# Accounting for the Effects of Environment on the Nutrient Requirements of Dairy Cattle

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## ABSTRACT

The maintenance requirements of the Cornell Net Carbohydrate and Protein System were revised to evaluate the effects of activity, temperature, and humidity. Four dairy heifer situations were simulated (1 = clean and dry, 2 = moderately matted hair coat, 3 = condition 2 plus 10-cm lot mud from November to March, and 4 = condition 1 plus 16-kph wind) to represent typical conditions of the northern and southwestern US. In the northern condition, predicted daily gain was 0.88, 0.60, 0.53, and 0.68 kg/d for the four environmental situations; corresponding values for the Southwest were 0.88, 0.88, 0.78, and 0.88. Environmentally neutral daily gain was 0.94 kg/d to a BW of 603 kg at first calving at 20.3 mo of age. Calving age was increased when environmental stress extended the age at which puberty weight was reached. Calving weight was decreased when environmental stress occurred after conception. Twelve environmental conditions (variable temperature, humidity, and housing) for lactating dairy cows were simulated. At 30°C and no night cooling, predicted milk production decreased 2.6 and 11.9 kg/d at 20 and 80% humidity, respectively. Increased activity reduced predicted milk production to 0.4 to 1.3 kg/d in confinement scenarios and to 0.9 to 7.5 kg in grazing scenarios.

(**Key words**: nutrient requirements, environmental effects, maintenance requirements, models)

**Abbreviation key**: **AFRC** = Agricultural and Food Research Council, **BCS** = body condition score, **CETI** = current month's effective temperature index, **CNCPS** = Cornell Net Carbohydrate and Protein System, **CSIRO** = Commonwealth Scientific and Industrial Research Organization, **ME** = metabolizable energy, $\mathbf{NE_m}$ = net energy for maintenance, adjusted for acclimatization, activity, and excess N.

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## INTRODUCTION

A more accurate accounting of the effect of environment on milk production or growth rate is needed to diagnose performance problems and to make decisions about facility design and pasture systems. One purpose of this paper is to present a revision of the Cornell Net Carbohydrate and Protein System [**CNCPS** (5)] maintenance requirement submodel that can be used to account for the effects of environment on the nutrient requirements of dairy cattle in different environmental conditions. An additional objective is to evaluate predicted responses of dairy heifers and lactating dairy cows to environmental effects. It is assumed that the effects of environment are primarily reflected through a change in the requirement for maintenance energy and DMI and that the impacts on requirements for pregnancy, growth, and lactation are secondary to energy available after the maintenance requirement is met.

## MATERIALS AND METHODS

### Prediction Equations and Computer Model

The CNCPS maintenance requirement submodel was developed for predicting the effect of environment on maintenance requirements and feed intake (5). The base requirement for net energy for maintenance ($\mathbf{NE_m}$) is adjusted for physiological state, activity, and heat or cold stress. The CNCPS model predicts the interaction of environmental temperature and wind with animal heat production and loss, depending on heat increment and animal insulation. In this model, it is critical to describe DMI and diet energy values accurately because animal requirements and diet are interactive, including calculating feed digestibility under specific conditions, the heat increment to compute lower critical temperature, and the nutrients left for productive purposes after maintenance requirements are met. Therefore, this environmental submodel was designed to be used within the structure of the CNCPS to predict animal responses to specific environmental conditions.

## Computing Maintenance Requirements

The maintenance requirement for energy is defined by the 1996 NRC (15) as the amount of feed energy intake that results in no net loss or gain of energy from the tissues of the animal body. This energy is required for essential metabolic processes, body temperature regulation, and physical activity. To predict the amount of feed intake required for these purposes in each situation, the metabolic requirement, physical activity, and energy that must be partitioned to maintain body temperature at 39°C must be determined.

***Base maintenance requirement.*** Maintenance requirement in a thermol neutral environment with minimum activity was defined for the CNCPS (5) as follows:

$$NE_m = SBW^{0.75} \times ((a1 \times BE \times L \times COMP) + a2) \quad [1]$$

TABLE 1. Definitions for abbreviations used in equations.

| | | |
|---|---|---|
| a1 | Thermoneutral maintenance requirement for fasting metabolism | Mcal/d/kg of $SBW^{0.75}$ |
| a2 | Maintenance adjustment for previous temperature effect | Mcal/d/kg of $SBW^{0.75}$ |
| ACT | Activity requirement for standing, changing position, and horizontal and slope walking | |
| BE | Breed effect on $NE_m$ requirement | |
| COMP | Compensation effect for previous plane of nutrition | |
| DMIAF | DMI adjustment factor | % |
| DMIAFN | DMI adjustment factor with no night cooling | % |
| DMIAFC | DMI adjustment factor with night cooling | % |
| DMIAFMUD | DMI adjustment factor for mud depth | |
| Distance flat | Distance traveled daily on flat surface | m |
| Distance sloped | Distance traveled daily on sloped surface | m |
| EI | External insulation value | °C/Mcal per $m^2$ per d |
| GU | Grazing unit | ha |
| HAIR | Effective hair depth | cm |
| HE | Heat production | Mcal/$m^2$ per d |
| HIDE | Hide adjustment factor for external insulation | |
| HRS | Hours per day exposed to direct sunlight | |
| FBW | Full body weight | |
| I | Insulation value | °C/Mcal per $m^2$ per d |
| $I_m$ | DMI for maintenance | (no stress) |
| $k_m$ | Diet $NE_m$/diet metabolizable energy (ME) | |
| L | Lactation effect on $NE_m$ requirement in beef breeds | |
| LE | Net energy required for lactation | Mcal/d |
| LCT | Animal's lower critical temperature | °C |
| Mcal | Megacalorie | |
| $ME_{cs}$ | Metabolizable energy required for cold stress | Mcal/d |
| MEI | Metabolizable energy intake | Mcal/d |
| MUD2 | Mud adjustment factor for external insulation | |
| $NE_{mact}$ | Activity effect on $NE_m$ requirement | Mcal/d |
| $NE_{mcs}$ | Net energy (NE) required for cold stress | Mcal/d |
| $NE_{ma}$ | NE value of diet for maintenance | Mcal/kg |
| $NE_{mhs}$ | $NE_m$ adjustment for heat stress | % |
| Position changes | Number of changes between lying and standing | |
| RE | NE retained | Mcal/d |
| RHP | Previous month's average relative humidity | % |
| RHC | Current month's average relative humidity | % |
| SA | Surface area | $m^2$ |
| SBW | Shrunken BW, which is defined as 96% of full weight | |
| Standing | Time spent standing | h/d |
| $T_c$ | Current mean daily (24 h) temperature | °C |
| TI | Tissue (internal) insulation value | °C/Mcal per $m^2$ per d |
| $T_p$ | Previous month's average temperature | °C |
| $T_c$ | Current month's average temperature | °C |
| UREA | Cost of excreting excess N | Mcal of ME |
| WIND | Wind speed | kph |
| WS | Wind speed | m/s |
| YE | NE required for pregnancy | Mcal/d |

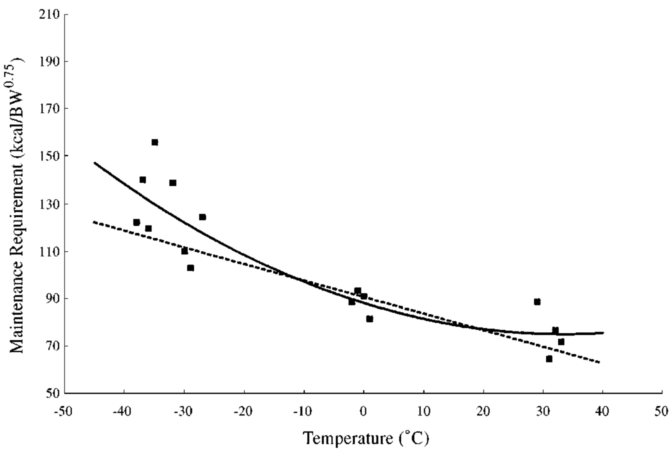


Figure 1. The effect of previous temperature on the maintenance requirement per kilogram of metabolic BW (MBW) developed from the data of Young (18, 19). The dashed line represents the linear equation used in the Cornell Net Carbohydrate and Protein System (5) and NRC (15) models, and the solid line represents Equation [3] developed for this revision.

where a1 is 0.077 Mcal/d per $SBW^{0.75}$, a2 is $0.0007 \times (20 - T_p)$ and BE is 1.12 for dairy breeds. Table 1 contains definitions of abbreviations used in equations.

The 1989 NRC (14) equivalent of a1 is 0.080 for dairy cows based on equations of Moe (11) and 0.086 for dairy heifers based on studies using calorimetry (7, 8) and comparative slaughter (4). In summarizing the USDA calorimetry studies, Moe (11) indicated the equation describing the relationship between metabolizable energy (**ME**) and milk energy was linear; the slope was 0.644, and the intercept was 0.0733 Mcal/kg of $BW^{0.75}$ at 0 ME intake. These results indicate that in lactating dairy cows the efficiency of ME for milk and maintenance (64.4%) was the same. The NRC (14) then added 10% for activity, giving a value of 0.080. This value gives a maintenance requirement that is identical to that of the 1993 Agricultural and Food Research Council (**AFRC**) Energy and Protein Requirements of Ruminants (1) when a 10% activity allowance is added to that fasting metabolism requirement. However, the AFRC recommended allowance for activity is 15.6% for lactating dairy cows and 11.6% for all other classes of cattle. The 1989 Institut National de la Recherche Agronomique (9) system concluded that, for data obtained in respiration chambers and checked in feeding trials, maintenance requirements for dairy cows average 1.17 Mcal of ME or 0.070 Mcal of net energy for maintenance/kg of live $weight^{0.75}$ per d. Institut National de la Recherche Agronomique uses this value with live weight for dairy cattle fed in stalls, which is increased 10% for loose-housed cows and 20% for cows at pasture.

We have modified our original equation to compute a1 to represent the fasting metabolism requirement and then to compute separately the activity requirements for the time spent walking (horizontal or vertical) and standing and to account for the megacalories of ME required to excrete excess N intake (5);

$$NE_m = SBW^{0.75} \times ((a1 \times L \times COMP) + a2) + ACT \times NE_{mcs} \times NE_{mhs}. \quad [2]$$

The cost of excreting excess N (urea) is subtracted from ME intake; urea (megacalories of ME) = (grams of rumen N balance – grams of recycled N) + (grams of excess N from metabolizable protein) × 0.0113 Mcal. The a1 values for the fasting metabolism requirement for use in this revision of the CNCPS, which were developed by removing the effect of activity, are as follows: 0.070 for *Bos taurus* beef cattle, which is the 1996 NRC (15) value of 0.077/1.1; 0.073 for *B. taurus* dairy cows, which is the 1989 NRC (14) value of 0.080/1.1; 0.078 for *B. taurus* dairy heifers and steers, which is the 1989 NRC (14) value of 0.086/1.1; and 0.064 for *Bos indicus*, which is the 1996 NRC (15) value of 0.070/1.1. Values for bulls are computed by increasing steer values 15%, based on the 1996 NRC (15) recommendation. Crossbred combinations can be computed as the proportion of each breed type present. The determination of a2, L, COMP, and ACT are discussed in subsequent sections, as are adjustments for the direct effects of heat stress and cold stress.

The value for shrunken BW we use (96% of full BW) is comparable with BW after 12 to 16 h of feed

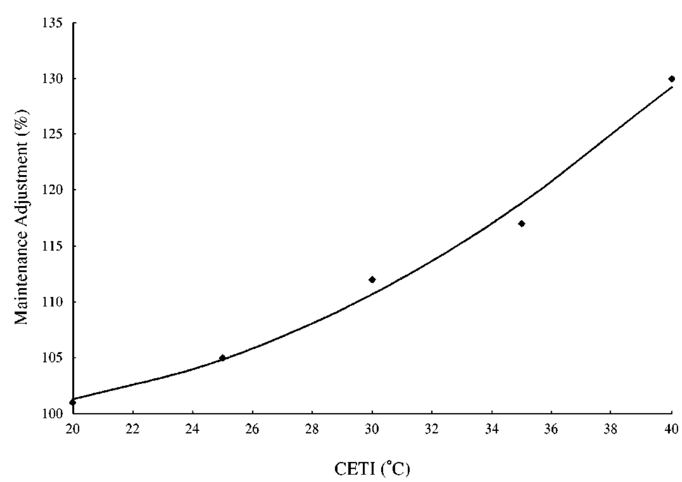


Figure 2. The effect of heat stress on the maintenance requirement. CETI = Current month's effective temperature index.

deprivation or typical sale weight taken after loading, followed by a short haul (<40 km), and unloading. There is much inconsistency and a lack of clarity among energy systems (1, 3, 9, 13, 14, 15) in the description of BW to be used for the calculation of the maintenance requirement. The maintenance requirements of most energy systems are based on calorimetric methods in which fasting heat production plus urinary energy lost during the same period provides an estimate of the fasting metabolism requirement. Because measurements are taken after the animal has been deprived of feed, some systems (1, 3) adjust live fed weight to a fasted live weight, but others (9, 14) use fed live weight directly. We use the approach described in the 1984 NRC [(13) page 4] requirements: "live weight is defined as weight after an overnight feed and water shrink, generally equivalent to about 96% of unshrunk weights taken in the early morning." This fasted weight, which we call shrunken BW, is not as reduced from full weight as used by the AFRC (1) and 1990 Commonwealth Scientific and Industrial Research Organization feeding standards for Australian [**CSIRO** (3)] livestock, which use 92.6% of fed weight to estimate a fasted weight comparable with that used for respiration chamber calorimetry measurements. The 1984 NRC (13) concluded that gut contents have to be carried and maintained at near body temperatures and, therefore, should be accounted for in computing $NE_m$ requirements.

***Adjustment for previous temperature.*** The 1981 NRC (12) concluded that the temperature to which an animal had been previously exposed had an effect on the animals current basal metabolic rate, and the current temperature an animal is exposed to affects the energy required to cope with the current direct effects of cold stress or heat stress. A temperature of 20°C was considered to have no effect on basal metabolic rate and there is no cold or heat stress at that temperature. Thus, a temperature of 20°C was described as being thermoneutral. The NRC (12) used the studies of Young (18, 19) to describe how the $NE_m$ requirement of cattle adapted to the thermal environment is related to the previous ambient air temperature, which was used in the CNCPS (5) and NRC (15) documents; $a2 = 0.0007 \times (20 - T_p)$. For example, this equation results in a base $NE_m$ for cows of 0.087 at 0°C to 0.068 at 27°C. Using only the data from cattle previously housed indoors to avoid other environmental interactions, our analysis of the data of Young (18) (Figure 1) indicates that a2 does not decrease above the thermoneutral temperature:

$$a2 = ((88.426 - (0.785 \times T_p) + (0.0116 \times T_p^2)) - 77)/1000; \quad R^2 = 0.81. \qquad [3]$$

On average, temperatures move slowly from one season to the next but can fluctuate widely from day to day. For these reasons, we recommend using the average mean daily temperature the animals have been exposed to over the previous month for $T_p$, and, for $T_c$, we recommend using the average mean daily temperature the animals are being exposed to for the current week. These temperatures are best obtained from thermometers kept in the animal's environment (e.g., barn and outside lot).

When the environmental temperature is above 20°C, a $T_p$ that is adjusted for the combined effects of

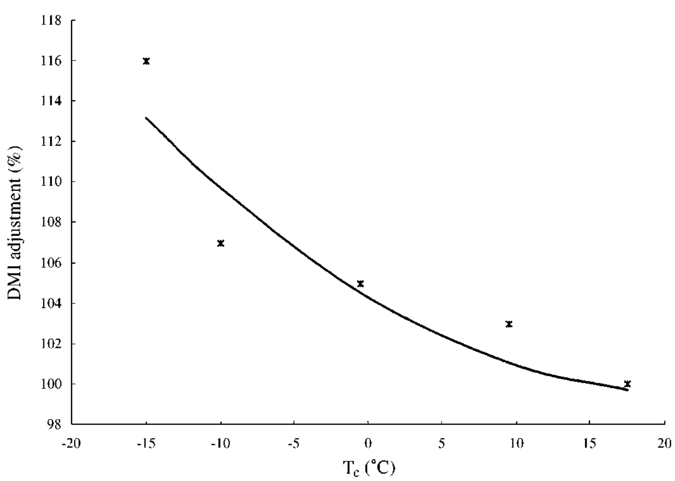


Figure 3. The effect of cold temperatures on DMI. $T_c$ = Current month's average temperature.

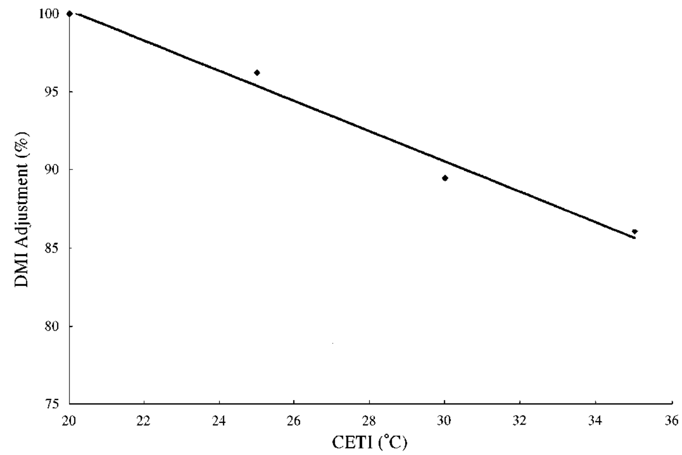


Figure 4. The effect of hot temperatures on DMI. CETI = Current month's effective temperature index.

TABLE 2. Maintenance requirement multipliers for representative conditions.[1,2]

| | −1.1°C | | −12°C | | −23°C | |
|---|---|---|---|---|---|---|
| 1[3] | 1[3] | 3 | 1 | 3 | 1 | 3 |
| Dry cow ration | | | | | | |
| Wind at 1.6 kph | 1.12 | 1.17 | 1.25 | 1.53 | 1.51 | 1.90 |
| Wind at 16 kph | 1.12 | 1.33 | 1.47 | 1.72 | 1.82 | 2.14 |
| Replacement heifer ration | | | | | | |
| Wind at 1.6 kph | 1.12 | 1.29 | 1.26 | 1.78 | 1.66 | 2.29 |
| Wind at 16 kph | 1.21 | 1.57 | 1.67 | 2.13 | 2.11 | 2.72 |

[1]Simulations with the Cornell Net Carbohydrate and Protein System (5) revised to contain the environmental model presented in this paper. Temperature values are current temperature ($T_c$). The dry cow diet contained 1.40 Mcal $NE_L$/kg, and the heifer diet contained 1.55 Mcal $NE_L$/kg of DM.

[2]Values given are net energy maintenance requirement required for these conditions divided by no stress maintenance requirement.

[3]Hair coat code: 1 = dry and clean, 2 = mud on lower body (values not shown), and 3 = wet and matted.

temperature, humidity, and sunlight exposure can be computed as follows, based on data of Baeta et al. (2) and Furukawa et al.(6).

$$\text{Adjusted } T_p = 27.88 - (0.456 \times T_p) + (0.010754 \times T_p^2) - (0.4905 \times RHP) + (0.00088 \times RHP^2) + (1.1507 \times WS) - (0.126447 \times WS^2) + (0.019876 \times T_p \times RHP) - (0.046313 \times T_p \times WS) + (0.4167 \times HRS). \quad [4]$$

***Adjustment for the effect of lactation in beef cows.*** Taken in total, available data indicate that the maintenance requirements of lactating beef cows average 20% higher than those of nonlactating beef cows (15). The explanation is an increase in visceral organ size because of increased nutrient intake (5). No adjustment is made for dairy cows because lactating dairy cows were used to develop their fasting metabolism requirement (10, 11).

***Adjustment for previous plane of nutrition.*** Recent literature reviews (3, 15) describe and quantify the effects of restricted feeding on the fasting metabolic requirement. Studies show that fasting heat production decreases during a period of restricted energy intake. Sheep and cattle kept in drought conditions average 16% lower fasting metabolism (3). The factors responsible include increased amounts of ion pumping and metabolite cycling and altered size and metabolic rate of visceral organs (15). The 1996 NRC (15) concluded that a reduction of 20% in fasting metabolism in compensating animals is representative of the results of published studies. The duration of reduced maintenance is subject to the extent and duration of restricted growth and the plane of nutrition during recovery

TABLE 3. Ration formulas used to evaluate environmental effects.

| | Amount in DM | | | | |
|---|---|---|---|---|---|
| Ingredient[1] | Heifer 1 | Heifer 2 | Heifer 3 | Heifer 4 | Lactating |
| | (%) | | | | |
| Mixed hay, early bloom | 30.0 | 0 | 0 | 0 | 0 |
| Mixed hay, mature | 0 | 0 | 0 | 39.0 | 0 |
| Alfalfa silage | 30.0 | 42.0 | 42.0 | 0 | 19.6 |
| Corn silage | 20.0 | 42.0 | 42.0 | 45.0 | 26.4 |
| High moisture shelled corn | 0 | 0 | 0 | 0 | 20.5 |
| Corn meal | 9.8 | 7.8 | 7.8 | 8.9 | 11.1 |
| Whole cottonseed | 0 | 0 | 0 | 0 | 7.4 |
| Soybean meal, (48% CP) | 10.0 | 8.0 | 8.0 | 7.0 | 13.1 |
| Minerals | 0.2 | 0.2 | 0.2 | 0.1 | 1.8 |

[1]Feed composition values in the Cornell Net Carbohydrate and Protein System (5) feed library and model predicted DMI that were used in the evaluations.

TABLE 4. Effect of four environments on heifer performance and cost.

| | Neutral[1] | Northern[2] | | | | Southwest[3] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| ADG,[4] kg/d | 0.94 | 0.88 | 0.60 | 0.53 | 0.68 | 0.88 | 0.88 | 0.78 | 0.88 |
| Calving age, mo | 20.3 | 21.1 | 28.5 | 28.5 | 25.9 | 20.7 | 20.7 | 22.4 | 20.7 |
| Calving BW, kg | 603 | 588 | 560 | 501 | 574 | 580 | 580 | 561 | 580 |
| Cost, $ per head | 955 | 1002 | 1322 | 1292 | 1214 | 943 | 943 | 994 | 943 |

[1]Same maintenance requirement as in the 1989 NRC (14) requirements.

[2]Mean monthly environmental temperatures similar to the north central and northeastern US. Situation 1 = clean and dry, situation 2 = moderately matted hair coat, 3 = situation 2 plus 10 cm of mud from November through March, and situation 4 = situation 1 plus 16-kph wind velocity.

[3]Mean monthly temperatures similar to the southwestern region of the US.

[4]Average daily gain.

periods; typically 60 to 90 d of compensation is expected. For this revision, we have adopted the approach presented by the 1996 NRC requirements (15). The approach assumes that the body condition score (**BCS**; nine-point scale where 1 = emaciated to 9 = obese) reflects the previous plane of nutrition. A change of 5% in fasting metabolism can be expected for each BCS change from the average of 5 (a reduction below and an increase above):

$$\text{COMP} = 0.8 + ((\text{BCS} - 1) \times 0.05). \quad [5]$$

The five-point scale equivalent for dairy BCS is a 10% adjustment for each BCS above or below the mean score of 3 and is converted as follows for use in the 1996 NRC BCS system:

$$\text{1996 NRC BCS} = ((\text{BCS} - 1) \times 2) + 1. \quad [6]$$

***Adjustment for activity.*** We assume that all NRC recommendations for maintenance requirement (0.080 and 0.077 Mcal per shrunken $BW^{0.75}$, respectively) reflected a 10% addition to the basal maintenance requirement for animals kept in confinement. The 1989 NRC requirements recommended an addition of 10% for good grazing conditions and 20% for poor grazing conditions. The CNCPS used a simple equation to adjust for additional activity on pasture based on the added energy cost of grazing and walking:

$$NE_{mact} = 1.05 + (0.074 \times \text{GU}). \quad [7]$$

The typical dairy herd using pasture in North America uses intensive rotational grazing; paddock sizes are small, and cows are moved to new paddocks daily or after every milking. If the typical dairy herd is assumed to use 0.4 to 0.8 ha daily, equation [7] increases the maintenance requirement 8 to 11%. This range of values agrees with the 1989 NRC (14) adjustment of 10% to the maintenance requirement for grazing dairy cattle with good pasture. A paddock size of 2 ha in the CNCPS equation would give a 20% increase in maintenance requirement in agreement with the 1989 NRC (14) recommendation for poor grazing conditions. The 1996 NRC (15) used a complex equation to account for the additional activity of grazing cattle, based on the CSIRO (3) recommendations:

if grazing,

$$NE_{mact} = (((0.006 \times \text{pI} \times (0.9 - (\text{TDN}/100))) + (0.05 \times \text{TERRAIN}/(+3))) \times \text{SBW})/4.18 \quad [8]$$

TABLE 5. Animal factors inputs for the evaluation of lactating Holstein cows.

| Parameter | Value |
|---|---|
| Age, mo | 42 |
| Shrunk BW, kg | 636 |
| Body condition score[1] | 3.0 |
| Days pregnant | 0 |
| Days in milk | 90 |
| Lactation, no. | 4 |
| Milk production, kg/d | 46 |
| Milk fat, % | 3.5 |
| Milk true protein, % | 2.8 |
| Sunlight exposure, h/d | 0 |
| Time spent standing, h/d | 12 |
| Body position changes, no. | 6 |
| Horizontal distance walked, m/d | 0 |
| Vertical distance walked, m/d | 0 |

[1]Five-point scale (1 = thin to 5 = obese).

TABLE 6. The effects of environment [temperature, relative humidity (RH), and wind] on DMI and milk production.[1]

| | 20°C | | | 30°C | | | |
|---|---|---|---|---|---|---|---|
| | 20% RH | | 80% RH | 20% RH | | 80% RH | |
| | 1 kph | | 8 kph | 1 kph | 8 kph | 1 kph | 8 kph[2] |
| $NE_m$,[3] Mcal/d | 10.5 | 10.5 | 10.5 | 10.9 | 10.8 | 12.8 | 12.6 |
| | (kg/d) | | | | | | |
| DMI, Base | 24.4 | 24.4 | 24.4 | 24.4 | 24.4 | 24.4 | 24.4 |
| Milk, base | 46.0 | 46.0 | 46.0 | 46.0 | 46.0 | 46.0 | 46.0 |
| DMI, Adjusted | | 24.4 | 24.4 | 23.1 | 23.4 | 20.3 | 20.6 |
| Milk, Adjusted | | 46.0 | 46.0 | 42.5 | 43.4 | 33.1 | 34.1 |
| CETI (°C) | 22 | 22 | 20 | 26 | 25 | 38 | 37 |

[1]All temperature and RH conditions are daily averages with no night cooling.

[2]At 30°C and 80% RH with night cooling, DMI increases to 23.6, and milk increases to 41.3 kg/d.

[3]$NE_m$ = Net energy for maintenance adjusted for acclimatization, activity, and excess N; CETI = current month's effective temperature index.

where pI = pasture DMI (kilograms per day), TDN = total digestible nutrient content of the diet (percentage); TERRAIN = terrain factor (1 = level, 1.5 = undulating, and 2 = hilly), and pAVAIL = pasture mass available for grazing (kilograms per hectare). With a forage TDN of 75% and availability of 1500 kg/ha, Equation [8] gives an 18 and 46% increase in net energy for maintenance requirement for level and hilly terrain, respectively, for a 600-kg cow consuming 10 kg of pasture DM/d.

Using data from the AFRC (1) and CSIRO (3), we revised our system to adjust maintenance requirements for more diverse conditions. Cattle are kept in widely different confinement (ranging from tie stall barns to open lots) and pasture situations (ranging from level ground with high forage availability close to water and milking parlor to hilly ground with low forage availability and long distances to water). For confinement dairy operations, maintenance requirements can be influenced by time spent standing and walking and by surface conditions. We adopted the following equation to compute the activity requirement (megacalories per day), which is based on calorimetric studies (1):

$$\text{ACT} = (\text{standing} + \text{position changes} + \text{distance flat} + \text{distance sloped})/1000 \quad [9]$$

where standing (kilocalories per day) = (hours standing × 0.1) × FBW, position changes (kilocalories per day) = (number of standing and lying changes × 0.062) × FBW, distance flat (kilocalories per day) = (kilometers traveled daily × 0.621) × FBW, and distance sloped (kilocalories per day) = (kilometers traveled daily × 6.69) × FBW. Distance sloped is defined as any vertical movement (1).

***Adjustment for the direct effect of cold stress.*** The following series of equations are used to compute heat production and heat loss. These equations were developed from information presented in the CNCPS (5) and NRC (12, 15) requirements:

$$SA = 0.09 \times SBW^{0.67}. \quad [10]$$

$$HE = (MEI - (RE + YE + LE))/SA. \quad [11]$$

$$EI = (7.36 - (0.296 \times WIND) + (2.55 \times HAIR)) \times MUD2 \times HIDE. \quad [12]$$

MUD2 is a choice of four codes (1 = clean and dry, 2 = some mud on lower body, 3 = wet and matted, and 4 = covered with wet snow or mud). Factors used in Equation [12] for these codes are 1, 0.8, 0.5, and 0.2, respectively. HIDE is a choice of three codes (1 = thin, 2 = average, and 3 = thick). The factors used in Equation [12] for these codes are 0.8, 1, and 1.2, respectively.

$$TI = 2.5 \text{ for newborn calf,}$$
$$TI = 6.5 \text{ for 1-mo old calf,}$$
$$TI = 5.1875 + (0.3125 \times BCS) \text{ for yearlings, and}$$
$$TI = 5.25 + (0.75 \times BCS) \text{ for adult cattle.} \quad [13]$$

$$I = TI + EI. \quad [14]$$

$$LCT = 39 - (I \times (HE \times 0.85)). \quad [15]$$

$$ME_{cs} = SA \times (LCT - T_c)/I. \quad [16]$$

$$NE_{mcs} = k_m \times ME_{cs}. \quad [17]$$

$$\text{DMI for maintenance} = NE_m/NE_{ma}. \quad [18\}$$

***Adjustment for the direct effect of heat stress.*** The 1981 NRC indicated that $NE_m$ for lactating dairy cows increased above thermoneutral conditions because of the energy cost of getting rid of excess heat. Because of the difficulty in accounting for the complex interactions involved in predicting the upper critical temperature, a panting index ($NE_m$ multiplier of 1.07 if rapid shallow or 1.18 if open mouth panting) is used by CSIRO (3), CNCPS (5), and 1996 NRC (15) to adjust for the energy cost to dissipate excess heat. In this revision, we use this panting index for *B. indicus* breeds. To quantify the direct effects of heat stress on B. taurus breeds, the data presented in the dairy cattle chapter of the 1981 NRC (12) were used to develop the following equation to compute an adjustment factor for the $NE_m$ requirement for this effect (Figure 2).

a)

| Temperature (°C) | Relative Humidity (%) 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|
| 18 | 19 | 19 | 18 | 18 | 18 | 18 |
| 20 | 21 | 21 | 21 | 21 | 21 | 22 |
| 22 | 22 | 23 | 23 | 24 | 24 | 25 |
| 24 | 24 | 25 | 25 | 26 | 28 | 29 |
| 26 | 26 | 27 | 28 | 29 | 31 | 33 |
| 28 | 27 | 29 | 31 | 32 | 34 | 37 |
| 30 | 29 | 31 | 33 | 35 | 38 | 40 |
| 32 | 31 | 34 | 36 | 39 | 41 | 44 |
| 34 | 33 | 36 | 39 | 42 | 45 | 48 |
| 36 | 36 | 39 | 42 | 45 | 49 | 52 |
| 38 | 38 | 41 | 45 | 49 | 53 | 57 |
| 40 | 40 | 44 | 48 | 52 | 56 | 61 |

b)

| Temperature (°C) | Relative Humidity (%) 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|
| 18 | 19 | 18 | 18 | 17 | 17 | 18 |
| 20 | 20 | 19 | 20 | 20 | 20 | 21 |
| 22 | 21 | 21 | 22 | 22 | 23 | 24 |
| 24 | 22 | 23 | 24 | 25 | 26 | 27 |
| 26 | 24 | 25 | 26 | 27 | 29 | 31 |
| 28 | 25 | 26 | 28 | 30 | 32 | 34 |
| 30 | 27 | 28 | 30 | 33 | 35 | 38 |
| 32 | 28 | 30 | 33 | 35 | 38 | 41 |
| 34 | 30 | 33 | 35 | 38 | 42 | 45 |
| 36 | 32 | 35 | 38 | 41 | 45 | 49 |
| 38 | 34 | 37 | 41 | 44 | 48 | 53 |
| 40 | 36 | 39 | 43 | 48 | 52 | 57 |

Figure 5. Effective temperature index at different temperatures and relative humidity at wind speeds of a) 0.5 m/s (1.8 kph), and b) 4.0 m/s (14.4 kph). Values in the tables are 16 to 26 = safe range, 27 to 31 = caution range, 32 to 37 = extreme caution range, 38 to 43 = danger range, and >43 = extreme danger range.

TABLE 7. Inputs for evaluating activity.

| Parameter | Value |
|---|---|
| Time standing,[1] h/d | |
| Tie-stall barns | 12 |
| Small free stalls (<200 cows) | 12 |
| Large free stalls, close parlor | 15 |
| Large free stalls, far parlor | 15 |
| Drylots | 18 |
| Intensive grazing | 16 |
| Continuous grazing | 18 |
| Position changes, /d | |
| Tie-stall barns | 6 |
| Small free stalls (<200 cows) | 9 |
| Large free stalls, close parlor | 9 |
| Large free stalls, far parlor | 9 |
| Drylots | 6 |
| Intensive grazing | 6 |
| Continuous grazing | 6 |
| Walking, flat,[2] m/d | |
| Tie-stall barns | 0 |
| Small free stalls (<200 cows) | 500 |
| Large free stalls, close parlor | 1000 |
| Large free stalls, far parlor | 1500 |
| Drylots | 1500 |
| Intensive grazing | 500–1000 |
| Continuous grazing | 1000–2000 |
| Walking, sloped,[3] m/d | |
| Intensive grazing[4] | 0–500 |
| Continuous grazing[4] | 0–500 |

[1]Values vary by cow comfort, overcrowding, number of times milked per day, average time spent in holding area, and others. Values given are minimum estimates.

[2]Values vary dependent upon distance from milking center, number of times milked per day, and size of facility. Values given are minimum estimates.

[3]Defined as any vertical movement (1).

[4]Ranges are those used in this evaluation and are dependent upon the pastures.

$$NE_{mhs} = 1.09857 - (0.01343 \times CETI) + (0.000457 \times CETI^2); \quad R^2 = 0.99. \quad [21]$$

$$CETI = 27.88 - (0.456 \times T_c) + (0.010754 \times T_c^2) - (0.4905 \times RHC) + (0.00088 \times RHC^2) + (1.1507 \times WS) - (0.126447 \times WS^2) + (0.019876 \times T_c \times RHC) - (0.046313 \times T_c \times WS) + (0.4167 \times HRS). \quad [22]$$

## Computing the ME Requirement

The CNCPS computes a site- and group-specific ME value for feeds; the efficiency of use varies with physiological function, and ME must be computed in order to compute heat increment (5,16,17). The ME requirement is computed for each physiological function by dividing conceptus net energy requirements by 0.13, and $NE_m$ and $NE_L$ required by 0.644. The sum of the ME requirements then gives a single number to compare with ME intake for evaluating diets. For growing cattle, ME allowable daily gain is computed using the 1996 NRC equations to compute ingredient $NE_m$ and net energy for gain from ME to account for the effect of ME concentration in the diet on efficiency of use of ME for net energy for maintenance and gain.

## Adjustments of DMI for Temperature and Mud

The following equations were developed from Table 10-4 of the 1996 NRC (15) requirements, which are multiplied times the CNCPS predicted DMI (5).

For temperature <20°C (Figure 3),

$$\text{DMIAF} = 1.0433 - (0.0044 \times T_c) + (0.0001 \times T_c^2); \quad R^2 = 0.88. \qquad [23]$$

For temperature >20°C and no night cooling (Figure 4),

$$\text{DMIAFN} = (119.62 \times (-0.9708 \times \text{CETI}))/100; \quad R^2 = 0.98. \qquad [24]$$

For temperature >20°C with night cooling,

$$\text{DMIAFC} = ((1 - \text{DMIAFN}) \times 0.75) + \text{DMIAFN}. \qquad [25]$$

$$\text{DMIAFMUD} = 1 - (0.01 \times \text{mud depth (cm)}). \qquad [26]$$

## Model Evaluation

To predict the effects of environment on specific farms, DMI and available diet ME need to be determined accurately so that heat production can be estimated accurately. The CNCPS uses actual feed analysis to predict the fiber and nonfiber carbohydrates that are available for fermentation and their digestion and passage rates to predict feed ME values, which is used with retained and milk energy to compute heat increment. We did not have data to validate this environmental submodel; the submodel will be difficult to validate because of a lack of adequate input parameters for the CNCPS in published data and the large number of interacting variables. We evaluated this new maintenance model by predicting the growth rate or milk production of dairy cows under selected environmental conditions after the variables described were incorporated into the CNCPS.

## RESULTS AND DISCUSSION

Table 2 shows the response of the maintenance submodel (multiples of basal maintenance required under various environmental conditions) to the interaction of temperature and relative humidity, wind, and hair coat condition of dry dairy cows and replacement dairy heifers. The effects of acclimatization are accounted for by using the average temperature for the previous month. Current environmental effects are accounted for by computing heat loss relative to heat production, based on current temperature, internal and external insulation, wind, and hair coat depth and condition. This computation becomes important when the animal is below the computed lower critical temperature, and effects can range from no effect at 20°C to twice as high as basal (dirty hide at –12°C and 16 kph wind). The maintenance requirement multiplier of 1.12 at –1.1°C with clean and dry hair

TABLE 8. Effect of activity on milk production.

| Item | Tie-stall barn | Size of free-stall dairy: Small (<200 cows) | Large (close parlor) | Large (far parlor) | Grazing, intensive: Flat | Sloped | Grazing, continuous: Flat | Sloped |
|---|---|---|---|---|---|---|---|---|
| Standing, h/d | 12 | 12 | 15 | 15 | 16 | 16 | 18 | 18 |
| Changing body positions, times/d | 6 | 9 | 9 | 9 | 6 | 6 | 6 | 6 |
| Walking, flat, m/d | 0 | 500 | 1000 | 1500 | 1000 | 500 | 2000 | 1000 |
| Walking, sloped, m/d | 0 | 0 | 0 | 0 | 0 | 500 | 0 | 1000 |
| $NE_m$ Mcal/d | 10.5 | 10.9 | 11.4 | 11.7 | 11.3 | 13.4 | 11.9 | 15.9 |
| Change, % | | 4.8 | 8.6 | 11.4 | 7.6 | 27.6 | 13.3 | 51.4 |
| Milk cost, kg/d | | 0.4 | 1.0 | 1.3 | 0.9 | 3.9 | 1.7 | 7.5 |

coat for all classes and hide thickness indicates the adjustment for acclimatization, because all of these groups are above their lower critical temperature. Table 2 demonstrates how this model provides a way to quantify the general knowledge that, to minimize cold stress, cattle should be kept clean, dry, and protected from wind. Metabolizable energy intake is also important because increased ME intake provides more heat increment to combat cold stress.

Diets were formulated to evaluate the effects of environment on predicted performance of dairy heifers and lactating cows (Table 3). Table 4 shows the results of simulations for heifers from 8 wk to calving. A neutral environment (20°C) gives the same maintenance requirement as assumed by the 1989 NRC (14), Northern assumes mean monthly temperatures similar to the north central and northeastern US, and Southwest assumes mean monthly temperatures similar to the southwestern region of the US. Specific effects of temperature and hair coat during this period are demonstrated in Table 2. The energy that was available for growth depended on the interaction of environmental temperature and wind with animal heat production and loss, depending on DMI, heat increment, and animal insulation. Calving age was increased when environmental stress extended the age at which puberty weight was reached. Calving weight was decreased when environmental stress occurred after conception.

Table 5 shows the animal descriptions used in the lactating dairy cow simulations. Table 6 shows the predicted response of lactating dairy cows to environmental effects, based on the inputs shown in Tables 3 and 5. Lactating cows were not as likely to experience cold stress but were more sensitive to high (30°C) temperature and humidity because of their higher heat increment. The most sensitive environmental effect is on DMI, which can have dramatic impacts on nutrient intake above maintenance. Milk production was depressed the most (12.9 kg) by high temperature (30°C) and humidity (80%) with no night cooling or evaporative cooling (1 kph wind). Cattle performance was affected at temperature and humidity values at or above a current monthly effective temperature index (**CETI**) of 25°C.

Figure 5, developed from the equations of Baeta et al.(2), can be used to estimate when the current temperature and humidity are likely to influence animal performance. The CETI ranges in the table are 16 to 27, safe; 28 to 32, caution; 33 to 38, extreme caution; 39 to 44, danger; and > 44, extreme danger (2). For example, Table 6 shows no effect of temperature on $NE_m$ requirement with an CETI <27, but increases at CETI of 37.

Table 7 was constructed for use in evaluating the influence of activity on milk production. These estimates are based on AFRC (1). Table 8 shows the results of simulations with eight situations, using the animal factors in Tables 3 and 5 and model predicted DMI; tie stall barn, small free stall, large free stall with milking parlor close or distant, and intensive rotational or continuous grazing with level or hilly conditions. All variables except the activity requirement were held constant. Compared with the tie stall barn, milk production was reduced 0.4, 1.0, 1.3, 0.9, 1.7, 3.9, and 7.5 kg, respectively, for the seven other scenarios. Dry matter intake can also vary considerably in each of these situations because of CETI and mud, which, along with the activity requirement, may account for much of the cow comfort effects observed on farms.

## CONCLUSIONS

The goal of the CNCPS is to predict nutrient requirements, the supply of nutrients to meet requirements, and animal performance in various production situations using information that can be measured or observed on individual farms. The refinements described have the potential to improve the ability of the CNCPS to meet this objective by accounting for important effects generally described as cow comfort. Inputs are adjusted appropriately until the current observed performance is predicted; then, improvements expected from changes in environment can be evaluated. Validation studies are needed to evaluate the accuracy of these adjustments for environmental conditions and refinements to this model needed.

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