

A GENERAL SIMULATION MODEL FOR CATTLE GROWTH AND BEEF PRODUCTION

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Summary

A general model was developed to simulate cattle growth and beef production. The present model was constructed, based on ARC metabolizable energy system in principle, and incorporated up-to-date knowledge and information into previous models, which were reported by Sanders and Cartwright (1979a,b) and Kahn (1982). The model may apply to cover a wide range of genetic and environmental conditions, because many factors relating to cattle growth and beef production are taken into consideration. The model may provide better understanding of various components and processes of beef cattle production systems.

(Key Words: Beef Production, Cattle, Growth, Simulation Model)

Introduction

At the present time, a wide variety of cattle breeds are kept for beef production in various production systems all over the world. To examine the overall productivity of beef production systems, it is necessary to understand energy and material flow within such systems and make clear the relationships between inputs and outputs.

Conventional investigations of feeding standards relating to animal-feed-climate interactions have been conducted in western developed countries (e.g., ARC, 1980; NRC, 1981; NRC, 1984). Nevertheless, since relevant data are limited and fragmentary, even these systems can only be applied to narrowly constrained areas. Accordingly, a general model which is applicable to a wide variety of situations is required for simulation of various beef cattle production systems.

From this standpoint, several general models for evaluation of cattle production systems have been developed and applied to various production systems (Sanders and Cartwright 1979a,b; Kahn, 1982). More recently, we attempted to develop a new model for simulating cattle growth and beef

production generally, by incorporating up-to-date knowledge and information into above previous models. The model has been already used to answer some questions concerning cow-calf-feedlot beef production systems in Japan (Hirooka and Yamada, 1989a,b). The objective of this study is to describe the model in terms of its structure, concepts and functions.

General Structure of the Model

The present model consists of sub-models for breeding cows, pre-weaning calves and feedlot cattle, and can apply to simulate cow-calf-feedlot production systems in beef cattle. The computer program was written in FORTRAN 77, for running on the main frame of Kyoto University. The model simulates the cows from entrance into a breeding herd to culling and progeny of her whole life from birth to marketing. The time-step of the model, 1 day was chosen and up-dated. The practical examples of simulation are shown in Hirooka and Yamada (1989 a,b).

Model Description

1. Genetic potential of animal performance

The present model requires inputs of genetic potential parameters to specify genetic performance of various cattle breeds or strains.

Growth potential

In the TAMU model (Sanders and Cartwright,

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Received August 18, 1989

Accepted May 21, 1990

1979a,b) and the Kahn model (Kahn, 1982), genetic live weight (WM), assumed to be independent of animal condition, is estimated in addition to the actual live weight (W) to specify the genotype for the size of animals of interest and to monitor outputs from the model. The genetic weight is generally expressed in terms of growth curves. Various growth curves for beef cattle have been developed since Brody (1945) tried to describe animal growth with biologically meaningful parameters (Fitzhugh, 1976). Among them, the following Brody's curve (1945) is most widely used:

$$WM = W_A (1 - Be^{-kt}) \quad (1)$$

where W_A is the mature weight (kg),

k is the maturity index,

B is the scaling parameter,

t is the time (month or day).

In fact, the growth patterns for diverse cow breeds have been fitted by the Brody's curve (table 1).

Although the parameters shown in table 1 were estimated using cow's whole life cycle data from birth to maturity, in the strict sense, it may be impossible to describe completely the growth pattern on a cow's whole life cycle using only the Brody's curve. According to Brody (1945), animal growth is divided into two phases, self accelerating and self inhibiting phases, and the Brody's growth curve is applicable only in representing the self inhibiting phase. Therefore, Sanders and Cartwright (1979a,b) and Kahn (1982) assumed that the inflection point in growth curve takes place at the age of 12 months in the TAMU model and 6 months in the Kahn model, respectively, and they tried to describe the growth with two equations; a straight line before the inflection point and a Brody's curve thereafter. Brody (1945) suggested that the inflection point corresponds to puberty. If so, it is logical to consider that the degree of maturity of an animal may be a more adequate and reasonable measure of expressing the inflection point (i.e. puberty) than the chronological age or absolute live weight because the incidence of puberty may characterize the physiological time. Age, live weight, and degree of maturity at puberty for various cattle breeds are given in table 2. The average degree of maturity at puberty was about 0.52 and the coefficient of variability of degree of maturity at puberty was smaller compared with that of age and live weight

TABLE 1. LITERATURE VALUES OF MATURE WEIGHT AND MATURATION INDEX FOR VARIOUS COW BREED

Breed	Mature weight (kg)	Maturation index	Reference
Hereford	508	0.049	(1)
1B1H	543	0.057	
3H1B	542	0.060	
5H3B	499	0.073	
Angus	471	0.076	
Jersey	454	0.044	
Angus	421	0.058	(2)
Shorthorn	409	0.066	
Angus x Shorthorn	448	0.062	
Shorthorn x Angus	440	0.059	
Angus	485	0.058	(3)
Hereford	479	0.044	(4)
Angus	441	0.057	
Hereford	443	0.059	(5)
Brangus	432	0.071	
Angus	453	0.070	(6)
Charolais	608	0.055	
Angus x Charolais	511	0.068	
Holstein x Angus	491	0.070	
Angus	520	0.064	(7)
Japanese Black	456	0.087	(8)
Japanese Black	481	0.056	(9)
Japanese Black	474	0.055	(10)
Japanese Shorthorn	655	0.042	
Holstein	550	0.046	(11)
Ayrshire	460	0.050	
Jersey	420	0.054	
Jersey	436	0.050	
Hereford	514	0.043	(12)
Angus x Hereford	517	0.039	
Shorthorn x Hereford	502	0.043	
Charolais x Hereford	592	0.037	
Simmental x Hereford	552	0.043	
Brown Swiss x Hereford	546	0.039	
Holstein x Hereford	546	0.044	

(1) Brown et al. (1976), (2) Brown et al. (1972), (3) Stewart and Martin (1983), (4) Stewart and Martin (1981), (5) Torre and Rankins (1978), (6) Nadaraja et al. (1984), (7) Marrow et al. (1978), (8) Obata and Muka (1982), (9) Wada et al. (1983), (10) Mastukawa et al. (1979), (11) Brody (1945), (12) Nadaraja et al. (1985)

at puberty, although puberty for the Bos Indicus breeds is tend to occur at a slightly later degree of maturity.

Hence, assume that the degree of maturity at puberty is 0.52, then the live weight at puberty

TABLE 2. LITERATURE VALUES OF PUBERTY TRAITS FOR VARIOUS BREEDS

Breed	Weight at puberty (kg)	Age at puberty (days)	Degree of maturity at puberty
Jersey	235	308	0.486
Hereford-Angus	282	357	0.508
Red Poll	263	337	0.495
Devon	290	356	0.521
South Devon	290	350	0.505
Tarentaise	282	349	0.516
Pinzgauer	277	334	0.501
Brangus	308	377	0.556
Santa Gertrudis	315	383	0.554
Sahiwal	291	414	0.574
Brahman	323	429	0.555
Brown Swiss	279	332	0.496
Gerbvieh	284	326	0.488
Holstein	300	341	0.515
Simmmental	302	358	0.520
Maine Anjou	305	357	0.493
Limousin	308	384	0.550
Charolais	319	384	0.519
Chianina	317	384	0.510
Means	293	361	0.519
C.V.	0.074	0.084	0.051

From Cundiff et al (1986)

(W_{pub}) is:

$$W_{pub} = 0.52 W_A \quad (2)$$

and the age at puberty (t_{pub}) is derived from equation (1) as:

$$t_{pub} = - \ln [(1-0.52) / B] / k \quad (3)$$

The genetic growth curve is represented by a straight line from birth to puberty and by a Brody curve after puberty as:

$$WM = (W_{pub} - W_B) / t_{pub} \times t + W_B \quad \text{for } (t < t_{pub})$$

or

$$WM = W_A (1 - B e^{-kt}) \quad \text{for } (t \geq t_{pub}) \quad (4)$$

where W_B is birth weight (kg). This equation is different from the growth curve used in the TAMU model; parameters used (W_A , k and B) are estimated by fitting Brody's curve for cow's whole life period in the present model, whereas the same parameters are estimated for post-inflection period in the TAMU model. This modification is made because many literature values of parameters became available (See table 1). Figure 1 shows a representative growth curve used in the present model.

As shown in the equation (4), all parameters (i.e., W_A , k , B and W_B) are required to estimate the genetic weight. However, if there are inter-relationships among them, the number of parameters can be reduced.

For example, the B value is a scaling parameter and has no biological meaning. Since live weight at time zero is birth weight, the B value can be estimated from equation (1) as:

$$B = 1 - W_B / W_A \quad (5)$$

Taylor and Murray (1987) showed the following inter-breed relationships of birth weight (W_B) and cow's mature weight (A) using published data on over 200 different breeds:

$$W_B = 0.197 W_A^{0.83} \quad (6)$$

In regard to the relationship between W_A and k , Taylor (1965) defined the reciprocal of the maturation index as a maturing interval, MI and obtained the following inter-species regression equation using literature values reported by Brody (1945) for the various species:

$$\text{Log}_{10}(MI) = 0.27 \text{log}_{10}(W_A) + 2.0 \quad (7)$$

The literature values shown in table 1 were used to examine whether the same relationship holds true within those cattle breeds. The inter breed relationship between the maturing interval (MI) and the cow's mature weight in diverse cattle breeds is illustrated in figure 2. The result suggests that it is impossible to represent the inter-breed relationship by the Taylor's equation (7) because of the large variation. Thus, at least two parameters (W_A and k) should be given as external parameters in the present model.

In addition, although time-series data from birth to maturation are required to estimate growth curve, male and steer calves are seldom reared until maturation and therefore time-series

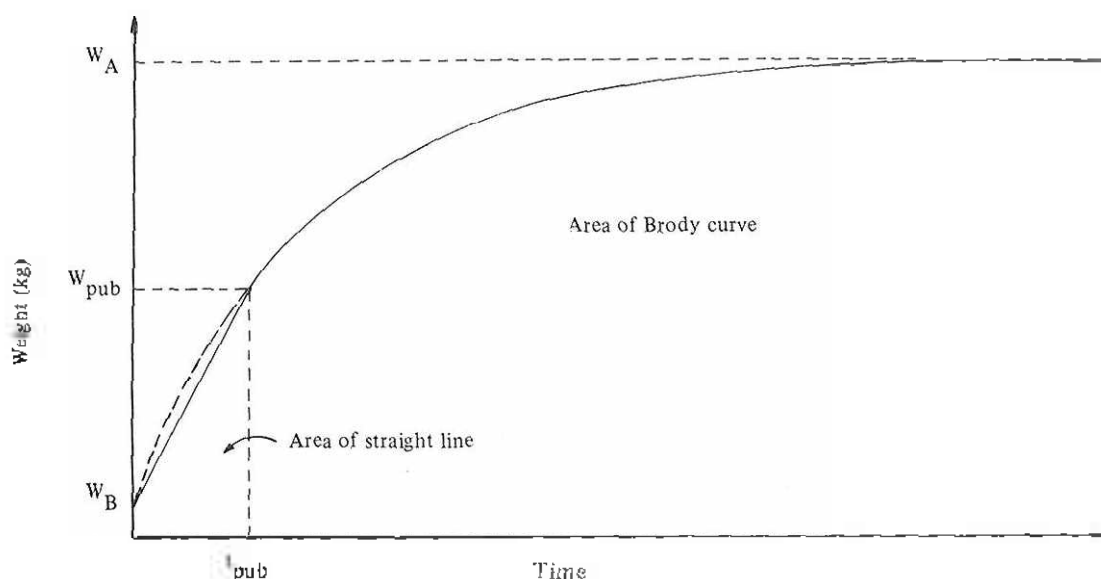


Figure 1. A representative of growth curve used in the present model. Symbols: W_B , birth weight, W_{pub} ; weight at puberty, W_A ; mature weight, t_{pub} ; time at puberty

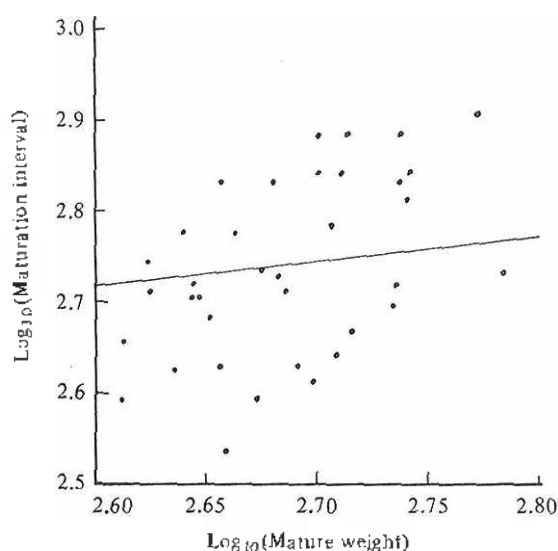


Figure 2. Inter-breed relationship of maturing interval to mature weight estimated from Brody's curve. Straight line expresses Taylor's inter-species equation (7).

data for these animals are not available in most cases. In the present model, it is assumed that the genetic weight of males is 30% higher and that of steers is 15% higher than that of females, as suggested by Kahn and Spedding (1984).

Lactation potential

In our model, genetic potential of milk yield must be also given as external parameters. Many attempts to describe daily milk yield by lactation curve have been made, especially for dairy cows (Gaines, 1927; Wood, 1967; Rowlands et al., 1982). In the present model, the widely used Wood's curve (Wood, 1967) was adopted:

$$Y = at^b e^{-ct} \quad (8)$$

where, Y is the potential daily milk yield (kg/day),
 t ; is the days of lactation,
 a, b and c are positive parameters describing the sharp of the curve.

These parameters, a, b and c are usually estimated by expressing the equation in logarithm:

$$\log Y = \log a + b \log t - ct \quad (9)$$

Taylor et al. (1986a) suggested that another useful measure of lactation potential for lactating cows may be "lactability", which represents the average daily yield of milk energy from day 14 to day 70 of lactation, expressed per unit body weight (W) per metabolic day, times 10:

$$\bar{y} = [EVM \int_{14}^{70} Y dt / (70 - 14 + 1) W_A^{0.27} / W] \times 10 \quad (10)$$

where EVM is the energy value of milk (MJ/kg). ARC (1980) expressed EVM by linear function for

milk fat concentration (BF; g/kg):

$$\text{EVM} = 0.0406 * \text{BF} + 1.509 \quad (11)$$

Since the lactation potential is defined as genetic milk yield concerning a mature cow, i.e. $W = W_A$ (mature weight), equation (10) becomes:

$$\bar{y} = \text{EVM} \left(\int_{14}^{36} Y \, dt / 57 \right) / W_A^{0.73} \times 10 \quad (12)$$

2. Sub-model for a breeding cow

The sub-model is constructed based on ME energy flow in a breeding cow and can estimate her live-weight change and milk yield from replacement to culling. Such performances are predicted from external inputs such as the quality (metabolizability) and quantity (ME energy) of supplied feed by considering the cow's genetic potentials and physiological status.

In pasture conditions, it is assumed that the ME feed supply is regulated by physical and physiological limits of appetite, and thereby apparent ME intake is determined (Sanders and Cartwright, 1979b).

The true ME intake (ME_i) is estimated by multiplying the apparent ME intake by feeding level correction factors, as shown by ARC(1965). The ME_i is divided into four energy requirements; maintenance, growth, pregnancy and lactation.

In addition, if necessary, the effect of temperature greater than 25 °C and less than 15 °C on feed intake could be adjusted using correction factors shown by Fox and Black (1984).

Correction factors for maintenance requirement

The energy requirement for maintenance (ME_m) is estimated as the sum of basal metabolism and activity allowance (ARC, 1980). However, it is known that the maintenance requirements are influenced by many factors.

Taylor et al. (1986) suggested that maintenance requirements for dairy, dual-purpose, beef and Zebu cattle are generally in this order, and they found the following relationship between maintenance efficiency (E_m) and lactability (\bar{y}):

$$E_m = 1 / (0.56 + 0.017 \bar{y}) \quad (13)$$

Taylor et al. (1986) also expressed the relationship between E_m and efficiency of utilization of energy for maintenance given in ARC (1980) (k_m) as:

$$\log k_m = \log E_m + \log 0.40 \quad (14)$$

If the average k_m of 0.70, which corresponds to the value for beef breed in the report by Taylor et al. (1986), is assumed, the correction coefficient of the maintenance efficiency for lactability (ADk_m) is given as follows:

$$\text{ADk}_m = [0.4 / (0.56 + 0.017 \bar{y})] / 0.70 \quad (15)$$

Several reports indicated that maintenance requirements of lactating cows are larger than those of dry cows (Neville, 1974; Ferrel and Jenkins, 1985). In the TAMU model, the maintenance requirements of lactating cows are increased by 30% in accordance with the finding of Neville (1974). However, this effect was neglected in the present model, because a large element of auto-correlation of the utilization efficiency is implicit in the analysis and ARC (1980) also allowed the maintenance requirements to be estimated without any adjustments for lactation.

Energy requirement for work

In many developing countries, cattle is still utilized as a draught animal. Therefore, with respect to draught cattle, the energy for work should be added to maintenance requirement.

Lawrence (1985) classified the energy for work into energies for walking, carrying loads, pulling loads and walking uphill, and he expressed the energy used for work of draught cattle (E_w; MJ/day) as follows:

$$E_w = (2.0 d_1 W + 2.6 d_1 L + P / 0.3 + 9.81 d_2 W / 0.35) / 1000 \quad (16)$$

where 2.0 is energy used to move 1 kg of body weight 1 meter horizontally (J)

- d₁ is distance traveled (km),
- W is live weight (kg),
- 2.6 is energy used to move 1 kg of applied loads 1 meter horizontally (J),
- L is load carried (kg),
- P is work done whilst pulling loads work,
- 0.3 is efficiency of doing mechanical work,
- d₂ is distance moved vertically upwards (km),
- 0.35 is efficiency of raising body weight.

Energy balance equations

It is suggested that retained energy (positive energy balance) and mobilized energy (negative energy balance) in a cow should be estimated

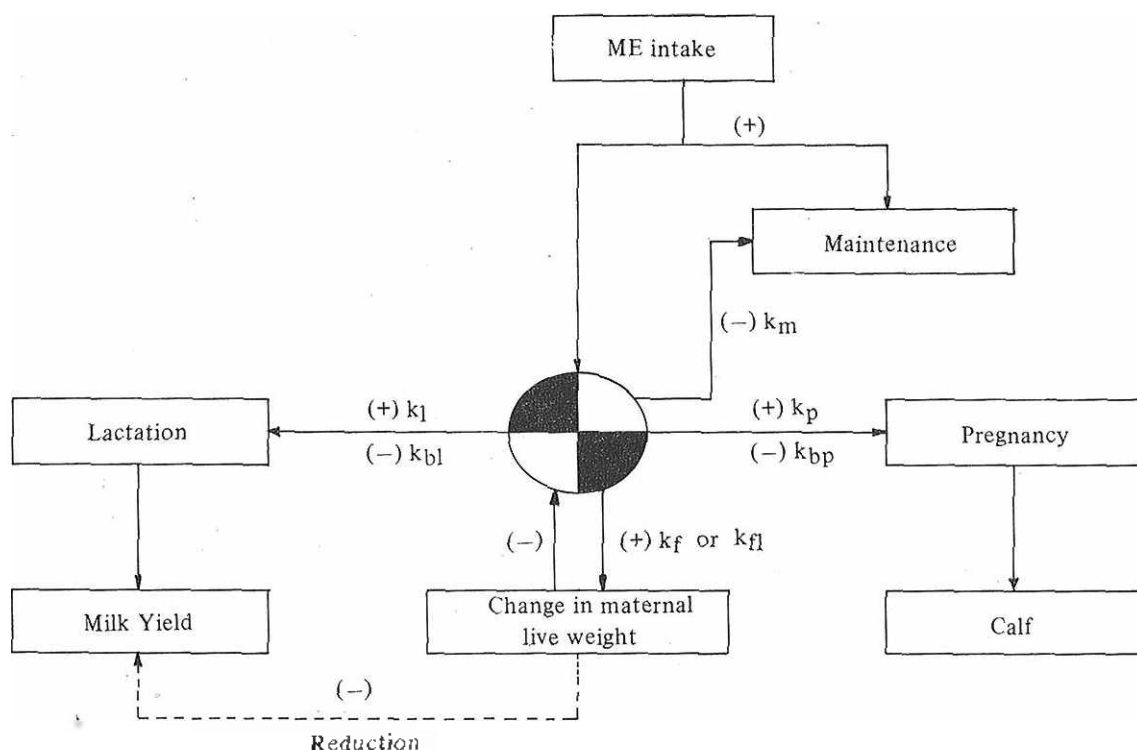


Figure 3. Schematic presentation of energy utilization pathways. (+) Positive energy balance, (-) Negative energy balance. See text for symbols of energy utilization efficiencies.

separately according to her physiological status. In the present model, it is assumed that intake ME energy is divided among various uses and in principle the partitions of energy is in the following order: (1) pregnancy, (2) maintenance, (3) lactation and (4) growth.

Figure 3 shows a schematic presentation of the pathways and efficiencies for the utilization of energy.

First, in a non-pregnant and non-lactating cow, the energy balance (EB; MJ/day) is given by:

$$\begin{aligned} EB &= k_m (ME_i - ME_m) \text{ for } (ME_i < ME_m) \\ EB &= k_f (ME_i - ME_m) \text{ for } (ME_i \geq ME_m) \end{aligned} \quad (17)$$

where k_m and k_f are the efficiencies of utilization of energy for maintenance and for growth, respectively, and ME_m is the maintenance requirement.

When $ME_i \geq ME_m$, equation (17) is identical with the ARC (1980) recommendation. When $ME_i < ME_m$, body energy mobilized per unit

deficit in ME_i is assumed to be equal to k_m .

Secondly, with respect to a pregnant cow from 141 and calving after conception, the energy balance (EB) is estimated as follows:

$$\begin{aligned} EB &= k_m (ME_i - ME_m) \cdot E_p / k_{bp} \\ &\text{for } (ME_i < ME_m) \\ EB &= k_p (ME_i - ME_m - E_p / k_p) / k_{bp} \\ &\text{for } (ME_m \leq ME_i < ME_m + E_p / k_p) \\ EB &= k_f (ME_i - ME_m - E_p / k_p) \\ &\text{for } (ME_i \geq ME_m + E_p / k_p) \end{aligned} \quad (18)$$

where E_p is the net energy for pregnancy (MJ/day) estimated from equation in ARC (1980),

k_p is the efficiency of utilization of ME to gravid uterus,

k_{bp} is the efficiency of utilization of maternal body to gravid uterus.

ARC (1980) provides k_p to be 0.133 and Bruce et al. (1984) provides k_{bp} to be 0.18.

Thirdly, the partition of energy for a lactating

cow is rather complicated, because the energy deficit is met by not only maternal tissue mobilization, but also reduction of milk yield. Bruce et al. (1984) constructed a model for lactating cows under the hypothesis that milk energy and mobilized energy from maternal tissue may be used by equal amounts to cover the deficit of metabolizable energy of feeds. Broadbent et al. (1984) proved the above hypothesis with actual data. However, the result of our preliminary analysis showed that the hypothesis proposed by Bruce et al. (1984) might be inadequate for beef cattle because negative milk yields may often occur in low milking cows at low energy intake level.

On the other hand, Kahn (1982) assumed that the reduction of milk yield may occur only when the deficit of energy is beyond the potential of mobilized energy from maternal tissue.

In the present model, both of the above hypotheses were adopted; the energy balance equations are solved similarly with Bruce et al. (1984) and the potential amounts of mobilizable body tissue are defined similarly with Kahn (1982).

Figure 4 demonstrates a flow chart of estimating energy balance (EB) and net energy for milk yield (E_l).

In a lactating cow, energy balance (EB) is estimated as:

$$\begin{aligned}
 EB &= k_m (ME_i - ME_m) - E_p/k_{bp} - E_l/k_{bl} \text{ for } (ME_i < ME_m) \\
 EB &= k_p (ME_i - ME_m - E_p/k_p) / k_{bp} - E_l/k_{bl} \text{ for } (ME_m \leq ME_i < ME_m + E_p/k_p) \\
 EB &= k_l (ME_i - ME_m - E_p/k_p) E_l/k_l / k_{bl} \text{ for } (ME_m + E_p/k_p < ME_i < ME_m + E_l/k_l) \\
 EB &= k_{fl} (ME_i - ME_m - E_p/k_p) E_l/k_l \text{ for } (ME_i \geq ME_m + E_l/k_l) \quad (19)
 \end{aligned}$$

where E_l is the net energy for milk yield (MJ/day), which is estimated in the same way as Kahn (1982),

- k_l is the utilization of feed ME to milk,
- k_{bl} is the utilization of maternal body to milk,
- k_{fl} is the utilization of feed ME to maternal body during lactation.

ARC (1980) provided k_l as a linear function of metabolizability (q):

$$k_l = 0.35 q + 0.420 \quad (20)$$

and also k_{bl} and k_{fl} as

$$k_{bl} = 0.84 \quad (21)$$

$$k_{fl} = 0.95 k_l \quad (22)$$

If the energy balance is negative and the absolute value of EB ($|EB|$) is greater than the potential energy of mobilizable body tissue (EB_{max}), then milk yield is reduced as:

$$E_l' = k_{bl} (E_l/k_{bl} + EB_{max} - |EB|) \quad (23)$$

By substituting E_l' instead of E_l into equation (23), EB can be re-calculated.

According to Brockington et al. (1983), the maximum daily energy of body tissue mobilization (EB_{max}) is:

$$EB_{max} = 0.2 W^{0.75} \quad (t_l < 90) \quad (24)$$

for the first 90 days of lactation and thereafter it decreases linearly to zero at the end of the lactation:

$$EB_{max} = 0.2 W_{t_l=90}^{0.75} (270 - t_l) / 180 \quad (t_l \geq 90) \quad (25)$$

where $W_{t_l=90}$ is the live weight at 90 days of lactation and t_l is days of lactation. Here the natural lactation period in beef breeds is assumed to be 270 days. In the present model, it is assumed that the live weight (W) is not smaller than 85 % of the genetic weight (WM) and if $W < 0.85 WM$, all energy deficits are covered by reducing milk yield.

Energy value of gain or loss

If the energy balance is positive, i.e. $EB \geq 0$, then daily gain can be estimated by dividing retained energy (RE; MJ/day) into energy value of gain (EVG; MJ/kg) (MAFF, 1975; ARC, 1980).

In general, variation of the energy value of gain can be accounted for by live weight; young and small animals have lower energy values of gain because of more protein and less fat deposit, whereas the older and larger animals have higher energy values of gain because of less protein and more fat deposit.

ARC (1980) provided the following equation of estimating energy value of gain (EVG) with data

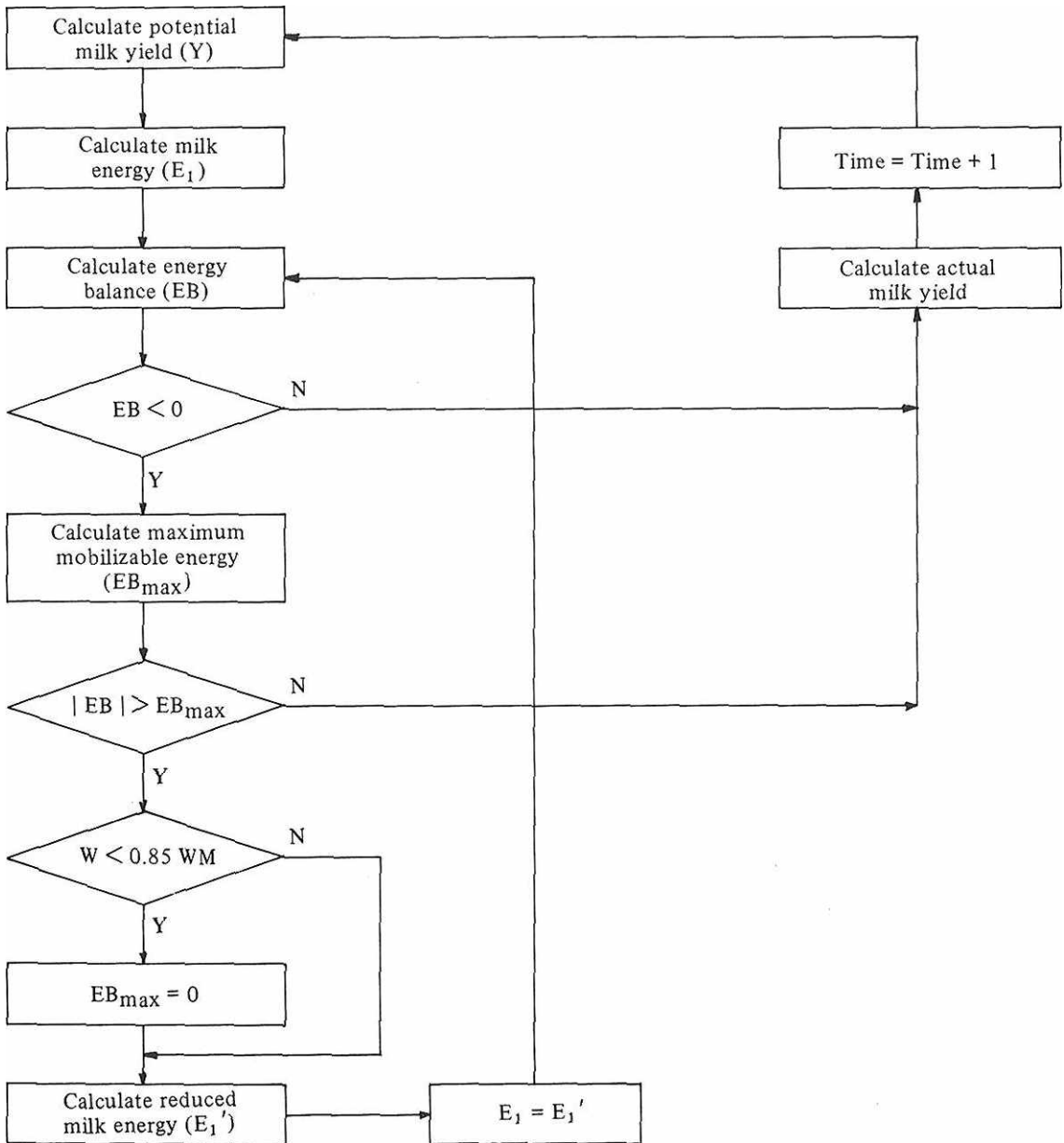


Figure 4. A flow chart of the algorithm for calculating energy balance and actual milk yield for the lactating cow.

from about 600 cattle which covered wide ranges in breed type, sex, diet and rate of growth:

$$\text{EVG} = 4.1 + 0.0332 W - 0.00009 W^2 + 0.1475 \text{RE} \quad (26)$$

ARC (1980) suggested that since this equation represents the energy value of gain only for steers

of medium size breed gaining about 0.6 kg empty body weight per day, corrections might required for the other cases. Nevertheless, ARC (1980) failed to quantify the effects of size, sex, and feeding level on the energy value of gain.

Kahn (1982) also expressed energy value of gain as a linear function of live weight using ARC

table (table 3.18, 1980):

$$EVG' = 5.12 + 0.317 W \quad (27)$$

Assuming that the maximum EVG of all breeds is equally 26 MJ/kg according to ARC (1980), Kahn (1982) extended the linear EVG equation (27) so that EVG can be estimated for all breeds being mature weight of W_A kg by:

$$EVG'' = 5.12 + [(26 - 5.12) / W_A] W \quad (28)$$

In the Kahn's model, however, the effect of feeding level (i.e. retained energy, RE) was not considered. Thus, in the present model, EVG was corrected by combining ARC's EVG equation (26) with Kahn's EVG equations (27) and (28) as:

$$\text{Corrected EVG} = EVG \times EVG' / EVG'' \quad (29)$$

Here, if the animal concerned is a medium size steer, EVG' and EVG'' cancel each other, and if RE is equal to the energy corresponding to a 0.75 kg empty body weight gain, EVG and EVG'' cancel each other.

On the other hand, if energy balance is negative, i.e. $EB < 0$, then daily loss (DL; kg) occurs. By definition, the daily loss is given by:

$$DL = EB / EVL \quad (30)$$

where EVL is the energy value of 1 kg mobilization of body tissue.

In the TAMU model, all mobilized tissues are assumed to consist of pure fat with an energy value of 39 MJ/kg (Sanders and Cartwright, 1979b). This hypothesis, however, appears to contradict a number of results obtained from actual experiments. For example, Seebeck and Tullor (1969), by comparing the chemical composition of Angus steers, showed that the changes in weight of protein and fat during the growing phase are approximately similar with those during the weight loss phase. With respect to dairy cows, Reid and Robb (1971) calculated from comparative slaughter and whole body specific gravity data on lactating Holstein heifers that 1 kg of empty body weight loss contained energy of 28.7 MJ/kg. Also, Moe et al. (1971) calculated from energy balance trials on two non-pregnant, non-lactating cows that the energy value of empty body weight loss was 26.0 MJ/kg. Using deuterium oxide (D_2O) dilutions, Chigaru and Topps (1981) showed that each kg of live-weight loss in lactating beef cow contains 27 MJ/kg

energy.

For these reasons, in the present model, it is assumed that the energy value of loss is equal to that of gain, i.e. $EVG = EVL$.

3. Sub-model for a pre-weaning calf

In this sub-model, three kinds of feed resources, namely, dam's milk, creep feed and hay feed, are taken into account. It is assumed that a calf intakes only the dam's milk up to two months of age and thereafter it intakes creep feed and hay feed as well as dam's milk.

Assuming metabolizability of the dam's milk (q_m) to be 0.91 (0.93×0.98) according to Kahn (1982, p.57), the ME energy from dam's milk ($ME_{i(m)}$; MJ/day) is given by:

$$ME_{i(m)} = 0.91 E_l \quad (31)$$

where E_l is the available cow's milk (MJ/day).

For a calf older than two months, the ME energy from creep feed ($ME_{i(c)}$; MJ/day) is given as an external parameter, and the deficiency of energy requirement is supplemented by the ME energy of hay feed ($ME_{i(h)}$; MJ/day).

If metabolizabilities of creep feed and hay feed are defined as q_c and q_h respectively, the overall metabolizability for all feeds (q) is estimated from:

$$q = [0.91 ME_{i(m)} + q_c ME_{i(c)} + q_h ME_{i(h)}] / ME_i \quad (32)$$

where ME_i is the voluntary ME feed intake (MJ/day). Thus:

$$ME_i = ME_{i(m)} + ME_{i(c)} + ME_{i(h)} \quad (33)$$

The elimination of $ME_{i(h)}$ using equations (32) and (33) yields:

$$ME_i = [ME_{i(m)} (0.91 - q_h) + ME_{i(c)} (q_c - q_h)] / (q - q_h) \quad (34)$$

The ME_i in this equation should be equal to the feed intake limit. In the TAMU model and the Kahn model, it is assumed that voluntary feed intake is regulated by physical and physiological limits.

For the physical limit phase, the voluntary energy intake (ME_{iv} ; MJ/day) was regulated by the rate of passage and the roughage volume;

$$ME_{iv} = 0.0086 W / (1 - 1.22 q) \times 18.4 q \quad (35)$$

where 0.0086 is the average fecal DM output rate

per kilogram live-weight (W), and since 1.22 times metabolizability (q) is equal to digestibility, $(1 - 1.22q)$ denotes the ratio of undigested material in the digestive tract.

On the other hand, for the physiological-limit phase, the voluntary energy intake (ME_{ip} ; MJ/day) was estimated from:

$$ME_{ip} \text{ (MJ/day)} = 1.025 \left\{ \frac{(F + AC)}{k_m} + \frac{EVG \times WMDG}{k_f} \right\} \quad (36)$$

where F is the basal metabolism (MJ/day),
 AC is the activity allowance (MJ/day),
 EVG is the energy value of gain (MJ/kg),
 $WMDG$ is the live-weight increment (kg/day),
 1.025 is a factor used to allow for slight over-consumption above the strict energy need.

In the present model, F and AC can be estimated in the same way as ARC (1980) and $WMDG$ is estimated by differentiating equation (4) with respect to time (t),

$$\begin{aligned} WMDG &= (W_{pub} - W_B) / t \text{ for } (t < t_{pub}) \\ WMDG &= k(W_A - W) \text{ for } (t \geq t_{pub}) \end{aligned} \quad (37)$$

By definition, the following relationships can be obtained:

$$\frac{0.0086 W}{(1-1.22q) \times 18.4 q} = \frac{[ME_{i(m)}(0.91-q_h) + ME_{i(c)}(q_c-q_h)]}{(q-q_h)} \quad (38)$$

$$\frac{(F+AC)/k_m + EVG \cdot WMDG/k_f}{[ME_{i(m)}(0.91-q_h) + ME_{i(c)}(q_c-q_h)]} = \frac{1}{(q-q_h)} \quad (39)$$

Since both k_m and k_f are linear functions with respect to the metabolizability and other variables are not concerned with metabolizability, these equations can be regarded as quadratic equations of q . By solving with respect to q in equation (38) and (39) and substituting each q value into each equation, ME_{iv} and ME_{ip} are derived. If $ME_{iv} \geq ME_{ip}$, then q from equation (39) is used as an overall metabolizability, otherwise q from equation (38) is used as another overall metabolizability. Once q is given, $ME_{i(h)}$ can be estimated from:

$$ME_{i(h)} = \text{Min}(ME_{iv}, ME_{ip}) \cdot ME_{i(m)} - ME_{i(c)} \quad (40)$$

where $\text{Min}(ME_{iv}, ME_{ip})$ denotes a minimum value of ME_{iv} and ME_{ip} .

If the voluntary feed ME intake is less than the sum of the ME energy from dam's milk and creep feed, i.e. $ME_j < ME_{j(m)} + ME_{j(c)}$, then $ME_{j(h)}$ would be unconditionally set to be 0.

The way of estimating retained energy and daily gain in this sub-model is similar to that of the case of a non-pregnant and non-lactating cow in the sub-model for breeding cows. However, in preliminary model runs, when the equation recommended by ARC (1980) to estimate basal metabolism was adopted to simulate preweaning calves, it gave unrealistically high calf weight gains despite the fact that ARC (1980) did not distinguish between preweaning and weaned calves. The obtained result indicated that it appears inadequate to use the ARC-recommended equation without modifications.

Zulberti and Reid (1972) expressed the basal metabolism (F ; MJ/day) using the following equation which includes both age (d) and live weight (W) of an animal:

$$F = (141.39 - 0.1036 d + 0.000052 d) W^{0.73} \cdot 4.184/1000 \quad (41)$$

where 4.184/1000 is the coefficient for transforming a unit from Kcal to Mega-joule. At birth (i.e. when $d = 0$), F becomes $0.59 W^{0.73}$ MJ/day. The coefficient of 0.59 agrees well with the literature value of 0.58 reported by Roy (1980).

Since the basal metabolism in a weaned calf is estimated by the ARC-recommended equation, equation (39) and the ARC-recommendation must be continuous at weaning age. When weaning age is set to be t_w , weaning weight (W_{tw}) can be estimated from equation (4). Assuming the basal metabolism at weaning to be $p W_{tw}^{0.73}$, the following relationship is established.

$$0.53 (W_{tw}/1.08)^{0.67} = p W_{tw}^{0.73} \quad (42)$$

When assumed that this coefficient, p , decreases linearly from birth to weaning, the basal metabolism for a pre-weaning calf (F ; MJ/day) is given by:

$$F = [(p - 0.59) * t/t_w + 0.59] W^{0.73} \quad (43)$$

where t is age of calf ($t \leq t_w$).

4. Sub-model for beef production

With regard to a feedlot cattle, not only live-weight but also body and carcass composition are

estimated using theoretical and empirical equations in the present model.

In a positive energy balance, retained energy is utilized for protein and fat tissue gains. Let 1 kg of protein and fat contain 23.6 MJ and 39.3 MJ, respectively, (ARC 1980), daily gain for protein (dP; kg) and fat (dF; kg) are predicted from:

$$dP = RE(1-s)/23.6 \quad (44)$$

$$dF = REs/39.3 \quad (45)$$

where s ($0 \leq s \leq 1$) is the fraction of retained energy (RE: MJ/day) used for fat synthesis and $(1-s)$ is the fraction of RE for protein synthesis. The parameter s is not constant in whole life of the animal, because it is affected by various factors such as feeding level, age and live-weight of the animal.

First, as the age and live-weight of an animal increase, the proportion of RE used for fat synthesis increases and eventually reaches a plateau in a later age stage. In the present model, it is assumed that in principle the partition of retained energy for fat and protein synthesis in all cattle breeds be equal when compared at the same degree of maturity. By using the degree of maturity ($u = W/W_A$) as a measure to consider the effects of age and live weight simultaneously, the change of s with increased age and live-weight is expressed by a Michaelis-Menten type equation (Michaelis and Menten, 1931) as:

$$s = s_{\max} u / (u + m) \quad (46)$$

where s_{\max} is the maximum fraction of retained energy that can be used for fat synthesis and m represents the level of RE at which 50% of the maximum fraction of RE is used for fat synthesis.

Taking a reciprocal of equation (46) and rearranging it yields:

$$1/s = (m/s_{\max})(1/u) + 1/s_{\max} \quad (47)$$

Let $1/s$ and $1/u$ be replaced by S and U respectively, this equation can be written as a linear function of S and U :

$$S = (m/s_{\max})U + 1/s_{\max} \quad (48)$$

The constant parameters m and s_{\max} can be estimated by fitting actual data to equation (47). If the average values of ARC (1980, table 1.21) assumes animals of mature weight of 650 kg, then $m = 0.134$ and $s_{\max} = 1.0$. Thus, equation (46)

is expressed as:

$$s = u/(u + 0.134) \quad (49)$$

Secondly, it is well known that as feeding level increases, the proportion of retained energy used for fat synthesis increases. ARC (1980) recommended simple percentage correction factors (i.e. 1.3% increase of the protein gain for each 0.1 kg/day empty weight gain) about animals having growth rates other than 0.6 kg/day.

The ARC recommendations can be formulated as follows:

$$dP' = [1 - 0.013(DG/1.09 - 0.6)10] \times dP \quad (50)$$

where dP' is the daily protein gain corrected by feeding level. Thus corrected daily fat gain (dF') is given by:

$$dF' = (RE - 23.6 dP')/39.3 \quad (51)$$

Protein (PR_t); kg) and fat (FAT_t); kg) weight at time t can be calculated by accumulating the daily protein and the fat tissue gains as:

$$PR_t = PR_{t-1} + dP' \quad (52)$$

$$FAT_t = FAT_{t-1} + dF' \quad (53)$$

According to Bird et al. (1982), ash weight at time t (ASH_t); kg) is expressed by the function of fasting weight ($W/1.09$; kg) as:

$$ASH_t = 0.046 (W_t/1.09)^{0.966} \quad r = 0.964 \quad (54)$$

In addition, we formulated the following equation to correct the effect of mature size on ash weight, based on Robelin and Gear (1984):

$$ASH_t' = (0.0001 W_A + 0.35) ASH_t \quad (55)$$

where W_A is mature weight of the animal concerned. In this equation, ash weight is assumed to be reduced 10% with increasing 100 kg of mature weight of the animal.

Protein, fat and ash weights are generally derived on empty body basis. In ARC (1980), empty body weight at time t (EBW_t); kg) can be estimated from:

$$EBW_t = W_t/1.09 - 14 \quad (56)$$

In practice, predictions of body composition need to be expressed in terms of carcass composition basis. Therefore, for an assessment of overall

productivity in feedlot systems, it is necessary to formulate the equations which bridges the relationship between empty body composition and carcass composition. Nevertheless, such relationships are not yet definite and they are also likely to differ between sexes and breed types.

Garrett and Hinman (1969) indicated the linear relationships between major chemical composition of the carcass and that of the empty body of 48 beef steers using specific gravity procedure.

From these relationships, the amount of protein, fat and ash in a carcass at time t are estimated as:

$$\text{Protein; } \text{CWPR}_t = 6.25 \left[\frac{(100 \text{ PR}_t / (6.25 \text{ EBW}_t) - 0.713) / 0.7772}{\{(\text{EBW}_t - 30.26) / 1.362 \} / 100} \right] \times \quad (57)$$

$$\text{Fat; } \text{CWFAT}_t = \left[\frac{(100 \text{ FAT}_t / \text{EBW}_t + 0.646) / 0.9246}{\{(\text{EBW}_t - 30.26) / 1.362 \} / 100} \right] \times \quad (58)$$

$$\text{Ash; } \text{CWASH}_t = \left[\frac{(100 \text{ ASH}_t / \text{EBW}_t - 0.844) / 0.6895}{\{(\text{EBW}_t - 30.26) / 1.362 \} / 100} \right] \times \quad (59)$$

Ferrell et al. (1976) conducted the same type of experiment using 18 Hereford heifers and indicated the same kinds of relationships as equations (57) to (59).

$$\text{CWPR}_t = 6.25 \left[\frac{(100 \text{ PR}_t / 6.25 \text{ EBW}_t) - 0.6304}{\{(\text{EBW}_t - 24.12) / 1.413 \}} \right] \times \quad (60)$$

$$\text{CWFAT}_t = \left[\frac{(100 \text{ FAT}_t / \text{EBW}_t + 1.700) / 0.8431}{\{(\text{EBW}_t - 24.12) / 1.413 \}} \right] \times \quad (61)$$

$$\text{CWASH}_t = \left[\frac{(100 \text{ ASH}_t / \text{EBW}_t - 1.409) / 0.863}{\{(\text{EBW}_t - 24.12) / 1.413 \}} \right] \times \quad (62)$$

Murray et al. (1975) reported regression equations relating the dissected components of right side of a carcass to the appropriate chemical components of the left side of the same carcass with the data of Angus steers growing from 300 kg to 440 kg. These are:

$$\text{Log}_{10}(\text{Md}_t) = 0.282 + 1.061 \text{Log}_{10}(\text{CWPR}_t) \quad (63)$$

$$\text{Log}_{10}(\text{Fd}_t) = -0.9380 + 1.076 \text{Log}_{10}(\text{CWFAT}_t) \quad (64)$$

$$\text{Log}_{10}(\text{Bd}_t) = 1.055 + 0.836 \text{Log}_{10}(\text{CWASH}_t) \quad (65)$$

where

Md_t is the total side muscle at time t from the right side of the carcass (kg),

Fd_t is the total side bone at time t including subcutaneous, intermuscular and kidney and channel fat from right side of the carcass (kg),

Bd_t is the total side bone at time t from the right side of the carcass (kg).

In spite of the narrow weight range of the animals used in the experiments, the above equations were adopted in the present model because another alternative data were not available.

Finally, carcass weight at time t (CW_t) is estimated by summing up each components as:

$$\text{CW}_t = \text{Md}_t + \text{Fd}_t + \text{Bd}_t \quad (66)$$

Discussion

Generally speaking, the aims of modeling are to organize available knowledge about the system concerned and to make clear the problems which must be solved by further research. Accordingly, with accumulating new knowledge and information, a model should be always improved. In this study, a model was developed from the following standpoints.

First, we aimed at development of a general model which can apply sufficiently to cover a wide range of feeding conditions of beef cattle. It is suggested that most valuable use of a model may be extrapolation from known to unknown situations; if a model developed in known systems (e.g. systems in western developed countries) can apply to unknown systems (e.g. systems in developing countries) without changes of many variables and parameters, such a model might provide preliminary solutions against the problems in unknown systems. Therefore, developing a general model is practical and useful since such a model excludes the necessity of building a specific model for various individual conditions.

Secondly, the present model enables us to estimate body and carcass composition as well as live-weight. In spite of the fact that estimation of

body and carcass composition is inevitable to evaluate beef production systems, only a few model can do so (Oltjen et al., 1986; Korver et al., 1988). The sub-model to estimate body and carcass composition was constructed under the assumption that the partition of energy for fat and protein synthesis in all cattle breeds is equal when compared at the same degree of maturity. This part has already tested using independent actual data by Hirooka and Yamada (1987).

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