A COMPARISON OF SIMULATION MODELS BASED ON ARC METABOLIZABLE ENERGY SYSTEM AND NRC NET ENERGY SYSTEM WITH SPECIAL REFERENCE TO GROWING STEERS

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Summary

A comparison of the ARC metabolizable energy system and the NRC net energy system was made with special reference to growing steers. Two simulation models, one based on the ARC and other on the NRC system, were constructed to examine differences between the energy systems. The average daily live-weight gains predicted from both models for growing steers were compared under various conditions in which equal feeding levels and metabolizabilities were assumed. The two simulation models yielded similar results with very high energy intake with high quality feed. Difference between the two systems became larger as feeding conditions deviated from the above. The ARC system generally predicted higher daily live-weight gains than the NRC system. This appeared to be due to the higher efficiency of utilization of metabolizable energy (k_m and k_f) and basal metabolism (F), and lower energy value of growth (EVG) in the ARC system.
(Key words: Cattle, Growth, Metabolizable Energy, Net Energy, Simulation Model)

Introduction

Since the late 19th century, one of the most important research topics in animal science has been to predict animal performance given a particular feed resource, or conversely to predict the feed requirement necessary to attain a given level of production. As a result, many studies for developing feeding standards have been conducted in various countries.

Blaxter and colleagues first proposed a new approach to describe the energy values of feeds and the requirement of ruminant (Blaxter, 1962). Their concepts were accepted by the Agricultural Research Council of U.K. (ARC, 1965) as the metabolizable energy system. The ME system was later modified for practical use by MAFF (1975), and the ARC (1980) recently made further modifications by incorporating up-to-date information.

In the U.S.A., the California net energy system, which was developed by Lofgreen and Garrett (1968), was widely adopted by the National Research Council (1970), and the NRC (1984) recently improved it so that the effects of sex and breed could be taken account into considerations.

Simulation models to predict the growth performance of beef cattle under various feeding conditions were constructed using one or the other of the above energy system (Fox and Black, 1984; Kahn, 1982; Loewer et al., 1983). It is known however that the two energy systems yield different results because of different experimental techniques and breeds (Garrett and Johnson, 1983). For this reason, it appears that the results of simulation depend upon the energy system used. Nevertheless, there is no direct comparison of the current ARC (1980) and NRC (1984) system.

The objective of this study was to construct two simulation models to compare the ARC (1980) system with the NRC (1984) system and to examine the difference between the energy systems by comparing average daily live-weight gain simulated from both models. In this study, the models simulated the energy requirement for growing steers because differences between the energy systems are most obvious in the growth process.

Materials and Methods

System dynamics technique

In the system dynamics technique (Forrester, 1968), the system of interest is reproduced by

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Received June 27, 1989
Accepted October 4, 1989

regarding loops of cause and effect relationships as the system's structure and by considering the effects of changing individual elements and time lag. In general, a dynamic systems simulation model is denoted as a set of non-linear first order differential equations:

$$dx/dt = f(\ x(t), u(t), p,t) \text{ with } x(t_0) = x_0 \qquad (1)$$

where x is the state variable vector, u is the input variable (exogenous variable) vector, p is the model parameter vector and t is the variable time.

Time stepping simulation is generally used to solve the above differential equation. In this procedure, the present time is defined as t, and after calculations of state variables were conducted at time t, time advances one fixed interval (Δt); the state variable at time $t+\Delta t$. $x(t+\Delta t)$ is calculated by adding the state variable at time t, x(t) to the changing rate of x for one interval, dx/dt as follows:

$$x(t + t) = x(t) + dx/dt \times \Delta t \qquad (2)$$

where dx/dt is estimated as the function of x(t), as shown in equation (1). Two simulation models of steer growth were developed based on the ARC and NRC energy systems. In these models, x corresponds to the live weight (W) and u consists of the quality and quantity of feed. Since each day is used as one time interval, live weight at t+1 days is calculated one by one as follows:

$$W(t+1) = W(t) + DG \text{ with } W(0) = W_0 \qquad (3)$$

where DG is daily live-weight gain and W_0 is initial live weight. The procedure of estimating DG will be described below.

Description of ARC system

ARC system is constructed on metabolizable energy (ME) basis and Mega-joule is used as the energy unit.

ARC (1980) gives the fasting metabolism, F, of a steer of live weight W(t) at time t (days) as an allometric function:

$$F = 0.53\ [\ W(t)/\ 1.08]^{0.67} \qquad (4)$$

and an allowance for standing and walking, AC, as:

$$AC = 0.0043\ W(t) \qquad (5)$$

and the efficiency of utilization of ME for maintenance, k_m, as:

$$k_m = 0.35\ q + 0.503 \qquad (6)$$

where W(t)/1.08 denotes fasted weight (kg) and q is the metabolizability of feed (i.e. ME / Gross energy) which represents quality of feed.

The ME requirement for maintenance, ME_m (MJ/day), is given by:

$$ME_m = (F + AC)\ /\ k_m \qquad (7)$$

The total energy retained, RE (MJ/day), is estimated as:

$$RE = k_f\ (ME_i - ME_m) \qquad (8)$$

where ME_i denotes the energy intake (MJ/day) and k_f is the efficiency of utilization of ME for growth. The ARC (1980) gives k_f as:

$$k_f = 0.78\ q + 0.006 \qquad (9)$$

In addition, the ARC (1980) states that because the linear relation between k_f and q is correct only when the level of feeding is equal to twice the maintenance requirements, gain is progressively overestimated above this level. As a result, the ARC (1980) suggests the following correction factor for feeding level:

$$c = k_m\ /\ (k_m - k_f)\ /\ (L - 1) \times [1 - (k_f/k_m)^{L-1}] \qquad (10)$$

where L is the feeding level expressed as a multiplier of the maintenance requirements (i.e. ME_i/ME_m). The energy value of gain, EVG (MJ/kg), is given in the ARC (1980) as :

$$EVG = 4.1 + 0.0332\ W(t) - 0.000009\ W(t)^2 + 0.1475\ RE \qquad (11)$$

Therefore, daily live-weight gain, DG (kg/day), is derived using equations (8) and (11) as:

$$DG = RE\ /\ EVG \qquad (12)$$

Description of NRC system

NRC system (1984) is constructed on a net energy basis and Mega-calorie (Mcal) is used as the energy value.

The net energy required for maintenance, NER_m (Mcal/day), is given in the NRC (1984) as follows:

$$NER_m = 0.077\ EBW(t)^{0.75} \qquad (13)$$

where EBW(t) is the empty body weight (kg). The following approximate equation proposed by the ARC (1980) to relate empty body weight to live weight was used to estimate EBW(t):

$$EBW(t) = W(t) / 1.09 - 14 \quad (14)$$

In the NRC (1984) system, the net energy requirement for gain, NER_g (Mcal/day), is estimated for a medium-frame steer as:

$$NER_g = 0.0557\ W(t)^{0.75} \times DG^{1.097} \quad (15)$$

However, since the goal here is to estimate the unknown DG (daily gain), other information is required to estimate NER_g. The net energy content of feed stuff for maintenance, NEA_m (Mcal/kg DMI), and for gain, NEA_g (Mcal/kg DMI) are also given in the NRC (1984) as:

$$NEA_m = 1.37\ (ME_i/DMI) - 0.138\ (ME_i/DMI)^2 + 0.0105\ (ME_i/DMI)^3 - 1.12 \quad (16)$$

$$NEA_g = 1.42\ (ME_i/DMI) - 0.174\ (ME_i/DMI)^2 + 0.0122\ (ME_i/DMI)^3 - 1.65 \quad (17)$$

where, MEi/DMI is the ME value of 1 kg dry matter of feed stuff and is:

$$ME_i / DMI = 18.4\ q / 4.184\ \text{(ARC, 1980)} \quad (18)$$

The daily dry matter intake for maintenance, DM_m (kg/day), is expected using the equations (13) and (16) as:

$$DM_m = NER_m / NEA_m \quad (19)$$

and the net energy required for gain, NER_g (Mcal/day), is given by:

$$NER_g = (DMI - DM_m) \times NEA_g \quad (20)$$

where if ME_i and q are known, DMI can be calculated as follows:

$$DMI = (18.4\ q / 4.184) / ME_i \quad (21)$$

Given NER_g, equation (15) is solved to estimate DG as:

$$DG = 13.91\ NER_g^{0.9116} \times W(t)^{-0.6837} \quad (22)$$

Simulation method

In spite of different energy values (i.e., ME vs NE) and units (i.e. MJ vs Mcal), both of the ARC and NRC systems are conceptually similar; fasting metabolism (F) and retained energy (RE) in the ARC (1980) system correspond to the net energy requirements for maintenance (NER_m) and gain (NER_g) in the NRC (1984) system, respectively (figure 1).

Figure 2 illustrates the procedure for comparing the two simulation models based on the ARC and the NRC energy systems. The following daily energy intake (ME_i), metabolizability (q) and initial live weight (W_0) were given as common input variables in all model runs.

ME_i was calculated using the Japanese Feeding Standard (1975) for various expected (assigned) daily gains (DG′) as follows:

$$ME_i = 15.13\ [(0.0255 + 0.0436\ DG')\ W(t)'^{0.75}]$$
$$W(t+1)' = W(t)' + DG' \quad (23)$$

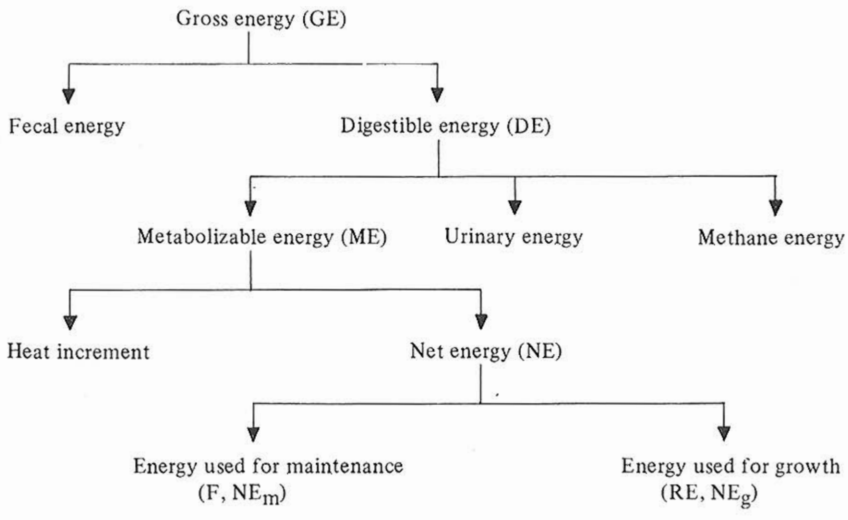

Figure 1. Partitioning of food energy within the animal.

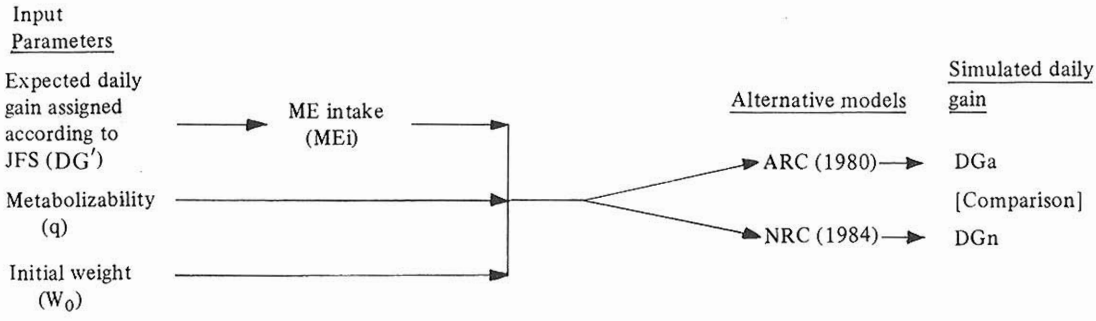

Figure 2. The procedure of model comparison. JFS; Japanese Feeding Standard

This equation was derived from data with Japanese Black steers (Japanese native cattle) reared in fattening experiments.

In the base run, constant metabolizability (q) was assumed (0.58), and in alternative model runs, q values from 0.40 to 0.70 were used. Initial live weight was set at 250 kg.

Simulated average daily gains (ADG) until live-weight of 500 kg were estimated for each simulation model as:

$$ADG = (500-250) / (\text{days on feed}) \qquad (24)$$

ADGs obtained from the ARC model and the NRC model were defined as ADGa and ADGn, respectively.

The difference between ADGa and ADGn were represented by the ratio (R) of ADGa to ADGn under various simulation conditions:

$$R = ADGa / ADGn \qquad (25)$$

If R is equal to 1.0, it means that the same ADG was obtained at an assumed input condition whichever energy systems was adopted as a basis of simulation model. Furthermore, comparisons of ADGn and ADGa with DG′ correspond to comparisons of NRC and ARC systems with Japanese Feeding Standard (1975) indirectly.

Results and Discussion

Table 1 shows the comparison of simulated average daily gains (ADGa and ADGn) from ME intake levels based on Japanese Feeding Standard (1975) requirements for various expected daily gains (DG′). When a constant metabolizability was assumed (0.58), ADGa generally tended to be larger compared with ADGn. Further, when compared with expected daily gain (DG′), ADGa was larger but ADGn was almost equal to DG′. The results indicate that the NRC system may be a suitable representation of growth for Japanese Black steers in Japanese fattening conditions.

TABLE 1. SIMULATED AVERAGE DAILY LIVE-WEIGHT GAIN FROM MODELS BASED ON ARC AND NRC ENERGY SYSTEMS WHEN VARIOUS EXPECTED DAILY GAIN WERE ASSIGNED ACCORDING TO JAPANESE FEEDING STANDARD

Expected daily gain	Simulated average daily gain based on	
	ARC (1980) [ADGa]	NRC (1984) [ADGn]
0.40	0.447	0.389
0.50	0.578	0.497
0.60	0.704	0.604
0.70	0.822	0.711
0.80	0.931	0.817
0.90	1.033	0.922
1.00	1.128	1.027
1.10	1.215	1.131
1.20	1.296	1.234

Foot note: Constant metabolizability of 0.58 was assumed.

Table 2 shows comparisons between the two models at various diet metabolizabilities for a ME intake level corresponding to 0.6 kg/day gain (equation 23). ADGa was greater at all levels of metabolizability compared with ADGn. Moreover, table 2 suggests that if either ARC or NRC system was adopted as a basis of the model for simulating Japanese fattening condition, ADGn would be smaller when low metabolizability (i.e. low quality feed) was assumed while ADGa would be larger when very high metabolizability (i.e. very high quality feed) was assumed.

To illustrate the combined effects of ME intake level and metabolizability upon the difference between the ARC and NRC systems, the ratio (R) obtained from equation (25) was regarded as a response surface on DG′ and q. DG′ values from 0.4 kg/day to 1.2 kg/day by 0.1kg and q from 0.40 to 0.70 by 0.05, representing a wide range of beef cattle production are included (figure 3).

TABLE 2. SIMULATED AVERAGE DAILY LIVE-WEIGHT GAIN FROM MODELS BASED ON ARC AND NRC ENERGY SYSTEMS WHEN VARIOUS METABOLIZABILITIES WERE ASSIGNED

Metabolizability	Simulated average daily gain based on	
	ARC (1980) [ADGa]	NRC (1984) [ADGn]
0.40	0.542	0.360
0.45	0.587	0.452
0.50	0.631	0.523
0.55	0.676	0.578
0.60	0.722	0.620
0.65	0.768	0.653
0.70	0.815	0.679

Foot note: ME intake level for a live-weight gain of 0.6kg/day in Japanese Feeding Standard was assumed.

The estimated response surfaces were expressed by fitting the following second degree polynomial equation:

$$R = 4.041 + 0.00291DG' - 9.552\,q - 0.268\,DG'^2 + 0.464\,DG'\,q + 7.659\,q^2 \quad r^2 = 0.96 \qquad (26)$$

The difference between the two systems (R) generally decreased with increasing ME intake level (i.e. DG′), and was minimized where metabolizability was about 0.60. R becomes smallest under the fattening conditions widely used in Western countries (*ad. lib* feeding with high quality diets). The result indicates that the two simulation models, either energy system may be used as a basis, can be applied to the ordinary fattening condition in Western countries without a large difference.

It is difficult to adequately compare the models without using independent actual data for validation, because data for model development and

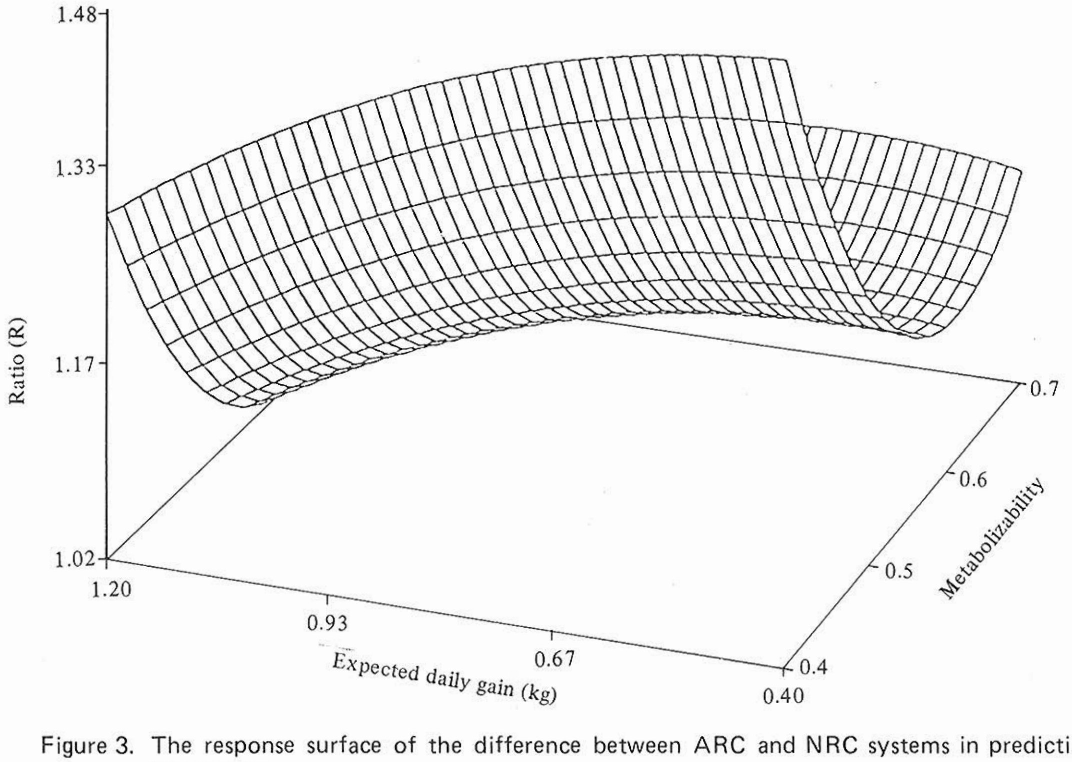

Figure 3. The response surface of the difference between ARC and NRC systems in predicting live-weight gain of beef cattle.

TABLE 3. COMPARISON BETWEEN VARIOUS PARAMETERS OF THE ARC AND NRC ENERGY SYSTEMS

Parameters	ARC (1980)	NRC (1984)
Efficiency of utilization for maintenance (k_m) [q = 0.60]	0.73	0.65
Efficiency of utilization for growth (k_f) [q = 0.60]	0.47	0.42
Basal metabolism (FM) MJ/day [W = 300 kg]	23.0	20.7
Energy value of gain (EVG) MJ/kg [W = 300 kg]	14.3	16.3

their collection methods are different. To clarify causes of the difference between the two systems, variables such as F (or NER_m), EVG, k_m and k_f used in the ARC or the NRC systems were compared (table 3). Although EVG, k_m and k_f are not given by NRC (1984), calculations using the NRC equations enable derivation of these variables. EVG can be estimated from equations (12) and (22):

$$EVG = 0.0557\ W(t)^{0.75} \times DG^{1.097} \times DG^{-1} = 0.0557\ W(t)^{0.75} \times DG^{0.097} \quad (27)$$

and k_m and k_f are obtained using equations (6), (9) and (18):

$$k_m = NEA_m / (18.4q/4.184) \quad (28)$$

$$k_f = NEA_g / (18.4q/4.184) \quad (29)$$

The ARC system gave higher k_m, kf and F but lower EVG values than the NRC system did, when compared at the same input conditions. It is suggested that the higher k_f, k_m and lower EVG values in the ARC system may lead to the larger simulated average daily gains, and conversely, the higher F values the smaller ones. In spite of these counterbalance effects, the simulation model based on the ARC system provided larger daily gains than that based on the NRC system did.

Burroughs et al. (1970) compared the ARC (1965) and the NRC (1970) systems using data from steers for both growing and fattening periods. They reported that the ARC system predicted a 25% larger average daily gain and the NRC system a 5% smaller gain. Garrett and Johnson (1983) suggested that the difference between the two systems might be because the NRC system is based exclusively on long-term comparative slaughter trials while the ARC system is based primarily on short-term respiration calorimetry experiments. This is also supported by the fact that the NRC system yields almost the same average daily gains (DGn) as the expected daily gains (DG′) in the Japanese Feeding Standard which is also based on the same long term feeding experiments (i.e. DGn is nearly equal to DG′).

In conclusion, which system should be adopted as a basis of a simulation model? Danham and Spreen (1986) pointed out that NRC data base and equations are derived from predominately concentrate fed animals, so that growth rate of cattle can be predicted very well in such feeding conditions. This is supported by the results of Knox and Handley (1973) which suggested that the NRC system can be applied to feedlot systems without large error. Loewer et al. (1983) and Fox and Black (1984) constructed simulation models for steer fattening productions based on the NRC systems and showed that the simulated values agreed well with observed ones.

On the other hand, Kromann (1973) mentioned that the ARC (1965) system takes into account more variables than the NRC (1970) system, which assumes some of the variables to be constant under different environmental conditions; for example, metabolizability as well as effect of feed ME intake levels are considered in the ARC system, but only feed energy levels are considered in the NRC system. This holds true even in comparisons of both current energy systems. Thus, the ARC system may be more general and flexible than the NRC system. Furthermore, Alderman et al. (1974) tested the ARC (1965) system by comparing it with actual data and their results contributed to the development of the later systems (MAFF, 1975; ARC, 1980). Kahn (1982) and Hirooka and Yamada (1985) constructed simulation models based on the current ARC system and indicated that such simulation models might apply to wide-ranging feeding conditions.

From the above comparisons, it is very difficult to answer the question which system is more desirable as a basis of a simulation model. Figure 3 also indicates that the difference between the two systems became larger when feeding conditions other than ordinary fattening were assumed. Garrett and Johnson (1983) pointed out that although basic animal biology and metabolic pathways are much the same in all areas of the world, the dominant cattle types, primary feed recources and economic pressures differ considerably from one country to another. Thus, the authors proposed a local adjustment of the energy systems under the different conditions.

At the present time, either the ARC or the NRC system is adopted as the feeding standard in many areas of the world. However, the results in the present study indicate that more attention should be paid when these energy systems are applied to rather specialized feeding conditions such as utilization of shrub and tree fodders, agro-industrial by-products and crop residues which is common in tropical areas.

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