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Modeling the Dietary Intake of Lactating Dairy Cows and Its Simulation

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SUMMARY

We constructed and tested a model to explain the relationship between the dietary intake of lactating dairy cows and their physiological requirements and physical limits. The physiological requirements were estimated from equations based on energy requirements, which consider lactation, growth, and the environment. Physical limits were estimated from the rate of passage through the digestive tract and the rate of digestion. To evaluate this model, simulations were compared with published intake models, and a sensitivity analysis was performed for some parameters. The results indicated that the model provides useful information about the intake of cows under different management and physiological conditions.

INTRODUCTION

The dietary intake of dairy cows has a great impact on their milk production. However, the mechanism regulating this intake is complex. Consequently, many different predictive models have been proposed. Most models are multiple regression models that include the animals, their food, or environment factors as independent variables¹⁾. However, these models are often limited and are difficult to improve upon¹⁾. Furthermore, ARC (Agricultural Research Council)²⁾ argued that multiple regression analysis might give misleading results because the factors involved are to some extent interdependent.

Conrad^{3,4)} proposed that either physical or physiological factors regulate a cow's intake. He showed that nutrient requirements determined the dry matter intake on highly digestible diets, while a full rumen limited the intake on less digestible diets. Sanders & Cartwright⁵⁾, and Kahn & Spedding⁶⁾ modeled Conrad's hypothesis, and demonstrated its usefulness. Their mechanistic models integrate a large amount of information and further our understanding of the regulation of food intake. In order to predict a cow's intake in different environments, however, additional factors must be added to such mechanistic models. Therefore, we designed a model based on Conrad's hypothesis that included such additional factors, and examined the effects of these factors on the intake of lactating cows.

MATERIALS AND METHODS

1. Construction of the model

We constructed a model to estimate the intake of dairy cows based on four premises.

- (i) A cow's intake is determined as the minimum; physiological requirements, physical limits, and dietary allowance.
- (ii) The physiological requirements are regulated by the nutrient requirements. Lactating cows are unable to eat enough to meet their requirements during the first few weeks of lactation, and have a characteristic intake pattern discussed below.

(iii) The physical limits are determined by the rate of passage through the digestive tract and the amount of material digested^{3,4)}.

(iv) This model is affected by factors including stage of lactation, potential milk yield, growth, diet, feeding level, and environmental temperature.

The symbols used in this paper and their units are listed in Table 1.

Table.1. The explanation of symbols used in this model.

| | | | |
|-----------------------|---|----------------------|---|
| <i>A</i> | Mature weight (kg) | <i>MEr</i> | <i>ME</i> requirement (MJ/day) |
| | | <i>MEr'</i> | <i>ME</i> requirement corrected with feeding level (MJ/day) |
| <i>b</i> | Parameter deciding the shape of <i>Mo</i> | <i>MEr(tpi)</i> | <i>ME</i> requirement corrected at <i>tpi</i> (MJ/day) |
| <i>b'</i> | Parameter deciding the shape of <i>SMEr</i> | <i>MEy</i> | <i>ME</i> requirement for <i>Mo</i> (MJ/day) |
| <i>Bo</i> | Potential energy for maternal growth (MJ/day) | <i>Mo</i> | Potential energy in milk produced (MJ/day) |
| <i>D</i> | <i>ME</i> contents per <i>PDMi</i> 1 kg (MJ/kg) | <i>P</i> | Potential milk energy in start of lactation (MJ/day) |
| <i>D'</i> | <i>ME</i> contents per <i>MDMi</i> 1 kg (MJ/kg) | <i>p</i> | <i>P</i> per metabolic body size (MJ/mbs/day) |
| <i>dEc</i> | Daily gain of conceptus energy (MJ/day) | <i>PDMi</i> | Physiological dry matter intake (kg/day) |
| <i>DG</i> | Daily gain of maternal body weight (kg/day) | <i>PMEr</i> | Physiological <i>ME</i> requirement (MJ/day) |
| <i>DMi</i> | Real dry matter intake (kg/day) | <i>PMEr'</i> | <i>PMEr</i> ignoring hot environment (MJ/day) |
| <i>DMA</i> | Dry matter allowance (kg/day) | <i>Ps</i> | <i>SMEr</i> at <i>tpi</i> (MJ/day) |
| <i>Ea</i> | Energy expenditure for activity (MJ/day) | <i>q</i> | Metabolizability for <i>PMEr</i> |
| <i>Ec</i> | Conceptus energy (MJ) | <i>q_m</i> | Metabolizability for maintenance |
| <i>EDW</i> | Energy value per 1 kg change of <i>W</i> (MJ/kg) | <i>q_l</i> | Metabolizability at physical intake limit |
| <i>F</i> | Fasting metabolism (MJ/day) | <i>SMEr</i> | <i>ME</i> requirement on first period of lactation (MJ/day) |
| <i>k_c</i> | Utilization efficiency of <i>ME</i> for conceptus | <i>T</i> | Environmental temperature (°C) |
| <i>k_g</i> | Utilization efficiency of <i>ME</i> for growth in lactation | <i>t</i> | Post-calving time (day) |
| <i>k_l</i> | Utilization efficiency of <i>ME</i> for lactation | <i>Tc</i> | Temperature at which the reduction of <i>PMEr</i> starts (°C) |
| <i>k_m</i> | Utilization efficiency of <i>ME</i> for maintenance | <i>tc</i> | Time after conception (day) |
| <i>L</i> | Feeding level for <i>PMEr</i> | <i>Tmax</i> | Temperature at which <i>PMEr</i> becomes zero (°C) |
| <i>L'</i> | Feeding level for <i>MDMi</i> | <i>tp</i> | Post-calving time when <i>Mo</i> becomes maximum (day) |
| | | <i>tpi</i> | Post-calving time when <i>SMEr</i> becomes maximum (day) |
| <i>MDMi</i> | Physical limit of dry matter intake (kg/day) | <i>W</i> | Maternal body weight (kg) |
| <i>MEc</i> | <i>ME</i> requirement for <i>dEc</i> (MJ/day) | <i>Wc</i> | Conceptus weight (kg) |
| <i>MEg</i> | <i>ME</i> requirement for <i>Bo</i> (MJ/day) | <i>W0</i> | Maternal body weight at start of lactation (kg) |
| <i>ME_m</i> | <i>ME</i> requirement for maintenance (MJ/day) | | |

ME : Metabolizable energy

2. Simulations with the model

To determine how the model responded to certain factors, we conducted two simulation experiments. The first compared our model with other models, and the second was a sensitivity analysis of our model. We fixed several parameters: the energy required to change the live weight by one kilogram, $EDW = 26 \text{ MJ/kg}^2$; a lactation parameter representing the metabolizable energy requirements: $b' = 0.257^2$ in the early stage of lactation and $b = 0.1047^7$ for lactation curve later on; the days post-calving when *Mo* and *SMEr* reach maximums are $tp = 30.03^7$ and $tpi = 112.59^2$, respectively.

We compared our model with five others: the Conrad³⁾, ARC²⁾, MAFF (Ministry of Agriculture, Fisheries, and Food)⁸⁾, Neal *et al.*⁹⁾, and Japanese Standard¹⁰⁾ models (Table 2). We used four different conditions: ¹⁾ a high-yield cow on a good diet (HH: $p = 0.6$, $q_m = 0.6$); ²⁾ a high-yield cow on a standard diet (HM: $p = 0.6$, $q_m = 0.5$); ³⁾ a low-yield cow on a good diet (LH: $p = 0.4$, $q_m = 0.6$); and ⁴⁾ a low-yield cow on a standard diet (LM: $p = 0.4$, $q_m = 0.5$), where *p* is the potential milk production per metabolic body size at the start of lactation and q_m is the diet metabolizability at maintenance. In all cases, we assumed that the cow's mature weight (*A*) was 650 kg.

Next, we performed a sensitivity analysis to examine the effect of related factors on the model's output.

The factors examined were mature weight (A), potential milk production per metabolic body size at the start of lactation (p), diet metabolizability at maintenance (q_m), and environmental temperature (T), at 40, 120 and 250 days post-calving. The analysis was performed for cows weighing 450, 500, 550, and 650 kg. The standard conditions for each factor were $A=650$ kg, $p=0.50$ MJ/mbs, $q_m=0.55$, $T=24$ °C.

Table. 2. Published Models for dairy cow's intake simulated.

| Model | Equations | Explanation |
|--------------------------------------|--|--|
| 1. Conrad ⁸⁾ | $DMi = \text{Minimum} [PDMi, MDMi]$ $PDMi = (0.526 + 0.333FCM + 0.056W^{0.75} + 3.08DG) / dig$ $MDMi = 0.0107W / (1 - dig)$ | $PDMi$: physiological dry matter intake, $MDMi$: physical limit of a dry matter intake, FCM : 4% fat corrected milk, W : body weight, DG : daily gain, dig : dry matter digestibility. |
| 2. ARC ²⁾ | $DMi = [0.135W_{av}^{0.75} + 0.2(FCM_{av} - 16)] \Gamma_c$ $\Gamma_c = 0.4157t^{0.267} \exp(-0.0023 \cdot t)$ Provided that q is more less 0.55, as follows: $DMi' = DMi [1 - 0.15(0.55 - q_m) / 0.05]$ | W_{av} and FCM_{av} are average of live weight and FCM during lactation. t : post-calving days, q : diets metabolizability, and q_m : diets metabolizability at maintenance. Γ_c is the corrected equation taking lactating stage into consideration. |
| 3. MAFF ⁶⁾ | $DMi = 0.1FCM + 0.025W$ | |
| 4. Neal <i>et al</i> . ⁹⁾ | $DMi = 0.2FCM + 0.022W$ | |
| 5. Japanese Standard ¹⁰⁾ | $DMi = 0.2714FCM / q_m + 0.01W + 1.5$ | |

RESULTS

1. Model

The equations used in this model are shown in Table 3.

Physiological requirements

The potential metabolizable energy requirement (MEr) is the sum of the metabolizable energy requirements for maintenance (ME_m), conceptus gain (ME_c), potential lactation (ME_y), and potential maternal growth (ME_g) [Eq. 17].

ME_m was obtained by dividing the minimum metabolism by the efficiency with which metabolizable energy is utilized for maintenance (k_m) [Eq. 5]. The minimum metabolism included the fasting metabolism (F), and the energy expended standing and walking (Ea) in Eqs. 6 and 7.

ME_c was estimated by dividing the rate of conceptus energy gain (dEc) by the utilization efficiency for the conceptus (k_c) [Eq. 8]. Eq. 10 for dEc was obtained by differentiating Eq. 9²⁾ for the total energy stored in the conceptus (Ec).

ME_y was estimated by dividing the potential milk energy yield (Mo) by the efficiency of utilization for lactation (k_l) [Eq. 11]. We obtained the equation for Mo by rewriting the lactation curve proposed by Wood¹¹⁾ in 1967.

$$Mo = P \times t^b \exp \{ b(1-t) / tp \} \quad [\text{Eq. 12}]$$

Here, P is the potential milk yield at the start of lactation [Eq. 13], tp is the day post-calving when Mo reaches a maximum, and b is a genetic parameter that determines the shape of the lactation curve.

ME_g was obtained by dividing the potential energy for maternal growth (Bo) by the efficiency with which it is utilized for a dairy cow's gain (k_r) [Eq. 14]. Bo is determined by multiplying the rate of growth (DG) by EDW , which is the energy required to change the live weight by one kilogram [Eq. 16]. In this paper, we used a Gompertz function to model the maternal body weight growth curve. DG can be expressed by the following differential equation.

$$DG = -n \times W \times \ln(W/A) \quad [\text{Eq. 15}]$$

Here, n is a growth rate parameter. Taylor¹²⁾ proposed using $1/(31.6 \times A^{0.27})$ to estimate n for domesticated

mammals. We adopted his equation to determine DG for potential maternal growth.

To explain the above utilized efficiency of metabolizable energy: k_m , k_e , k_p , and k_f , we used equations represented in ARC^2 , and these were calculated from diet metabolizability (q_m) [Eqs. 1, 2, 3, and 4].

The calculated metabolizable energy requirement (MEr) is based on the maintenance feeding level; however, lactating cows are usually fed more than this. The potential energy requirement, MEr' , was estimated by multiplying MEr by the following equation²⁾.

$$f = 1 + 0.018(MEr'/ME_m - 1)$$

From this equation we derive:

$$MEr' = (0.982 \times ME_m \times MEr) / (ME_m - 0.018 \times MEr) \quad [\text{Eq. 18}]$$

For several months after calving, lactating cows are characteristically unable to eat their potential requirement, as shown in Fig. 1. The lag between requirements and intake causes a negative energy balance in early lactation, which results in weight loss. We assumed that this intake pattern only affected the physiological requirements, and determined the metabolizable energy requirement in early lactation, $SMEr$ (MJ/day), with the following equation.

$$SMEr = Ps (t/tpi)^b \times \exp \{b'(1 - t/tpi)\} \quad [\text{Eq. 19}]$$

In this equation, the parameters b' and tpi are genetic factors that determine the shape of the curve independently, according to the intake level. The parameter tpi is the post-calving day when $SMEr$ becomes maximal; the metabolizable energy requirement at this point is Ps . From our assumptions, Ps is equal to the potential energy requirement at tpi ($MEr(tpi)$). If the effect of the amount of feeding is considered, then Ps is obtained from:

$$Ps = 0.982 \times ME_m \times MEr(tpi) / (ME_m - 0.018 \times MEr(tpi)) \quad [\text{Eq. 20}]$$

Here $MEr(tpi)$ for maintenance feeding is the total requirement for maintenance, conceptus, potential lactation, and potential maternal growth at tpi . As mentioned above, it was assumed that the physiological metabolizable energy requirement ($PMEr$) was equal to $SMEr$, which quantitatively and formally limits MEr' from calving to tpi . After tpi , $PMEr$ equals MEr' [Eq. 21]. In our model, $SMEr$ also equals MEr' at tpi .

In hot weather, cows generally reduce heat production by controlling intake because homeothermal animals need to maintain a constant body temperature. Consequently, their milk production decreases in summer. This is a significant problem for dairy farmers in Japan. Therefore, we tried to integrate the effect of temperature into our model. First, we defined two parameters: the environmental temperature at which the physiological metabolizable energy requirement starts to decrease (T_c : °C), and the temperature at which it becomes zero (T_{max} : °C). Next, we assumed that the physiological requirement decreased linearly from T_c to T_{max} . Therefore, the physiological metabolizable energy requirement taking temperature into consideration ($PMEr'$) becomes:

$$\begin{aligned} \text{If } T < T_c, & \quad PME_r' = PME_r, \\ \text{if } T_c \leq T < T_{max}, & \quad PME_r' = PME_r \times \{1 - (T - T_c) / (T_{max} - T_c)\}, \\ \text{if } T_{max} \leq T, & \quad PME_r' = 0 \end{aligned} \quad [\text{Eq. 22}]$$

Here T is the environmental temperature (°C). The parameters T_c and T_{max} are also presumed to explain the extent of intake reduction under warm conditions, so we do not always need to assign them genetic or physiological fixed values. Since the temperature at which a cow's intake starts to decrease and the degree of reduction differ with feeding management, the breed, and even from cow to cow, the values assigned to these parameters need to be set for different conditions.

Finally, the physiological dry matter requirement ($PDMi$) was calculated from $PMEr'$ using:

$$PDMi = PME_r' / (18.4 \times q) \quad [\text{Eq. 23}]$$

The denominator in this equation is the metabolizable energy content per kilogram of dry matter (MJ/kg), and can be calculated by multiplying the diet metabolizability (q) by the heat of combustion

per kilogram of dry matter, for which ARC gave a value of 18.4 MJ/kg. The value of q varies with the feeding level (L : $PMER'/MEM$) and the metabolizability at maintenance (q_m). We used the following expressions to calculate q :

$$\begin{aligned} \text{If } L \leq 1 \text{ or } q_m \geq 0.623, q &= q_m, \\ \text{if } L > 1 \text{ and } q_m > 0.623, q &= q_m + (L - 1) \{0.20 (q_m - 0.623)\} \end{aligned} \quad [\text{Eq. 24}]$$

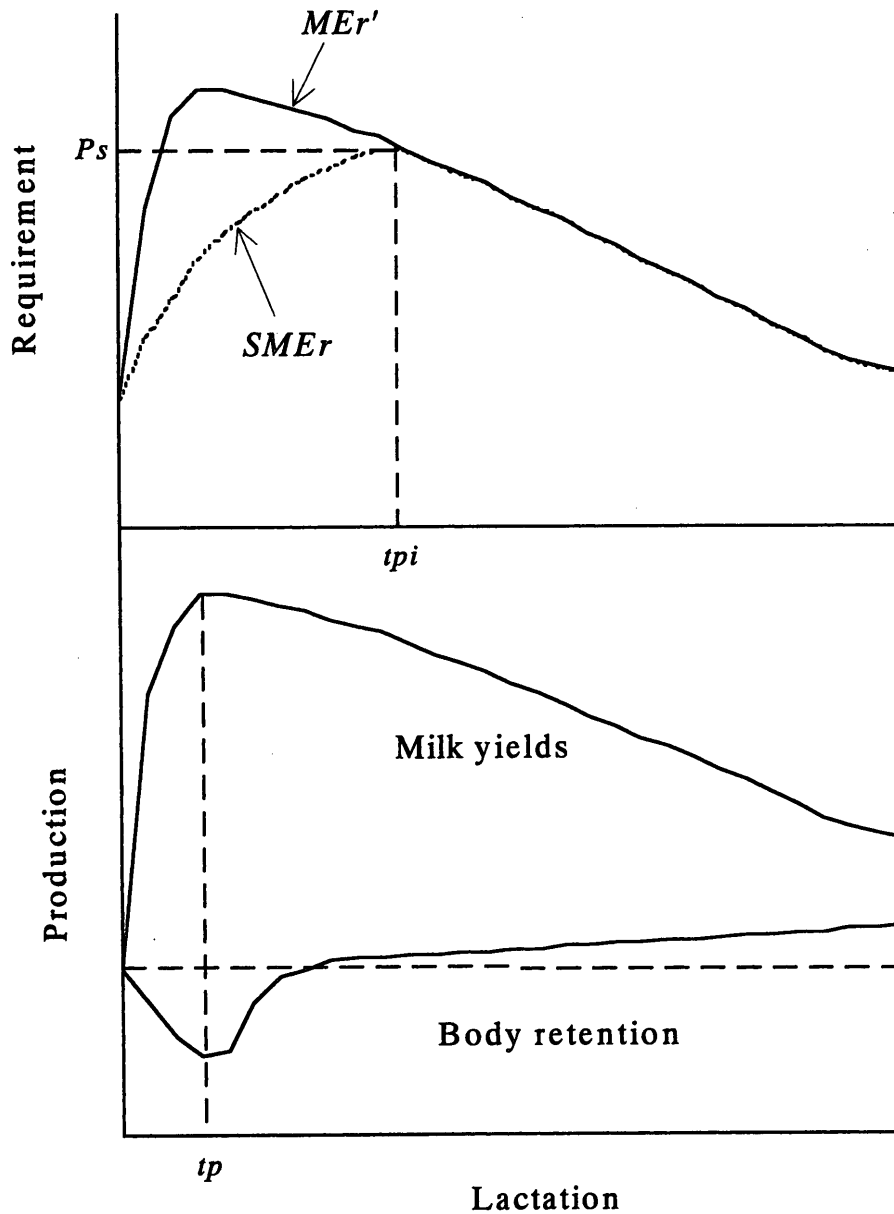


Fig.1. The change of nutritional requirement and production during lactation. The calculated requirement based on a cow's productivity (MEr') probably has its peak at the point of maximum of milk yields (tp). The peak of actual requirements (tpi), however, arises behind than tp . The lag of time usually causes a negative body change in early lactation. Authors expressed the real requirement from parturition to tpi ($SMER$) as in Eq. 19.

Physical limits

Conrad³⁾ reported that the daily rate of defecation of a lactating cow was 0.0107 kg per kg body weight. He argued that the capacity of the digestive tract was limited and proposed the following equation to calculate the physical limits of dry matter intake ($MDMi$: kg/day).

$$MDMi = 0.0107 \times BW / Fec$$

Here BW is body weight and Fec is the indigestibility of dry matter. We rewrote this equation to include diet metabolizability.

$$MDMi = 0.0107(W + Wc) / (1 - 1.33837 \times q_t) \quad [\text{Eq. 25}]$$

Here q_t is the diet metabolizability when the digestive tract is completely filled. As mentioned above, q varies with the feeding level (L') and diet metabolizability (q_m). L' can be calculated from ME_m using:

$$L' = 18.4 \times q_t \times MDMi / ME_m \quad [\text{Eq. 26}]$$

The value of q_t was derived by simultaneously solving Eqs. 24 (given $q = q_t$, $L = L'$), 25, and 26, to obtain:

$$\begin{aligned} \text{If } L' \geq 1 \text{ or } q_m \leq 0.623, \quad q_t &= q_m, \\ \text{if } L' > 1 \text{ and } q_m < 0.623, \quad q_t &= \{a - \text{sqr}(a^2 - 4.2828(q_m - 0.6670))\} / 2.6767 \end{aligned}$$

$$\begin{aligned} \text{Where, } a = \{0.1969 \times (0.1246 - 0.2 \times q_m) \times (W + Wc)\} / ME_m \\ + 1.3384 \times (0.1246 + 0.8 \times q_m) + 1 \quad [\text{Eq. 27}] \end{aligned}$$

Table 3. The main equations of the model for estimating a dairy cow's intake.

| Equations | Equations no. |
|--|---------------|
| [Physiological intake] | |
| $k_m = 0.35 q_m + 0.503$ | Eq. 1 |
| $k_l = 0.35 q_m + 0.420$ | Eq. 2 |
| $k_{fl} = 0.95 k_l$ | Eq. 3 |
| $k_c = 0.133$ | Eq. 4 |
| $ME_m = (F + Ea) / k_m$ | Eq. 5 |
| $F = 0.53 [(W + Wc) / 1.08]^{0.67}$ | Eq. 6 |
| $Ea = 0.0043 (W + Wc)$ | Eq. 7 |
| $ME_c = dEc / k_c$ | Eq. 8 |
| $\log Ec = 2.932 - 3.347 \exp(-0.00406 tc)$ | Eq. 9 |
| $dEc = Ec 0.0201 \exp(-0.0000576 tc)$ | Eq. 10 |
| $ME_y = Mo / k_l$ | Eq. 11 |
| $Mo = P t^b \exp [b(1 - t) / tp]$ | Eq. 12 |
| $P = p W^{0.75}$ | Eq. 13 |
| $ME_g = Bo / k_{fl}$ | Eq. 14 |
| $DG = -W \ln(W/A) / (31.6 A^{0.27})$ | Eq. 15 |
| $Bo = EDW DG$ | Eq. 16 |
| $ME_r = ME_m + ME_c + ME_y + ME_g$ | Eq. 17 |
| $ME_r' = (0.982 ME_m ME_r) / (ME_m - 0.018 ME_r)$ | Eq. 18 |
| $SME_r = Ps(t / tpi)^{b'} \exp[b'(1 - t / tpi)]$ | Eq. 19 |
| $Ps = 0.982 ME_m ME_r(tpi) / (ME_m - 0.018 ME_r(tpi))$ | Eq. 20 |
| $PME_r (t < tpi) = SME_r$ | |
| $(t \geq tpi) = ME_r'$ | Eq. 21 |
| $PME_r' (T \leq Tc) = PME_r$ | |
| $(Tc < T \leq Tmax) = PME_r [1 - (T - Tc) / (Tmax - Tc)]$ | |
| $(Tmax < T) = 0$ | Eq. 22 |
| $PDMi = PME_r' / (18.4 q)$ | Eq. 23 |
| $q (L \leq 1 \text{ or } q_m \geq 0.623), q = q_m$ | |
| $(L > 1 \text{ and } q_m < 0.623), q = q_m + (L - 1)[0.20(q_m - 0.623)]$ | Eq. 24 |
| [Physical limit] | |
| $MDMi = 0.0107(W + Wc) / (1 - 1.33837 q_t)$ | Eq. 25 |
| $L' = 18.4 q_t MDMi / ME_m$ | Eq. 26 |
| $q_t (L' \leq 1 \text{ or } q_m \geq 0.623) = q_m$ | |
| $(L' > 1 \text{ and } q_m < 0.623) = [a - \text{sqr}(a^2 - 4.2828 q_m - 0.6670)] / 2.6767$ | |
| Where, $a = [0.1969 (0.1246 - 0.2 q_m)(W + Wc)] / ME_m$ | |
| $+ 1.3384 (0.1246 + 0.8 q_m) + 1$ | Eq. 27 |
| [Actual intake] | |
| $DMi = \text{Minimum } [DMa, PDMi, MDMi]$ | Eq. 28 |

The explanation of the symbols were shown in Table 1.

Actual intake

Based on the model's assumptions, the actual dry matter intake (DMi) was determined as the minimum a) the dry matter allowance (DMa), b) the physiological dry matter intake ($PDMi$), and c) the physical limit of dry matter intake ($MDMi$).

$$DMi = \text{Minimum } [DMa, PDMi, MDMi] \quad [\text{Eq. 28}]$$

2. Simulations with the model

Comparison between our model and published food intake models

As shown in Fig. 2, the mean daily intake in our model throughout lactation ranged from 12.14 (LH) to 16.36 (HH) kg/day. This was similar to the range of values in all the models: 13.84 (LH) to 16.14 (HH) kg/day. The standard deviation of the mean values among models ranges from 0.93 (LM)-1.25 (HH) kg/day, with the exception of HM (1.65 kg/day). The maximum average daily intake in each model occurred under HH conditions, except with the Japanese Standard model (HM). In contrast, the minimum values occurred under low milk yield conditions: Our model and the Japanese Standard model under LH condition, the Conrad and ARC models under LM condition, and the MAFF and Neal *et al.* models under both LH and LM conditions.

For the variation in the daily intake during lactation, only the ARC model explained the characteristic pattern seen in early lactation under all conditions. Our model only reproduced this pattern under good diet conditions (HH and LH). The Conrad model also showed this intake pattern under good diet conditions, but the observed difference was small. The other models did not reproduce the pattern, because the simulated intake variation matched the lactating curve and peaked early in lactation.

In the middle of lactation (120 days post calving), the mean daily intake in all models ranged from 14.16 to 17.29 kg/day for all conditions. Our values ranged from 13.94-18.99 kg/day, and were similar to those in the other models. However, the daily intake under high-milk conditions during this period varied widely among the models. The differences between the maximum and minimum intake under HH and HM conditions were 4.97 ± 1.88 and 5.13 ± 1.89 kg/day (mean \pm S.D.), respectively. On the other hand, under LH and LM conditions the differences were 2.97 ± 1.10 and 1.82 ± 0.61 kg/day. The main reason for this was that high milk yields in this period strongly affected the intake response to milk yield in each model.

In the later period of lactation (260 days post calving), the simulated daily intake was similar in all the models. The differences between maximum and minimum intake in the models under all conditions ranged from 1.21-3.99 kg/day, while the standard deviations ranged from 0.88-1.59 kg/day. Except under the LH condition, the values produced by the model had smaller differences (0.4-1.3 kg/day) than the mean values in all the models under each condition. The difference for the LH condition was 2.14 kg/day.

Sensitivity analysis

As shown in Figs. 3 and 4, for some values of p and T , the dry matter intake (DMi) of the smaller cows (450 and 500 kg) was less than that of the bigger cows. The differences were more marked 120 days post-calving, when the cow's intake was greater, because the physical limits of the digestive tract strongly affected lighter cows.

DMi was directly proportional to mature weight: A to match the increased nutrient requirement with body size. For the same reason, increasing the parameter for milk production (p) also increased DMi , provided that the increase from p was greater than that from A .

As q_m increased, DMi increased initially, reached a maximum, and then decreased. When q_m was small, larger cows had higher values of DMi , but when q_m exceeded 0.55 the DMi of each cow was essentially the same. With increasing body weight, the peak occurred at lower values of q_m and higher values of DMi . This was due to the interaction between physiological nutrient requirements and the volume of the digestive tract

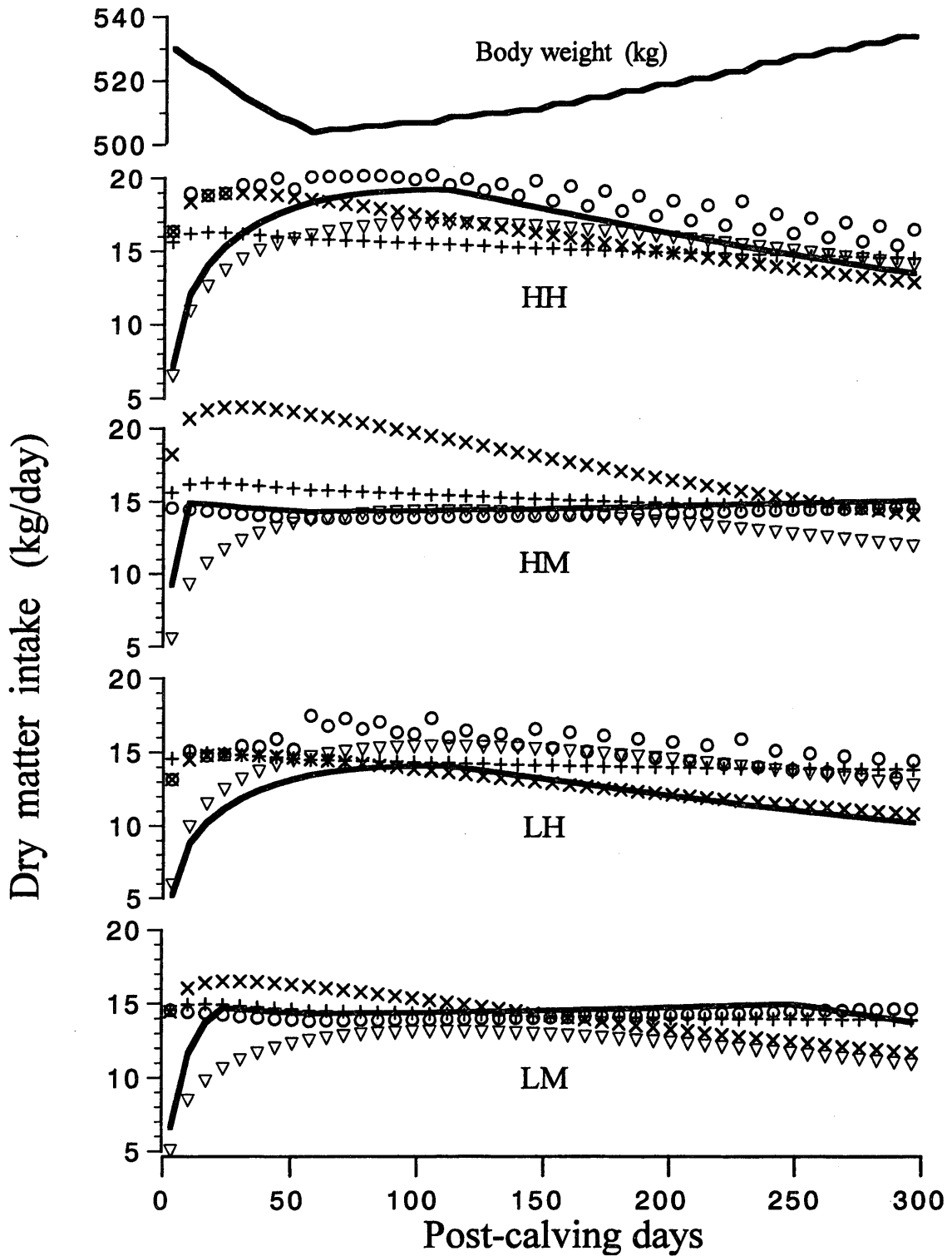


Fig.2. Comparison among simulations of authors' intake model and published intake models. The top shows a change of body weight in lactation. The bottom four show changes of intake under the following conditions. First character H and L show the high and low milk productivity, respectively ($p = 0.6$ and $p = 0.4$). Next character H and M show the high and standard diet quality, respectively ($q_m = 0.5$ and $q_m = 0.6$). Solid line: Authors' model, Circle: Conrad⁶⁾, Reverse triangle: ARC²⁾, Plus: (MAFF⁸⁾ + Neal *et al.*⁹⁾ /2., Cross: Jap. Feed. Std.¹³⁾. Since similar values are shown between MAFF and Neal *et al.*, the mean values between the both are illustrated on the figure.

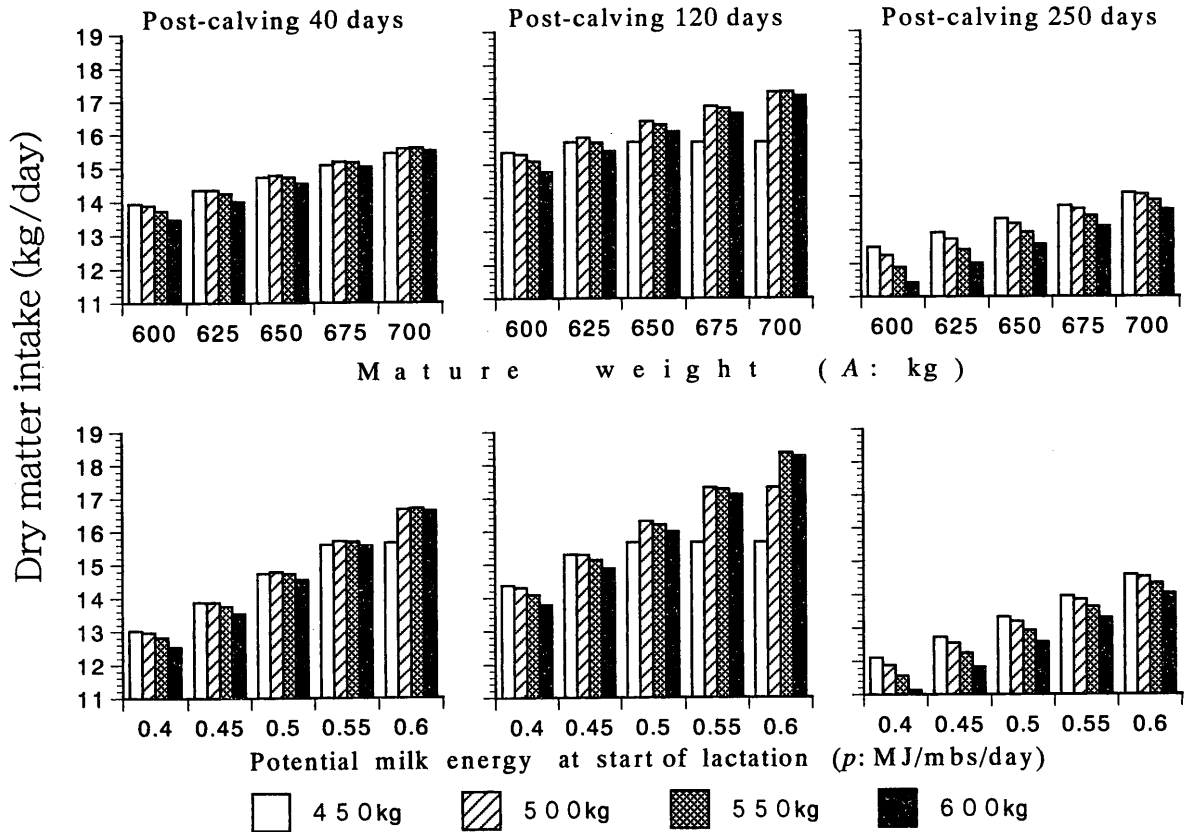


Fig.3. Sensitivity analysis of the model for the mature weight (A : kg) and the milk parameter (p : MJ/mbs/day) of each body weight cow at 40, 120 and 250 days post-calving. Standard conditions for four parameters were as follows. A : 650 kg, p : 0.50 MJ/mbs/day; q_m : 0.55; T :24 degrees centigrade.

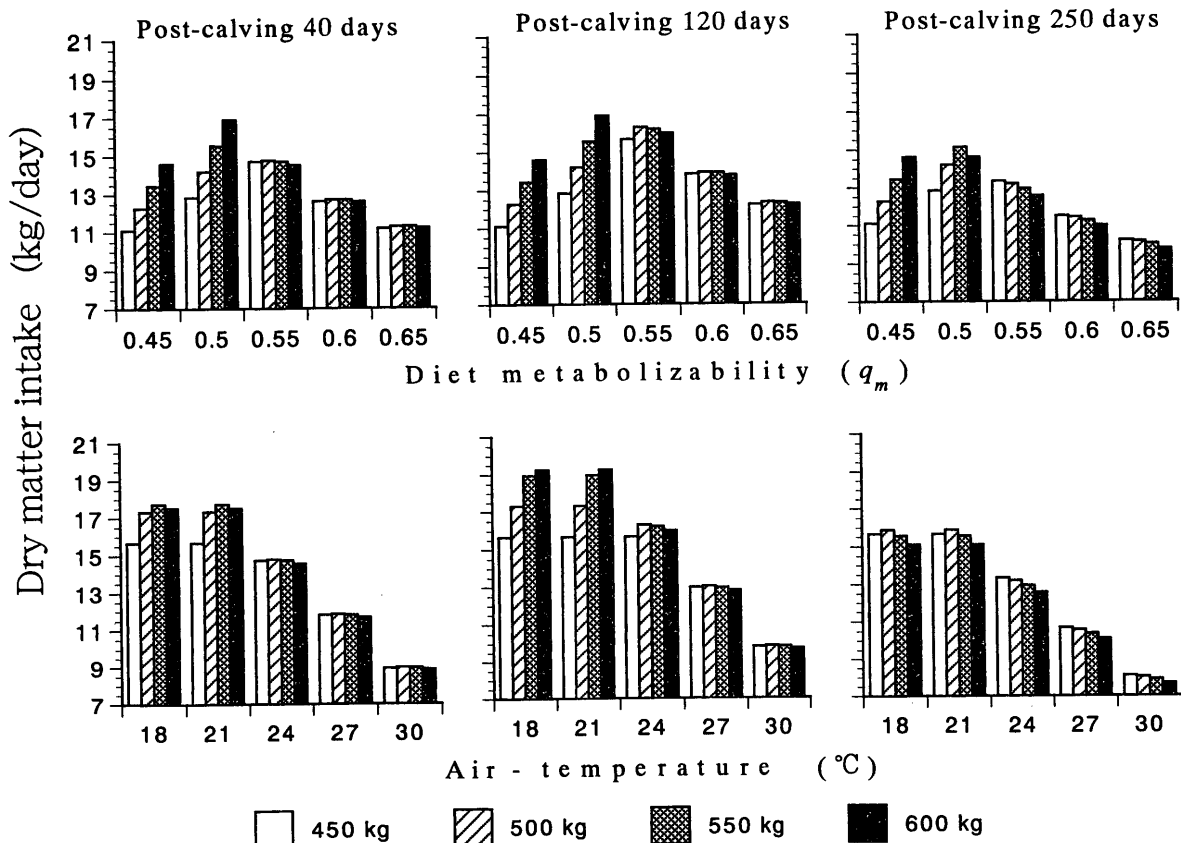


Fig. 4. Sensitivity analysis of the model for diet metabolizability (q_m) and air-temperature (T : $^{\circ}$ C) of each body weight cow at 40, 120 and 250 days post-calving. Standard conditions were shown with the same way as Fig. 3.

as it related to the cows' body weight.

When it was hot, *DMI* started to decrease at lower temperatures in larger cows and decreased more strongly. This trend was especially marked 120 days post-calving.

DISCUSSION

The underlying concept of our model is that a cow's intake is determined by the relationship between physiological requirements and physical limits to intake. The physiological requirements are based on nutrient requirements. This was also adopted in the NRC (National Research Council's Nutrient Requirements of Dairy Cattle)¹³⁾. To estimate physiological requirements, Conrad³⁾ used a multiple regression formula factoring in milk production, body weight, and daily gain, as shown in Table 2. However, this model could not explain how the intake amount was regulated. Most other models for estimating a cow's intake are also based on multiple regression. However, regression models have several problems: they are only available for limited feeding periods, they are difficult to improve, and they don't provide insight into the extent of interdependence among the factors^{1,2,6)}.

We used the ARC system²⁾, which is based on the theory of energy metabolism, to calculate the physiological nutrition requirements. Consequently, we were able to integrate into our model such factors as milk production ability, maternal growth, conceptus, diet metabolizability, and feeding level, using nutrition science theory.

Lactating cows usually do not meet their nutrient requirements during the initial months after parturition. The peak of milk production, which affects a cow's nutrient requirements, is in the period 20-50 days post-calving, while the peak intake generally occurs later. For example, in the ARC²⁾ and NRC¹³⁾, the peak is 100-150 and 70-90 days post-calving, respectively. Therefore, the actual intake during this period cannot be estimated just from the potential nutrient requirements. The NRC¹³⁾ indicated that the lag between intake and milk production is maximal in early lactation when maternal weight decreases, as seen in Fig. 1. Regression models, however, have difficulty explaining this well, as shown in the simulations in Fig. 2. Nevertheless, it seems important to estimate a cow's intake correctly during this period when milk yields are greatest. Therefore, we proposed using Equation 19 to express the characteristic pattern seen from parturition to the peak of intake. Our model explained this intake pattern well under good dietary conditions, but was not as clear with a standard diet, as seen in Fig. 2. This difference may result from the slower passage of a poorer quality diet through the digestive tract, meaning that the physiological requirements are not met.

As mentioned above, we assumed that the physiological requirements have a characteristic intake pattern in early lactation; however, this pattern may be caused by physical limits, as explained by Khan¹⁴⁾. Monteiro¹⁵⁾ tried to model the lag between intake and milk yield with a dynamic model that changed the intake in response to changes in production. It is also possible that the pattern is caused by variations in the utilization efficiency for milk (k_p) during lactation. The mechanism for this pattern remains unclear, and requires further investigation¹⁾.

We also tried to integrate environmental heat into our model. It is well known that food intake and milk production decrease when it is hot, as a physiological control to maintain body temperature. NRC (Requirements of Beef Cattle)¹⁶⁾ indicated that ambient temperatures outside the range 15-25°C could affect the intake of beef cattle, and that intake might be depressed by up to 30% when it is hot and humid. Arnold & Dudzinski¹⁷⁾ showed that grazing time decreased when the temperature exceeded 21°C. Brody¹⁸⁾ also reported that decreased food intake under hot conditions caused decreased production. Therefore, the ability to predict when the decrease is likely to occur would provide valuable information for managing cows. Accordingly, Tsuiki¹⁹⁾ proposed a model that considered declining intake under hot conditions, but neglected breed and management methods. However, these other factors should not be ignored, because they can also

affect the magnitude of the decline in intake.

We incorporated two temperature parameters in our model: the temperature at which the physiological requirements start to decrease, and the temperature at which they become zero. By using appropriate values, we can examine the variation in intake decline under different conditions. However, we would like to emphasize that the values we used were assumed values that matched different conditions and do not mirror the physiological mechanism linking a cow's requirements and temperature. To make the model more realistic, we need to determine appropriate values for a specific herd or conditions.

We did not examine the relationship between environmental temperatures and the physical limit to a cow's intake. The digestibility of food usually increases when it is warm because the rate of passage through the digestive tract decreases. This suggests that the value of 0.0107 we used in Eq. 25, which was determined from the passage rate and diet metabolizability (q_1), may vary with temperature. These parameters may also vary throughout lactation; however, we have no information confirming this.

We adopted a Gompertz function to calculate the growth of the cow and conceptus. A variety of functions, such as Brody, logistic, and Bertalanffy functions, have been used to model the maternal growth curve, but the only information we could obtain on the growth of the conceptus was the Gompertz function in the ARC²⁾, which is why we used a Gompertz function to model growth. The accuracy of these functions has been evaluated for the growth of beef cattle^{20, 21, 22)}, but not for dairy cows. Therefore, we tested the Gompertz function on the growth of dairy cows, and it showed a good fit²³⁾.

The main focus of our model was to include more factors that affect a cow's intake than other intake models. The relationship between these factors and intake is based on animal nutritional science. Tests of the model shown in Figs. 2, 3, and 4, allowed us to examine variation in intake along with differences in management and physiological condition. The results should provide useful information for actual farm management.

Additional factors not included in our model also affect the intake of lactating cows. For example, the palatability of the diet may be more important than its nutritional value. Hodgson²⁴⁾ also pointed out the importance of behavioral limitations in the control of herbage intake. Demment & Greenwood²⁵⁾ made an intake model that considered differences in feeding behavior. However, knowledge of the interactions between these factors and food intake is still insufficient, and must be clarified in the future.

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泌乳牛の飼料摂取量のモデル化とその動態

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泌乳牛の飼料摂取量, 生理的要求量, 及び物理的制限の間の関係を説明するためのモデルを構築しその分析を行った。生理的要求量は泌乳, 成長, 及び環境を考慮したエネルギー要求に基づく方程式から推定され, 物理的制限は消化管の通過速度とその消化率から推定された。モデルを評価するため, 他文献の摂取モデルとのシミュレーション比較試験と, いくつかのパラメータに対する感度分析を実行し, その結果は現在のモデルが, 種々の管理条件及び生理条件下での牛の飼料摂取量の有用な情報を与えることを示した。

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