digestibility (%)
TDI	Total diet intake (kg DM/d)
TDM	Total diet dry matter (% as fed)
TDMD	Total diet DM digestibility (%)
TMT	Treatment number
TNDD	Total diet NDF digestibility (%)
TNDF	Total diet NDF (% DM)
TNEL	Total diet NE_l (Mcal/kg DM)
TOM	Total diet organic matter (% DM)
TOMD	Total diet organic matter digestibility (%)
WBAS	Basis for weight (shrunk or full)

TYPE, a classification variable, was created to classify the type of forage as hays (code 1), silage (code 2), straws (code 3), and cut fresh forage (code 4). The following variables were recalculated from presented information when it was not readily available in the publication: TDM, TOM, TCP, TADF, and TNDF. They were calculated from the concentration in forage and concentrate, and from the percentage contribution of the forage and the concentrate to the total diet. The analysis of the information revealed that in some cases the amount of forage provided in the diet was a minor component of the total diet. Percentage of forage in the diet was calculated and all observations having less than 50% forage in the diet were excluded from the database. Voluntary intake in Burgess et al. (1973) was expressed as percentage of body weight, and could not be recalculated as kg/d, so these observations were excluded from the analyzed observations. The database was reduced to 269 observations as a result of this process. Missing values in the database lead to a preselection of variables considered to be important in the development of the prediction equation. The variables selected for an observation to be included in the database were: BW, DIM, MILK4, TNDF, FDM, FCP, FADF, and FNDF. The study of the plot between TDI and MILK4 showed the presence of outliers. In Muinga et al. (1993) and Khalili et al. (1992), MILK4 was between 4 and 8 kg/day, a value out of the range of the remaining observations. In the case of Nocek et al. (1986), there was a marked difference between TDI that had a mean of 14.1 kg DM/d and MILK4 that was 29.7 kg/d. An explanation for this was that this study was conducted in the immediate postpartum period. Observations where the experimental period began in the immediate postpartum period (DIM < 20) were discarded. The application of this selection criteria rendered a database with 129 observations.

The database was split into two new databases, one the development data set with 70 observations, from which the equations were generated, and another the evaluation data set, that was used later for the evaluation of the generated equations, that comprised 59 observations. The data set was divided maintaining the integrity of the observations within a publication. All observations within a publication were assigned to the same database.

Reduction of the Number of Independent variables.

The equations were developed by using multiple regression analysis using the REG procedure of SAS (1988b). The initial model tested included TDI as the dependent variable and as independent variables: BW, DIM, MILK4, MPP, TCP, TADF, TNDF, FDM, FCP, FADF, FNDF, and TYPE. The detection of multicollinearity was performed calculating the variance inflation factors (VIF), with the VIF option within PROC REG. To determine the presence of multicollinearities, the variance inflation factors calculated were compared against $1/(1-R^2)$, a value larger than the calculated $1/(1-R^2)$ was indicative of the presence of multicollinearity (Freund and Littel, 1991).

The all-possible-regressions procedure was used for variable selection. The comparison of the different equations was made with the use of the RSQUARE and C_p criterion. The C_p criterion is concerned with the total mean squared error of the n fitted values for each subset regression model. MacNeil (1983) states that the C_p statistic identifies the relative contribution of squared true error and squared lack of fit, avoiding the problem of over-fitting. It is calculated as:

$$C_p = (SSE_p/MSE\ (X_1,\ldots,X_{p-1})) - (n - 2p),$$

where SSE is the error sum of squares for the fitted subset regression model with p parameters, MSE is the mean square error, an unbiased estimator of σ^2, and p is the number of independent variables in the model including the intercept. When the C_p values for all possible regression models are plotted against p, those models with little bias will tend to fall near the line C_p=p. A model with substantial bias will tend to fall considerably above this line. Values below the line C_p=p are interpreted as showing no bias, being below the line due to sampling error (Neter et al., 1996). As a criterion for selecting the models, a C_p value lower than p was required. The variable selection procedure was performed within the REG procedure (SAS, 1988b), using the SELECTION= rsquare C_p option. C_p was the primary selection criteria.

Model Refinement and Selection

Once the variables were selected from the original pool, a check on the curvature and interactions was conducted. The square of the original variables was calculated and the simple interaction variables were created multiplying each variable pair. With the enlarged data set a REG procedure was performed, another selection procedure was conducted using the all-possible-equations procedure and C_p as the selection criterion. The option INCLUDE of the REG procedure was used to develop the equations, keeping the previously selected linear terms.

A sensitivity analysis (Brant, 1993) was performed with the selected equations. The analysis involved the use of the means of the variables included in the equations as the average set of inputs. The parameters estimates and their associated standard errors were used to calculate the variation of the predicted value of TDI. One parameter estimate was varied throughout one standard error while the remaining parameters were maintained fixed in their mean value. The result was then compared to the value of the prediction when all parameter estimates were held constant at their predicted value.

Model Evaluation

The predictive ability of the selected models were tested using the evaluation data set. The predicted TDI was calculated using the regression coefficients derived from the selected equations. A simple linear regression analysis using the REG procedure (SAS, 1988b) was performed with observed TDI as the dependent variable and predicted TDI as the independent variable. The evaluation of the regression adjustment was made with the use of R^2 and RMSE. Also some DMI prediction equations developed elsewhere were included for comparative evaluation of the equations generated with the generation data set. Due to limitations of variables available in the evaluation data set, only the following equations were included: a) the NRC (1989) equation calculated from the intake table by Rayburn and Fox (1993), b) the equation from Vadiveloo and Holmes(1979), selected as a general equation by AFRC(1991), and c) the equation proposed by Mertens(1987) for fill regulated intake.

The equations were:

Rayburn and Fox(1993)

$$\text{DMI (kg/d)} = -0.293 + 0.372\ \text{FCM (kg/d)} + 0.0968\ \text{BW}^{0.75}\text{(kg)}$$

Vadiveloo and Holmes(1979)

$$\text{DMI(kg/d)} = 0.076 + 0.404\ \text{C(kg/d)} + 0.013\ \text{BW(kg)} - 0.129\ \text{WL} + 4.12\log \text{WL} + 0.140\ \text{MY(kg/d)}$$

Mertens (1987)

DMI(kg/d) = (0.012*BW(kg))/NDF(decimal fraction)

To evaluate the accuracy of the equation, the mean square prediction error (MSPE) was used (Theil, 1966; Bibby and Toutenburg, 1977). The MSPE is defined as:

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

where P is the predicted value for one observation, A is the actual observed value for the same observation and n is the number of paired values of P and A.

The MSPE can be partitioned into components to realize a more detailed analysis. The MSPE is partitioned into three components representing errors in the central tendency or mean bias, errors in the regression and errors due to disturbances or unexplained variation, respectively. This partition is represented by:

$$MSPE = (\bar{A} - \bar{P})^2 + sP^2(1 - b)^2 + (1 - r^2)sA^2$$

Where sP^2 and sA^2 are the variances of the predicted and actual intakes respectively. The coefficient, b, is the slope of the regression of A on P and r is the correlation coefficient between actual and predicted values. A large regression bias is indicative of inadequacies in the structure of the model. The preferred model for predicting DMI should be biologically relevant, without regression bias, and have the smallest unexplained variation. The criterion proposed by Fuentes-Pila et al.(1996) to determine if the prediction accuracy is acceptable or not, was adopted. If the square root of the overall MSPE(MPE) is lower than 10% of the mean intake of the data set, the prediction of DMI is considered satisfactory, if MPE has a value between 10 and 20%, it indicates a good or acceptable prediction, and if MPE is higher than 20%, the prediction is unsatisfactory.

Results and Discussion

The complete data set compiled contained 129 observations. The means, standard deviations and range of the variables included are presented in Table 16. The data set mean values characterize high producing lactating dairy

Table 16. Mean, standard deviation and range of the variables included in the complete data set (n= 129), after deleting those containing missing values for selected variables.

Variable	Mean	Std Dev	Minimum	Maximum
BW (kg)	597	43.2	505	688
DIM (d)	76.6	49.5	20	209
MILK (kg/d)	27.8	5.44	14.5	39.6
MFP (%)	3.66	0.327	2.66	4.6
MPP (%)	3.11	0.19	2.8	3.62
TDI (kg/d)	20.8	2.77	14.8	26.9
FFW (kg/d)	13.2	2.6	8.55	19.6
DS (kg/d)	7.64	2.93	0	12.5
TCP (% DM)	17.2	2.25	12.1	22.6
TADF (% DM)	23.7	3.74	17.1	33.3
TNDF (% DM)	36.5	6.24	24.9	58.8
FDM (%)	45.3	20.1	14.9	92.3
FCP (% DM)	16.9	4.34	5.1	23.8
FADF (% DM)	33.1	4.9	23.3	47.6
FNDF (% DM)	47.1	6.12	36.2	67.8
MILK4 (kg/d)	26.2	4.67	14.5	36.6

cows fed a high-quality high-forage diet. Scatter plots between the dependent variable TDI and some independent variables are presented in Figure 1. A positive relationship can be observed between: TDI and BW (Figure 1, a), TDI and MILK4 (Figure 1, c), TDI and TCP (Figure 1, e), and TDI and FDM (figure 1, h). A negative relationship was observed between TDI and TNDF (Figure 1, g). Variables such as BW and milk production have been recognized as important predictors of TDI and they were included as sole variables in some prediction equations (MAFF, 1975; Rayburn and Fox, 1993).

Crude protein concentration of the ration has been associated with TDI (Brant, 1993). In situations of protein deficit TDI is negatively affected. In Figure 1 (e) it can be observed that cows fed diets with less than 14 g CP/100g DM had lower TDI. In cows fed diets with a CP concentration of 15% or higher no relationship is found.

A negative relation between TNDF and TDI has been presented as the main predictor of voluntary TDI in cows where the mechanism regulating feed intake is predominantly the rumen fill (Mertens, 1987). As the diets in this databases were forage-based, the negative relationship between TNDF and TDI would be expected.

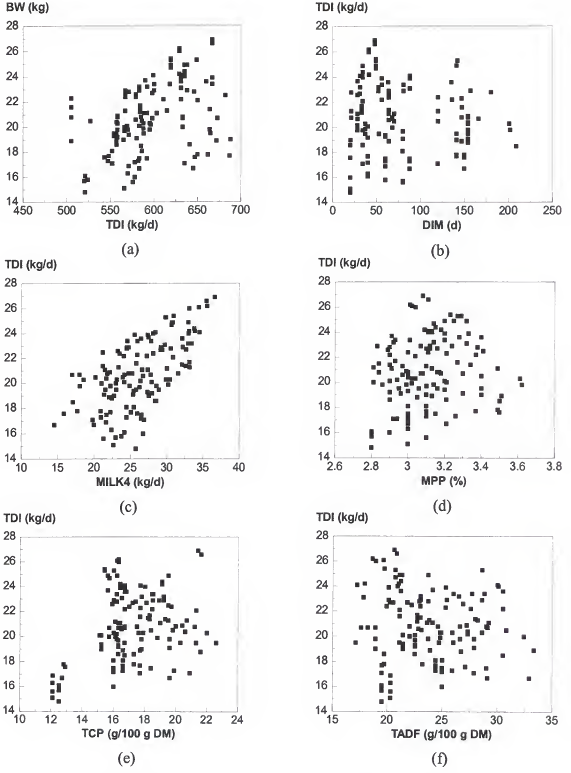
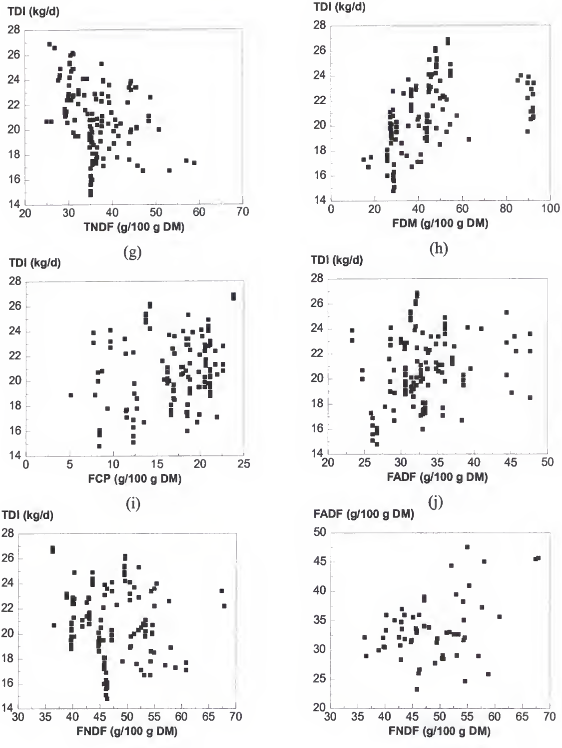


Figure 1. Relationships among selected variables in the complete dataset (n=129). a)Total dry matter intake (TDI) vs. bodyweight, b)TDI vs. days in milk, c)TDI vs. 4% fat corrected milk, d)TDI vs. milk protein concentration, e)TDI vs. diet crude protein, f)TDI vs. diet ADF.



(g) (h) (i) (j) (k) (l)

Figure 1. Continued. g) TDI vs. diet NDF, h) TDI vs. forage dry matter, i) TDI vs. forage crude protein, j) TDI vs. forage ADF, k) TDI vs. forage NDF, l) forage ADF vs. forage NDF.

The relationship between FDM and TDI has been included in some prediction equations to predict TDI from silage-fed cattle (Richards and Wolton, 1975). The complete data sets used in this study include different types of forage: silages, haylages, hays, straws, and fresh cut forage. The higher values of FDM observed (Figure 1, h) correspond to hays and straws. In this database forage with less than 60% DM correspond to a variety of silages and haylages. There is a positive relationship between DM concentration of silage and its intake by ruminants (Forbes, 1995). A decrease of the voluntary TDI of forages after ensiling them has been observed (Demarquilly, 1973), and the level of TDI reduction has been associated with the ensiling process. The reduction in TDI is much lower in silos which exclude oxygen/air, and when the forage is finely chopped, compared to a coarsely chopped forage. A way to relate the reduction of TDI to intrinsic factors of silage has been included in equations tested by the AFRC (1991). They studied the predictive value of the inclusion of pH, ammonia concentration, and butyric acid concentration in predictive equations of TDI of silage-fed cattle, but the selected equations did not include these variables. Buchanan-Smith (1990) reported that the increase of the acetic acid concentration without increases of the amount of other constituents decreases intake of silage in sheep through an effect on palatability. Coppock (1978) reported a positive relationship between DM concentration of alfalfa silage and TDI. In the case of corn silage a similar tendency exists, but a plateau exists for DM concentrations above 35%. Therefore, the lower TDI of diets of lower DM concentration in the databases would be expected.

The means, standard deviations and range of the observations included in the generation data set (n=70) are presented in Table 17. Besides the variables presented in Table 17, a classification variable TYPE was included. Sixty observations had as the forage component of the diet silage or haylage, eight observations had hays, and two had straws.

The correlations among variables used to develop the predictive equations are presented in Table 18. The full model included TDI as the dependent variable and 12 independent variables: BW, DIM, MILK4, MPP, TCP, TADF, TNDF, FDM, FCP, FADF, FNDF, and TYPE. The dependent variable, TDI, is positively correlated with MILK4 and negatively correlated with TNDF and TADF, the variables that characterize fiber in the diet. The variables FADF and FNDF

Table 17. Means, standard deviation, and range of selected variables included in the development data set (n=70).

Variable	Mean	Std Dev	Minimum	Maximum
BW (kg)	600	41.5	505	682
DIM (d)	85.6	55.8	21	209
MILK (kg/d)	27.7	5.92	14.5	39.6
MFP (%)	3.73	0.362	3.07	4.6
MPP (%)	3.13	0.208	2.81	3.62
TDI (kg/d)	21.6	2.08	16.7	26.9
FFW (kg/d)	14.2	2.14	10.2	19.6
DS (kg/d)	7.42	2.99	0.4	11.4
TCP (% DM)	17.7	2.05	12.7	22.6
TADF (% DM)	25	3.72	17.6	33.3
TNDF (% DM)	36.8	6.16	25.6	50.7
FDM (%)	46.8	17.7	27.1	92
FCP (% DM)	17.8	4.54	5.1	23.8
FADF (% DM)	34.9	5.66	23.3	47.6
FNDF (% DM)	46.7	6.89	36.2	67.8
MILK4 (kg/d)	25.5	4.69	14.2	34.6

Table 18. Correlation among the variables in the development dataset.

	TDI	BW	DIM	MILK4	MPP	TCP	TADF	TNDF	FDM	FCP	FADF	FNDF	TYPE
TDI	1.00												
BW	0.34	1.00											
DIM	-0.30	-0.17	1.00										
MILK4	0.72	0.12	-0.64	1.00									
MPP	-0.06	0.41	0.54	-0.44	1.00								
TCP	0.26	-0.22	-0.06	0.33	-0.30	1.00							
TADF	-0.39	-0.19	0.38	-0.53	0.01	-0.16	1.00						
TNDF	-0.54	-0.12	0.01	-0.56	-0.05	-0.46	0.65	1.00					
FDM	0.27	0.23	0.10	-0.11	0.33	0.19	0.12	-0.06	1.00				
FCP	0.31	-0.02	-0.14	0.41	-0.30	0.54	-0.14	-0.55	-0.11	1.00			
FADF	0.08	0.05	0.16	0.01	0.08	-0.17	0.57	0.15	0.27	0.08	1.00		
FNDF	-0.20	0.09	-0.04	-0.28	0.05	-0.56	0.48	0.73	0.18	-0.67	0.50	1.00	
TYPE	-0.18	-0.41	0.19	0.05	-0.17	-0.11	0.01	-0.04	-0.70	-0.12	-0.07	-0.12	1.00

have a low correlation with TDI, but they are correlated with TADF and TNDF.

The ANOVA table of the model including all the independent variables is presented in Table 19. The model is significant ($P<0.0001$), with an R^2 of 0.7654. The CV is 5.1%. From the R^2, the reference VIF value can be calculated, being 4.26. The VIF of DIM, MILK4, TADF, TNDF, FDM, FCP, FADF, FNDF, and TYPE are larger than the calculated, indicating the presence of multicollinearity in the data. The presence of serious multicollinearity often does not affect the usefulness of the fitted model for estimating mean responses or making predictions, provided that the values of the predictor variables for which inferences are to be made follow the same multicollinearity pattern as the data on which the regression model is based (Neter et al., 1996). One remedial measure under this situation can be the restriction of the use of the fitted regression model to inferences for values of the predictor variables that follow the same pattern of multicollinearity. One restriction that the presence of multicollinearity imposes is on the choice of the variable selection methodology that can be employed to reduce the number of

Table 19. ANOVA table of the predictive equation including all the variables as linear terms, and the variance inflation factor for each variable.

```
                              Analysis of Variance

                                 Sum of         Mean
          Source          DF    Squares        Square      F Value       Prob>F


          Model           12   228.95091     19.07924       15.497       0.0001

          Error           57    70.17552      1.23115

          C Total         69   299.12643


                 Root MSE       1.10957     R-square        0.7654

                 Dep Mean      21.60714     Adj R-sq        0.7160

                 C.V.           5.13521


                                     Parameter Estimates

                  Parameter      Standard     T for H0:                      Variance
 Variable  DF      Estimate         Error   Parameter=0    Prob > |T|       Inflation

 INTERCEP   1    -10.024881    7.38939638        -1.357        0.1802      0.00000000

 BW         1      0.008359    0.00468420         1.785        0.0797      2.11949511

 DIM        1      0.012406    0.00510246         2.431        0.0182      4.53738441

 MILK4      1      0.423373    0.06035477         7.015        0.0001      5.20354498

 MPP        1      1.391654    1.28739572         1.081        0.2843      4.03060358

 TCP        1     -0.130744    0.10403301        -1.257        0.2140      2.55006783

 TADF       1      0.046281    0.09400475         0.492        0.6244      6.83806907

 TNDF       1     -0.010160    0.07193822        -0.141        0.8882     10.99722929

 FDM        1      0.066800    0.01583282         4.219        0.0001      4.38995613

 FCP        1      0.244356    0.08934925         2.735        0.0083      9.23085643

 FADF       1     -0.182342    0.07273786        -2.507        0.0151      9.48607062

 FNDF       1      0.160710    0.08042721         1.998        0.0505     17.21897150

 TYPE       1      1.536804    0.77606194         1.980        0.0525      4.64036356
```

variables. Chatterjee and Price (1977) do not recommend the use of stepwise procedures in the presence of collinear data. The fitting of all the possible equations applies equally well to collinear and noncollinear data. Limitations to the use of this methodology arises from the fact that the number of equations to be examined increases exponentially, and needs large computing resources when the number of variables is large.

There is a controversy about how the variable selection process should be performed in regard to the methodology to select the variables to be included in the initial model. Poppi (1996) concludes that the development of equations to predict intake is a statistical procedure that is best approached with no preconceived ideas of the variables which are needed or should be included. Draper and Smith (1981) recommend caution in the use of unplanned data in regression analysis. Some important explanatory variables may be kept under a small range and their regression coefficients may be found nonsignificant when in reality it is the most effective predictor variable. Neter et al.(1996) ascribe an important role to the researcher's prior knowledge in the definition of the appropriate transformations and interactions to be considered. The variable selection process does not necessarily end with one equation selected, but sometimes with a group of 'good' equations that should be tested further to make the final selection.

The utilization of the all-possible-equations procedure for variable selection resulted in the selection of a prediction equation for TDI which includes as independent variables BW, DIM, MILK4, and FDM. The equation had a C_p = 3.75 and an $R^2 = 0.72$. For the evaluation process another equation was selected, which included BW, DIM, MILK4, TNDF, and FDM as the independent variables. This equation had a C_p = 5.59 and an $R^2 = 0.73$. The predicted voluntary dry matter intake (PDMI) was calculated using the coefficients calculated by regression for both equations. The equations were as follows:

Equation 1.

$$\text{PDMI1} = 2.82 + 0.0105\ \text{BW} + 0.0108\ \text{DIM} + 0.377\ \text{MILK4} + + 0.0348\ \text{FDM}$$

Equation 2.

$$\text{PDMI2} = 1.76 + 0.0107\ \text{BW} + 0.0116\ \text{DIM} + 0.392\ \text{MILK4} + + 0.0351\ \text{FDM} + 0.0128\ \text{TNDF}$$

The squared and linear interaction terms were calculated for BW, DIM, MILK4, TNDF, and FDM. A new model using the linear, quadratic and interaction terms was fitted and a new variable selection procedure evaluating all possible equations was performed, with the restriction that the model should include in every case the linear terms. The selected equation had nine variables including additionally FDM^2, $TNDF^2$, DIM^2, and DIM X MILK4, and had an $R^2 = 0.83$ and a $C_p = 3.97$. The parameter estimates for the terms of the equation to calculate PDMI were:

Equation 3.

$$PDMI3 = 18.8 + 0.0123\ BW - 0.0917\ DIM + 0.0790\ MILK4 + 0.131\ FDM - 0.547\ TNDF - 0.000836\ FDM^2 + 0.00695\ TNDF^2 + 0.000137\ DIM^2 + 0.00297\ DIM \times MILK4$$

The equations were evaluated using the evaluation data set. Means, standard deviations and ranges observed in the evaluation data set are presented in Table 20. Forty nine observations had silage or haylage as the principal forage component, in nine observations hay was the forage component

Table 20. Means, standard deviation and range of the evaluation data set (n = 59).

Variable	Mean	Std Dev	Minimum	Maximum
BW (kg)	594	45.3	520	688
DIM (d)	65.8	38.5	20	166
MILK (kg/d)	27.9	4.85	18.2	38.5
MFP (%)	3.57	0.258	2.66	4.1
MPP (%)	3.09	0.153	2.8	3.5
TDI (kg/d)	19.9	3.18	14.8	26.2
FFW (kg/d)	12	2.61	8.55	18.9
DS(kg/d)	7.9	2.86	0	12.5
TCP(% DM)	16.6	2.33	12.1	21.3
TADF(% DM)	22.1	3.11	17.1	29.1
TNDF(% DM)	36	6.35	24.9	58.8
FDM (%)	43.5	22.7	14.9	92.3
FCP(% DM)	15.8	3.86	8.4	21.9
FADF(% DM)	31.1	2.7	25.9	35.7
FNDF(% DM)	47.5	5.1	36.5	60.8
MILK4 (kg/d)	26	4.2	16.9	35.5

and the remaining one was fresh-cut forage. The data set was used to calculate the values of predicted TDI using equations 1 and 2. Linear simple regression analysis was performed using TDI as the dependant variable and predicted TDI as the independent variable. The ANOVA table for predicted TDI with equation 1 is presented in Table 21, and the ANOVA table for predicted TDI using equation 2 is presented in Table 22. Both equations gave similar R^2, 0.7986 with equation 1 predicted values, and 0.8041 using the TDI values predicted with equation 2. These RMSE values were almost equal, 1.42 vs. 1.44.

The evaluation of this equation with the evaluation data set was performed using a simple linear regression, with the observed TDI as the dependent variable and the predicted DMI using equation 3 as the independent variable. The ANOVA table for this analysis is presented in Table 23.The equation had a CV of 8.87%, when it was used with the evaluation data set, a coefficient that was twice that obtained with the development data set (CV = 4.06%). Prediction of the voluntary DMI with a CV lower than 10% can be considered acceptable for predictive purposes.

A scatter plot of the predicted DMI values and the residuals, and of the predicted DMI and the observed DMI is

Table 21. ANOVA table of the regression analysis of TDI as dependent variable and predicted TDI calculated with equation 1 as independent variable.

```
                         Analysis of Variance

                         Sum of         Mean
Source          DF      Squares       Square      F Value       Prob>F

Model            1    470.08037    470.08037      226.028       0.0001
Error           57    118.54539      2.07974
C Total         58    588.62576

     Root MSE       1.44213     R-square       0.7986
     Dep Mean      19.89153     Adj R-sq       0.7951
     C.V.           9.48113

                       Parameter Estimates

                 Parameter       Standard    T for H0:
Variable  DF      Estimate          Error   Parameter=0    Prob > |T|

INTERCEP   1    -12.565697     2.16703626        -5.799        0.0001
PDMI1      1      1.539948     0.10242949        15.024        0.0001
```

Table 22. ANOVA table of the regression analysis of TDI as the dependent variable and predicted TDI calculated using equation 2 as the independent variable.

```
                              Analysis of Variance

                              Sum of         Mean
     Source          DF      Squares        Square       F Value       Prob>F

     Model            1    473.32066     473.32066       233.982       0.0001

     Error           57    115.30511       3.02290

     C Total         58    588.62576

         Root MSE        1.42229      R-square        0.8041

         Dep Mean       19.89153      Adj R-sq        0.8007

         C.V.            7.15021

                            Parameter Estimates

                   Parameter       Standard    T for H0:
  Variable  DF      Estimate          Error   Parameter=0    Prob > |T|


 INTERCEP    1     -12.271694    2.11079529        -5.814        0.0001

  PDMI2      1       1.528517    0.09992619        15.296        0.0001
```

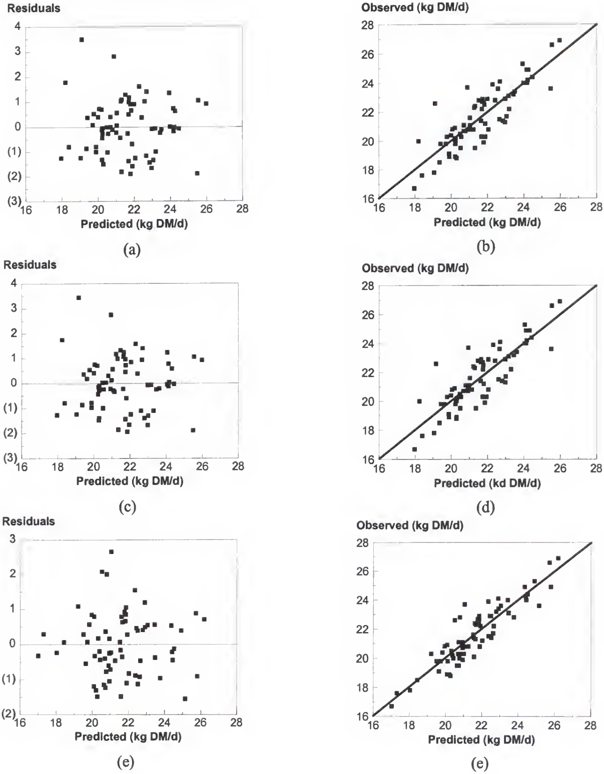
Table 23. ANOVA table of the regression analysis of TDI as the dependent variable and predicted DMI with equation 3 as the independent variable.

```
                          Analysis of Variance

                          Sum of         Mean
  Source          DF      Squares        Square       F Value       Prob>F

 Model             1    457.19643     457.19643       198.283       0.0001
 Error            57    131.42913       2.30578
 C Total          58    588.62576

       Root MSE        1.51848     R-square       0.7767
       Dep Mean       19.89153     Adj R-sq       0.7728
       C.V.            7.63380

                         Parameter Estimates

                    Parameter      Standard    T for H0:
  Variable  DF       Estimate         Error   Parameter=0    Prob > |T|

  INTERCEP   1     -14.254542    2.43296911        -5.859        0.0001
  PDMI3      1       1.627577    0.11558430        14.081        0.0001
```

presented in Figure 2. No anomalies are observed regarding the residual plot. The plot of predicted and observed DMI shows a good adjustment of the data to the model, no outliers are present, and the different equations do not result in major changes of those plots.

Sensitivity Analysis

The change observed in the predicted DMI as the mean parameter estimates were varied individually plus or minus one SE (δ) was used to evaluate the sensitivity of parameter estimates in the equation. The three equations developed with the generation data set were evaluated. The evaluation of equation 1 (Table 24) was made considering the mean predicted DMI (22.14 kg DM/d) together with δ. The mean predicted DMI was taken as reference to view the magnitude of the variation. The largest deviations in the prediction values were observed as a result of varying the parameter estimates for the intercept, and BW. The variation was higher for the intercept parameter. The prediction values generated with equation 2 (Table 25) showed higher deviations than those observed with equation 1. The predicted DMI was 22.14 kg DM/d. The largest deviations also



(a) (b)

(c) (d)

(e) (e)

Figure 2. Scatter plots of predicted vs. residual, and predicted vs. observed DMI obtained applying the equations developed to the generation dataset. a) and b) equation 1, c) and d) equation 2, and e) and f) equation 3.

Table 24. Results of sensitivity analysis on dry matter intake prediction using equation 1.

			Predicted Value		
Parameter	Parameter Estimate	Standard Error	@ -1 SE[a]	@ +1 SE[b]	δ[c]
Intercept	2.82	2.30	19.72	24.42	4.70
BW	0.0105	0.00343	20.08	24.16	4.08
DIM	0.0107	0.00320	21.93	23.39	1.46
MILK4	0.377	0.0351	21.12	23.06	1.94
FDM	0.0348	0.00800	21.71	22.46	1.28

[a] Forage intake change predicted by varying parameter estimates minus one standard error(SE).

[b] Forage intake change predicted by varying parameter estimates plus one SE. [c] δ = [(value@ +1 SE) - (value@-1SE)].

Table 25. Results of sensitivity analysis on dry matter intake prediction using equation 2.

Parameter	Parameter Estimate	Standard Error	Predicted Value @ -1 SE[a]	 @ +1 SE[b]	 δ^c
Intercept	1.76	3.55	18.59	25.69	7.09
BW	0.0107	0.00348	20.04	24.24	4.20
DIM	0.0116	0.00387	21.81	22.46	0.65
MILK4	0.392	0.0514	20.73	23.55	2.82
FDM	0.0351	0.00809	21.73	22.49	0.76
TNDF	0.0128	0.0326	21.99	22.23	0.24

[a] Forage intake change predicted by varying parameter estimates minus one standard error(SE).

[b] Forage intake change predicted by varying parameter estimates plus one SE. [c] δ = [(value@ +1 SE) - (value@-1SE)].

are associated with the intercept and BW. The maximal variation represented a DMI of 7.09 kg DM/d. The sensitivity analysis of the variation of the estimated parameters obtained with equation 3 (Table 26) indicates that the larger variation was obtained with the use of this equation. The deviation was above 10.0 kg DM/d for three of a total of 10 parameters, and for the case of TNDF the value was 20.56 kg DM/d, a value similar to the predicted DMI, 21.54 kg DM/d. Regarding the sensitivity analysis equation 1 showed the best behavior because the values of δ were the lowest of the three equations, indicating that the predictions of TDI with equation 1 were less sensitive to errors in the estimation of the parameters than with equations 2 and 3.

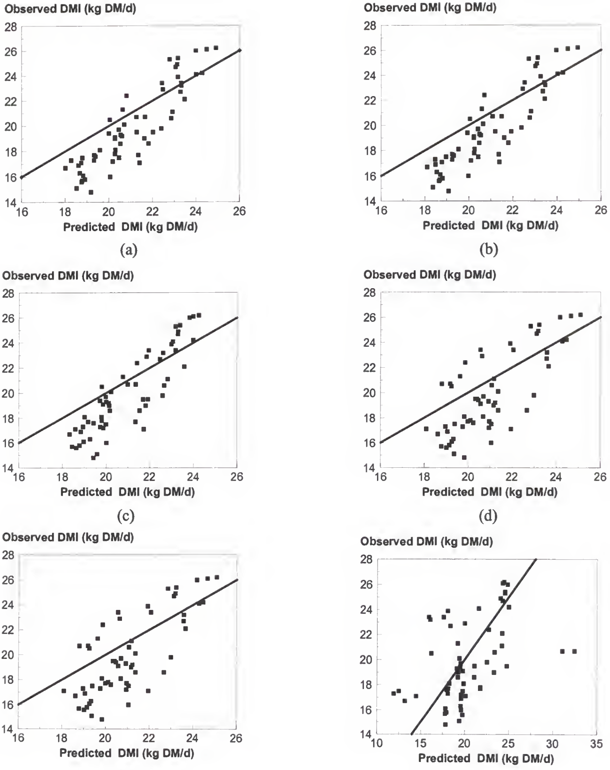
Comparative Evaluation of Predictive Equations

Predicted DMI values were calculated on the evaluation data set using the three equations developed with the generation dataset, and the three equations included from the literature (Mertens, 1987; Vadiveloo and Holmes, 1979; Rayburn and Fox, 1993). Plots of observed values versus predicted values are in Figure 3, along with lines representing unity (i.e., predicted = observed).

Table 26. Results of sensitivity analysis on dry matter intake prediction using equation 3.

			Predicted Value		
Parameter	Parameter Estimate	Standard Error	@ -1 SE[a]	@ +1 SE[b]	δ[c]
Intercept	18.8	7.22	14.32	28.80	14.44
BW	0.0123	0.00300	19.75	23.35	3.60
DIM	-0.0917	0.0285	19.11	23.99	4.88
MILK4	0.0790	0.0782	19.40	23.71	4.11
FDM	0.131	0.0635	18.56	24.55	5.99
TNDF	-0.547	0.293	10.77	32.33	21.56
FDM2	-0.000836	0.000527	22.84	20.24	2.60
TNDF2	0.00695	0.00383	16.19	26.89	10.70
DIM2	0.000137	0.0000711	21.18	22.30	0.72
DIMMILK	0.00297	0.000677	20.56	22.92	1.96

[a] Forage intake change predicted by varying parameter estimates minus one standard error(SE).
[b] Forage intake change predicted by varying parameter estimates plus one SE. [c] δ = [(value@ +1 SE) - (value@-1SE)].



(a)

(b)

(c)

(d)

(e)

(f)

Figure 3. Scatter plots of the observed vs. predicted values of DMI with different equations. a) One, b) Two, c) Three, d) Rayburn and Fox (1993), e) Vadiveloo and Holmes (1979), f) Mertens (1983).

The summary of the evaluation of the six equations is presented in Table 27. Equation 1, equation 2, and equation 3 presented the lowest MSPE, and the equations proposed by Vadiveloo and Holmes(1979) and Mertens(1987) presented the highest MSPE, and the highest RPE (the value of MPE relative to the observed mean DMI): 16.8% and 18.4%. They can be considered inadequate to be used for prediction purposes on the data set used to evaluate the equation. Equation 1, equation 2 and equation 3 had the highest R^2 values of the compared equations, probably caused by the fact that the generation and evaluation data sets were restricted to observations where the cows were fed total mixed rations formulated with more than 50% of forage, or where the recorded DMI of the forage fed *ad libitum* was greater than the supplement allowance. A lower degree of relation between the actual and the predicted values can be expected with the use of equations generated with data sets where the inclusion of an observation was not restricted by the level of forage in the feed.

The equation developed by Rayburn and Fox(1993) from the tabular data presented in the NRC(1989), gave reasonable results, with a MSPE value of 5.93 kg^2, and a MPE of 2.44 kg, a value that represents a deviation from the DMI mean of

Table 27. Mean square prediction errors observed with the application of different equations on the evaluation dataset.

Equation	MSPE[a]	R^2	MPE[b]	RPE[c]	Bias error[d]	Regression error[e]	Unexplained error[f]
1	4.39	0.80	2.10	10.6	1.39	1.00	2.03
2	4.24	0.80	2.06	10.4	1.32	0.98	1.98
3	4.56	0.78	2.14	10.8	1.17	1.18	2.26
Rayburn and Fox (1993)	5.93	0.58	2.44	12.3	1.28	0.45	4.27
Vadiveloo and Holmes (1979)	11.22	0.44	3.35	16.8	5.52	0.02	5.71
Mertens (1987)	13.41	0.21	3.66	18.4	0.21	5.41	7.97

[a] Mean square prediction error, $(kg/d)^2$. [b] Mean prediction error, kg. [c] Relative prediction error, MPE as a percentage of the observed mean DMI. [d] Component of the MSPE due to the bias, $(A - P)^2$. [e] Component of the MSPE due to the regression, $sP^2(1-b)^2$. [f] Component of the MSPE due to the variation unexplained by the regression, $sA^2(1-R^2)$.

12.3%, which is considered acceptable. The analysis of the partition components of MSPE (Table 27) shows that the equation of Mertens (1987) had a lower mean bias, but the other components of MSPE, the regression error and the unexplained error were the largest of the equations compared. Bias error can be accepted if the other two error components are low, as the bias can be corrected, but if the regression and unexplained errors are high there is an indication of lack of fit of the model for prediction purposes. The bias error for equation 1, 2, 3, and Rayburn and Fox (1993) are lower than the observed for the Vadiveloo and Holmes (1979) equation, which have the smallest regression error, but has a high unexplained error associated with a low R^2. Equations 1, 2, and 3 have the lowest unexplained error. Equation 1, 2, 3, and the Rayburn and Fox(1993) equation can be selected as predictors from the evaluation of MSPE and its components. Equation 2 including TNDF, a component of the quality of the diet, and fewer terms than equation 3 can be selected as the best equation from this analysis. The equations developed by Vadiveloo and Holmes (1979) and Mertens (1987) are not adequate prediction equations for the evaluation data set.

Summary

A data set to generate equations for the prediction of DMI was compiled from information obtained from the literature with diets where the main feed component was a forage. Three equations were generated and were evaluated with an independent data set, together with another three equations obtained from the literature. The results of the evaluation of predictive equations with the independent evaluation data set were better for the equations 1, 2 and 3, that were generated here than for the published equations. The generated equations that included only linear terms of the independent variables were better under the sensitivity analysis, and also had a lower overall MSPE. Equation 2 can be selected to predict DMI, as it has the lowest MSPE value.

CHAPTER 5
SUMMARY

The objectives of this dissertation were to provide information needed in forage-livestock models. Two areas were studied: the maintenance energy requirements of grazing cattle, and the prediction of voluntary dry matter intake by lactating dairy cattle fed high-forage diets.

The requirement of energy for maintenance is the amount of feed energy intake that will result in no net loss or gain of energy from the tissues of the animal body. In the case of grazing animals this concept includes the energy that the animal must expend to move around in the search of food, and to obtain their feed from the standing forage mass. The quantification of the additional energy requirement necessary to sustain the activity of grazing is needed in order to generate better models applicable to grazing cattle production systems.

A literature review was conducted on the energy requirements for activity in grazing cattle. The majority of the data on energy requirements for maintenance are the result of studies conducted under confinement conditions. Results from direct measurements of energy requirements of grazing cattle indicate higher requirements of energy for maintenance in grazing cattle. The energy required to perform the different factors that are included in the activity of cattle were studied under the standardized conditions of respiration or calorimetric chambers. The prevalent approach to account for the additional energy expenditure of grazing cattle has been the factorial approach. This approach includes knowledge of the energy required to do each factor included in the extra activity imposed by grazing, and also the amount of activity that an animal performs on a daily basis for each specific factor. The main factors that affect the energy requirements for maintenance of grazing cattle are walking, both the horizontal and vertical components, and eating. The energy requirements are 0.6 cal/kg BW/m, and 6.7 cal/kg BW/m for horizontal and vertical movement respectively. The increased energy requirement for eating in grazing animals has varied from 0.55 kcal/kg $BW^{0.75}$/h when grazing a good quality pasture with unlimited availability to 1.84 kcal/kg $BW^{0.75}$/h in a pasture of lower quality and limited availability.

In this dissertation, the following was accomplished:

1. Data obtained from the literature were analyzed and the relationship between paddock size and walking distance was explained with a regression equation having walking distance (WD) as the dependent variable and the linear and quadratic terms of the paddock size (P) as the independent variables:

$$WD = 2.90 + 0.0111\ P - 0.00000441\ P^2 \quad (R^2 = 0.70)$$

2. An energy requirement for activity adjustment was developed from the reviewed information. Input variables included paddock size, estimated vertical movement, pasture condition, and grazing time. The adjustments varied from 15% over the NRC (1996) energy for maintenance requirement for cattle grazing small paddocks with lush pastures, to 70% for cattle grazing a sparse pasture on large paddocks, with irregular terrain. These values are in the range of the few studies that measured directly the increase of energy requirements in grazing animals.

3. The prediction of the voluntary DMI of lactating dairy cows fed high forage diets was done with an equation

development procedure using multiple regression equations. A database was developed from a literature search of experiments published after 1970. Body weight, days in milk, 4% fat corrected milk, NDF concentration in the diet, forage dry matter, forage crude protein, forage ADF, and forage NDF, were available for 129 means. The complete dataset was divided into two independent datasets, a generation dataset, from where the predictive equations were generated, and an evaluation dataset, where the predictive ability of the generated equations was evaluated.

The equations were generated by multiple regression analysis. The all-possible-regression procedure was used for variable selection using PROC REG of SAS (1988b) with the RSQUARE selection and the C_p statistic to avoid overfitting. Three equations were generated: equation 1 which contained as independent variables bodyweight (BW), days in milk (DIM), 4% fat corrected milk (MILK4),and forage dry matter concentration (FDM) ($R^2 = 0.72$), equation 2 which included BW, DIM, MILK4, FDM, and diet NDF concentration (TNDF) ($R^2 = 0.73$), and equation 3 which included the terms of equation 2 plus the squared DIM, FDM and TNDF, and the interaction term DIM*MILK4 ($R^2 = 0.82$).

The equations were evaluated using sensitivity analysis. The analysis studied the effects on the predicted value of DMI of the error associated with each parameter estimate. Using as input the mean value for each variable of the generation dataset, each parameter was varied by plus and minus one standard error (SE) and the predicted DMI was calculated. The difference between the high and low DMI values was used to evaluate the sensitivity of the prediction to each parameter. Equation 1 and 2 predictions were less sensitive to the error associated with the estimated parameters than were those from equation 3.

The equations were also compared to three equations taken from the literature (Vadiveloo and Holmes, 1979, Mertens, 1987, and Rayburn and Fox, 1993) using the mean square prediction error (MSPE) criterion. The value of the mean prediction error (MPE, kg DM/d) was calculated as the square root of MSPE. The relative prediction error (RPE; MPE as a percentage of the DMI mean) was used to evaluate the equations. Equations with an RPE value below 20% were considered acceptable, and if the RPE was below 10%, the equation was considered satisfactory. Generated equations 1, 2, and 3 were the best performers under this evaluation

(10.6%, 10.4%, and 10.8%, respectively). The value was very close to the 10% target value and they can be considered satisfactory equations to predict DMI. The Rayburn and Fox (1993) equation gave a value slightly higher (12.3%), but still acceptable. The equation developed by Mertens (1987) and Vadiveloo and Holmes (1979) produced higher RPE values (18.4% and 16.8%, respectively), values closer to 20%, considered unacceptable and should not be used for prediction of DMI within this type of conditions. Equation 2 having the lowest RPE value can be selected for future use in predicting the DMI of lactating cows fed diets with more than 50% forage content.

The utilization of the table developed here to adjust the maintenance energy requirements of grazing cattle can improve the results of the calculation of energy requirements for maintenance in models used for feed management of grazing cattle. The application of the dry matter intake predictive equation can be recommended to estimate herd mean intake in situations where dairy cows are fed diets with high forage content.

APPENDIX
RAW DATA

Variable List

REF	Reference
TDI	Diet dry matter intake (kg/d)
BW	Body weight (kg)
DIM	Days in milk (d)
MILK	Milk production (kg/d)
MFP	Milk fat percentage (%)
MPP	Milk protein percentage (%)
MILK4	4% Fat corrected milk production (kg/d)
TCP	Diet crude protein concentration (g/100 g DM)
TADF	Diet ADF concentration (g/100 g DM)
TNDF	Diet NDF concentration (g/100 g DM)
FDM	Forage DM concentration (%)
FCP	Forage crude protein concentration (g/100 g DM)
FADF	Forage ADF concentration (g/100 g DM)
FNDF	Forage NDF concentration (g/100 g DM)
TYPE	Type of forage (hay = 1, silage = 2, straw = 3, and fresh cut = 4)

REF	Reference
1	Willcox et al.(1994)
2	Poore et al. (1993)
4	Beauchemin et al. (1994)
5	Beauchemin and Rode (1994)
7	Khorasani et al. (1993)
8	Cunningham et al. (1993)
12	Charmley et al. (1993)
21	Woodford et al. (1986)
23	Glenn et al. (1986)
24	Broderick et al (1993)
25	Poore et al. (1993)
27	Broderick (1985)
28	Broderick et al. (1993)
32	Deetz et al. (1989)
36	Canale et al. (1988)
38	Broderick (1992)
39	Cameron et al. (1991)
40	Petit and Tremblay (1995)
41	Cushnahan and Mayne (1995)
43	Nelson and Satter (1990)
48	Broderick et al. (1990)
49	Petit and Veira (1991)
52	Petit et al. (1993)
54	Weiss and Shockey (1991)

Table 28. Individual data information from the complete data set (n=129)

REF	TDI	BW	DIM	MILK	MFP	MPP	MILK4	TCP	TADF	TNDF	FDM	FCP	FADF	FNDF	TYPE
1	26.6	667	48	39.0	3.39	3.11	35.4315	21.60	20.80	26.80	53.4	23.80	32.2	36.2	2
1	26.9	667	48	39.6	3.49	3.08	36.5706	21.40	20.60	25.60	53.4	23.80	32.2	36.2	2
2	21.1	589	64	28.6	3.53	2.91	26.5837	16.40	23.60	29.20	92.0	18.00	35.1	41.7	1
2	20.6	579	64	31.3	3.02	2.97	26.6989	16.50	22.80	29.70	92.0	18.00	35.1	41.7	1
4	21.1	592	70	23.0	3.55	3.49	21.4475	19.00	24.10	37.70	91.0	17.80	35.6	45.1	1
4	20.5	586	70	22.0	3.45	3.40	20.1850	18.40	30.80	41.90	91.0	17.80	35.6	45.1	1
4	22.5	682	64	23.5	3.33	3.41	21.1383	19.50	22.20	36.30	92.0	18.80	32.2	42.5	1
4	21.4	664	64	21.7	3.83	3.34	21.1467	19.30	28.00	39.80	92.0	18.80	32.2	42.5	1
4	18.9	672	64	22.3	3.92	3.51	22.0324	17.70	23.90	40.40	29.6	7.90	29.1	50.5	2
5	19.5	554	53	32.2	2.66	3.16	25.7278	20.30	17.10	31.50	89.6	19.80	32.1	39.6	1
7	22.1	650	34	34.0	3.38	3.04	30.8380	21.30	21.10	32.20	52.8	19.90	33.7	45.6	2
7	19.8	664	34	31.2	3.43	3.14	28.5324	17.80	18.90	35.40	42.9	12.40	28.5	50.6	2
7	17.1	635	34	29.6	3.38	2.92	26.8472	17.70	19.50	37.90	41.1	11.50	35.7	60.8	2
7	18.6	641	34	29.4	3.81	3.21	28.5621	17.30	19.70	36.50	32.3	12.70	31.7	54.3	2
7	19.5	665	141	22.1	3.83	3.40	21.5365	21.30	21.10	32.20	52.8	19.90	33.7	45.6	2
7	19.0	688	141	23.3	3.83	3.40	22.7059	17.80	18.90	35.40	42.9	12.40	28.5	50.6	2
7	17.7	687	141	22.9	3.80	3.37	22.2130	17.70	19.50	37.90	41.1	11.50	35.7	60.8	2
7	17.8	662	141	20.9	3.99	3.49	20.8687	17.30	19.70	36.50	32.3	12.70	31.7	54.3	2
8	24.1	599	31	37.4	3.48	3.13	34.4828	16.70	17.20	33.30	44.6	9.66	28.6	50.4	2
8	22.7	598	31	35.5	3.46	3.16	32.6245	17.20	21.80	39.10	44.6	9.66	28.6	50.4	2
8	23.2	592	31	35.8	3.46	3.14	32.9002	17.80	26.50	44.30	44.6	9.66	28.6	50.4	2
12	16.7	645	150	14.9	3.82	3.21	14.4977	12.70	32.90	47.00	36.9	13.50	38.3	54.2	2
12	17.6	647	150	14.5	4.60	3.50	15.8050	12.90	27.10	43.90	34.7	11.40	33.1	51.7	2
12	17.8	650	150	16.7	4.39	3.49	17.6770	12.80	23.20	41.10	32.4	9.31	27.8	49.1	2
21	23.6	660	63	32.1	4.00	3.40	32.1000	16.80	21.20	30.10	85.1	20.20	36.0	46.2	1
23	14.8	521	20	27.8	3.50	2.80	25.7150	12.50	19.50	35.10	28.5	8.40	26.7	46.3	2

Table 28. Continued

REF	TDI	BW	DIM	MILK	MFP	MPP	MILK4	TCP	TADF	TNDF	FDM	FCP	FADF	FNDF	TYPE
23	17.6	543	20	26.7	3.80	3.10	25.8990	16.60	24.40	36.30	25.7	16.60	33.3	45.8	2
23	18.6	557	20	31.7	3.30	2.90	28.3715	16.30	22.50	34.80	27.5	16.90	31.7	44.8	2
23	15.1	566	20	24.5	3.50	3.00	22.6625	12.10	20.30	35.00	28.8	12.30	26.1	46.1	2
23	16.0	578	20	28.4	3.60	2.90	26.6960	16.00	25.00	35.40	25.8	18.50	33.0	45.7	2
23	19.0	565	20	28.8	3.70	3.10	27.5040	15.20	21.40	35.20	27.7	18.80	31.4	44.7	2
23	16.1	521	40	27.0	3.30	2.80	24.1650	12.50	19.50	35.10	28.5	8.40	26.7	46.3	2
23	17.7	548	40	26.2	3.70	3.10	25.0210	16.60	24.40	36.30	25.7	16.60	33.3	45.8	2
23	19.2	558	40	30.7	3.40	2.90	27.9370	16.30	22.50	34.80	27.5	16.90	31.7	44.8	2
23	16.3	570	40	24.2	3.50	3.00	22.3850	12.10	20.30	35.00	28.8	12.30	26.1	46.1	2
23	17.2	578	40	28.1	3.60	3.00	26.4140	16.00	25.00	35.40	25.8	18.50	33.0	45.7	2
23	20.1	569	40	28.3	3.90	3.20	27.8755	15.20	21.40	35.20	27.7	18.80	31.4	44.7	2
23	15.8	524	60	26.1	3.40	2.80	23.7510	12.50	19.50	35.10	28.5	8.40	26.7	46.3	2
23	17.3	547	60	25.6	3.70	3.10	24.4480	16.60	24.40	36.30	25.7	16.60	33.3	45.8	2
23	19.3	554	60	30.0	3.40	3.00	27.3000	16.30	22.50	34.80	27.5	16.90	31.7	44.8	2
23	16.9	571	60	23.0	3.60	3.00	21.6200	12.10	20.30	35.00	28.8	12.30	26.1	46.1	2
23	17.5	583	60	26.9	3.90	3.00	26.4965	16.00	25.00	35.40	25.8	18.50	33.0	45.7	2
23	19.4	571	60	26.6	3.70	3.20	25.4030	15.20	21.40	35.20	27.7	18.80	31.4	44.7	2
23	15.7	520	80	24.8	3.50	2.80	22.9400	12.50	19.50	35.10	28.5	8.40	26.7	46.3	2
23	18.1	552	80	25.2	3.80	3.10	24.4440	16.60	24.40	36.30	25.7	16.60	33.3	45.8	2
23	19.7	566	80	28.8	3.40	3.10	26.2080	16.30	22.50	34.80	27.5	16.90	31.7	44.8	2
23	15.6	576	80	22.3	3.70	3.10	21.2965	12.10	20.30	35.00	28.8	12.30	26.1	46.1	2
23	18.1	586	80	25.8	3.90	3.00	25.4130	16.00	25.00	35.40	25.8	18.50	33.0	45.7	2
23	19.1	580	80	25.7	3.90	3.30	25.3145	15.20	21.40	35.20	27.7	18.80	31.4	44.7	2
24	22.9	600	81	28.2	3.17	3.07	24.6891	18.50	25.40	36.00	91.3	18.40	30.8	42.8	1
24	23.4	600	81	27.2	3.34	3.01	24.5072	18.50	28.80	45.30	92.3	18.40	35.1	54.3	1
25	20.7	673	166	18.2	3.54	3.08	16.9442	16.70	18.20	24.90	92.2	19.80	29.0	36.5	1

Table 28. Continued

REF	TDI	BW	DIM	MILK	MFP	MPP	MILK4	TCP	TADF	TNDF	FDM	FCP	FADF	FNDF	TYPE
25	20.7	673	166	19.2	3.57	3.30	17.9616	16.40	18.90	26.00	92.2	19.80	29.0	36.5	1
27	20.8	633	68	26.3	3.72	3.16	25.1954	16.70	22.00	31.40	44.1	18.30	33.6	43.0	2
27	20.7	633	68	26.1	3.50	3.18	24.1425	15.70	17.60	37.60	40.2	8.20	24.7	54.6	2
27	20.0	633	68	23.9	3.74	3.21	22.9679	15.70	22.00	44.30	40.2	8.20	24.7	54.6	2
27	24.1	631	88	29.8	3.68	3.11	28.3696	17.70	30.00	34.20	46.1	20.10	39.1	47.1	2
27	24.0	631	88	29.4	3.70	3.11	28.0770	16.50	30.10	37.90	86.5	18.00	41.0	55.3	1
27	23.1	631	88	30.3	3.86	3.32	29.6637	16.50	17.80	32.40	45.6	7.70	23.3	45.8	2
27	23.9	631	88	28.0	3.84	3.33	27.3280	16.70	20.10	37.90	45.6	7.70	23.3	45.8	2
28	25.4	619	49	32.9	3.59	3.23	30.8767	15.40	19.70	30.30	48.3	13.70	31.3	49.4	2
28	25.3	619	49	32.6	3.44	3.27	29.8616	15.40	20.70	30.20	48.3	13.70	31.3	49.4	2
28	24.7	619	49	33.4	3.44	3.14	30.5944	15.70	20.70	30.60	48.3	13.70	31.3	49.4	2
28	24.9	619	49	32.9	3.57	3.25	30.7780	15.60	21.10	30.90	48.3	13.70	31.3	49.4	2
28	24.2	629	41	35.4	3.70	3.09	33.8070	16.40	17.90	30.20	47.8	14.20	32.0	49.5	2
28	26.2	629	41	38.5	3.48	3.01	35.4970	16.30	18.60	30.90	47.8	14.20	32.0	49.5	2
28	26.0	629	41	35.9	3.47	3.04	33.0460	16.30	18.90	30.40	47.8	14.20	32.0	49.5	2
28	26.1	629	41	36.9	3.54	3.02	34.3539	16.20	19.60	31.10	47.8	14.20	32.0	49.5	2
32	23.9	667	56	26.3	3.80	3.20	25.5110	16.40	25.30	44.30	90.0	19.10	31.9	43.6	1
32	23.4	667	56	26.3	3.90	3.20	25.9055	16.20	26.00	45.50	89.7	18.60	34.1	47.1	1
36	22.2	611	56	30.9	3.20	2.90	27.1920	18.47	27.59	43.53	89.7	11.40	45.7	67.8	1
36	23.4	618	56	32.3	3.07	2.93	27.7942	18.46	27.71	43.80	89.6	11.30	45.5	67.3	1
38	22.9	583	52	36.0	3.29	2.83	32.1660	19.20	23.00	32.30	38.9	21.10	30.0	38.8	2
38	23.2	583	52	37.1	3.33	2.92	33.3715	19.20	23.00	32.30	38.9	21.10	30.0	38.8	2
38	21.2	584	33	33.9	3.23	2.81	29.9846	16.10	22.70	29.40	36.6	20.60	37.0	43.0	2
38	21.5	584	33	35.7	3.32	2.84	32.0586	18.20	23.00	29.50	36.6	20.60	37.0	43.0	2
38	21.4	584	33	36.2	3.33	2.90	32.5619	18.30	22.70	29.10	36.6	20.60	37.0	43.0	2
38	21.7	584	33	36.9	3.31	2.93	33.0809	18.30	22.70	29.10	36.6	20.60	37.0	43.0	2

Table 28. Continued

REF	TDI	BW	DIM	MILK	MFP	MPP	MILK4	TCP	TADF	TNDF	FDM	FCP	FADF	FNDF	TYPE
38	19.8	558	154	23.9	3.53	2.99	22.2151	19.60	27.90	37.30	43.8	21.10	30.6	39.7	2
38	20.9	558	154	24.6	3.33	2.99	22.1277	20.40	27.20	36.50	43.8	21.10	30.6	39.7	2
38	20.8	558	154	24.3	3.31	3.00	21.7850	21.20	26.60	35.70	43.8	21.10	30.6	39.7	2
38	20.3	558	154	25.7	3.32	3.02	23.0786	22.00	25.90	34.90	43.8	21.10	30.6	39.7	2
38	19.1	557	154	23.6	3.36	2.96	21.3344	19.60	27.90	37.30	43.8	21.10	30.6	39.7	2
38	20.4	557	154	23.9	3.37	3.00	21.6415	20.60	27.30	36.50	43.8	21.10	30.6	39.7	2
38	18.8	557	154	25.0	3.31	3.05	22.4125	21.60	26.70	35.70	43.8	21.10	30.6	39.7	2
38	19.5	557	154	25.7	3.30	3.06	23.0015	22.60	26.00	34.80	43.8	21.10	30.6	39.7	2
39	21.6	505	147	26.9	3.72	3.27	25.7702	17.7	21.1	33.80	46.5	15.6	28.4	42.9	2
39	22.3	505	147	26.9	3.75	3.21	25.8913	17.7	25.3	37.50	51.9	12.3	33.9	48.0	2
39	20.8	505	147	25.9	3.69	3.17	24.6957	17.5	29.0	40.70	57.5	8.7	39.5	52.9	3
39	18.9	505	147	23.5	3.60	3.13	22.0900	16.6	33.3	43.80	63.0	5.1	45.1	58.0	3
40	19.8	570	28	26.0	3.71	2.86	24.8690	16.2	26.6	44.13	27.1	16.2	32.7	53.3	2
40	20.2	596	28	26.9	3.86	2.94	26.3351	16.2	27.3	45.52	27.1	16.2	32.7	53.3	2
40	21.1	603	28	26.3	4.26	3.13	27.3257	16.3	29.2	48.33	27.1	16.2	32.7	53.3	2
40	20.7	598	28	26.9	4.21	3.07	27.7474	16.3	29.1	48.32	27.1	16.2	32.7	53.3	2
41	17.3	582	88	20.7	4.07	3.26	20.9174	19.9	25.9	58.80	14.9	19.9	25.9	58.8	4
41	16.7	583	88	21.2	3.61	3.00	19.9598	19.6	29.1	53.10	17.1	19.6	29.1	53.1	2
41	17.5	592	88	21.8	3.96	3.15	21.6692	18.4	29.0	57.00	18.3	18.4	29.0	57.0	2
43	24.9	638	141	30.3	4.08	3.32	30.6636	16.2	23.7	31.10	48.1	20.9	36.0	40.2	2
43	22.8	646	180	23.2	4.35	3.38	24.4180	16.2	23.7	31.10	48.1	20.9	36.0	40.2	2
43	19.8	595	202	17.1	4.36	3.62	18.0234	16.2	23.7	31.10	48.1	20.9	36.0	40.2	2
43	25.3	649	142	28.9	4.20	3.29	29.7670	16.0	28.6	37.60	44.9	18.6	44.4	52.0	2
43	22.9	638	157	24.1	4.10	3.24	24.4615	16.0	28.6	37.60	44.9	18.6	44.4	52.0	2
43	20.3	595	201	18.3	4.08	3.61	18.5196	16.0	28.6	37.60	44.9	18.6	44.4	52.0	2

Table 28. Continued

REF	TDI	BW	DIM	MILK	MFP	MPP	MILK4	TCP	TADF	TNDF	FDM	FCP	FADF	FNDF	TYPE
43	23.6	631	135	26.2	4.05	3.28	26.3965	16.7	30.5	39.30	49.8	17.0	47.6	54.9	2
43	22.2	631	136	23.7	4.09	3.37	24.0200	16.7	30.5	39.30	49.8	17.0	47.6	54.9	2
43	18.5	585	209	16.0	4.43	3.50	17.0320	16.7	30.5	39.30	49.8	17.0	47.6	54.9	2
48	24.0	635	34	36.7	3.32	3.13	32.9566	18.0	20.9	27.60	54.6	20.9	36.0	43.5	2
48	24.2	635	34	36.5	3.37	3.18	33.0508	19.1	21.0	27.90	54.6	20.9	36.0	43.5	2
48	24.4	635	34	37.5	3.33	3.15	33.7313	19.1	21.2	28.00	54.6	20.9	36.0	43.5	2
48	24.9	635	34	36.5	3.35	3.20	32.9413	19.5	21.3	28.10	54.6	20.9	36.0	43.5	2
48	19.5	588	37	29.0	3.97	2.95	28.8695	16.7	24.7	41.40	29.9	20.5	38.5	47.1	2
48	20.3	588	37	30.2	3.92	3.04	29.8376	17.9	24.8	40.90	29.9	20.5	38.5	47.1	2
48	20.3	588	37	31.1	3.85	3.04	30.4003	17.6	24.9	40.90	29.9	20.5	38.5	47.1	2
48	19.9	588	37	30.7	3.88	3.02	30.1474	18.8	24.8	40.30	29.9	20.5	38.5	47.1	2
48	22.4	567	64	30.1	3.55	3.11	28.0683	17.0	19.9	29.60	36.7	20.5	30.5	39.9	2
48	22.7	567	64	31.0	3.64	3.12	29.3260	18.1	20.5	31.00	36.7	20.5	30.5	39.9	2
48	22.7	567	64	31.0	3.59	3.10	29.0935	18.1	20.2	29.90	36.7	20.5	30.5	39.9	2
48	22.9	567	64	31.1	3.58	3.12	29.1407	18.9	20.1	30.00	36.7	20.5	30.5	39.9	2
49	22.8	571	21	30.8	3.93	2.90	30.4766	17.4	22.9	33.59	28.4	22.6	34.8	42.9	2
49	20.8	585	21	32.2	3.86	2.84	31.5238	20.0	24.6	34.82	28.4	22.6	34.8	42.9	2
49	21.3	615	21	32.9	4.04	2.97	33.0974	19.5	23.8	34.34	28.4	22.6	34.8	42.9	2
52	20.0	566	28	20.8	4.06	2.81	20.9872	16.1	32.4	50.67	35.4	16.4	33.0	51.2	2
52	23.7	590	28	26.6	4.21	2.91	27.4379	15.6	24.1	44.15	35.4	16.4	33.0	51.2	2
52	22.6	579	28	22.7	4.15	2.89	23.2108	15.9	26.9	48.71	33.3	16.8	37.3	57.6	2
52	20.1	583	28	24.1	4.00	2.90	24.1000	15.1	22.5	45.60	54.3	15.8	32.1	54.5	2
54	17.1	552	120	21.1	3.58	2.94	19.7707	20.9	27.9	45.80	39.6	21.9	32.7	52.5	2
54	20.5	527	120	26.8	3.28	3.00	23.9056	19.8	23.1	39.10	39.6	21.9	32.7	52.5	2
54	21.3	567	120	23.8	3.86	3.10	23.3002	20.7	28.2	35.40	51.1	21.7	33.4	40.1	2
54	22.4	579	120	27.3	3.06	3.00	23.4507	19.7	23.0	30.60	51.1	21.7	33.4	40.1	2

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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