Tissue and External Insulation Estimates and Their Effects on Prediction of Energy Requirements and of Heat Stress

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ABSTRACT

Published data were used to develop improved equations to predict tissue insulation (TI) and external insulation (EI) and their effects on maintenance requirements of Holstein cattle. These are used to calculate lower critical temperature (LCT), energy cost of exposure to temperatures below LCT, and excess heat accumulating in the body at temperatures above LCT. The National Research Council classifies TI by age groups and body condition score; and in the EI equation air velocity effects are linear and coat insulation values are derived from beef animals in cold climates. These lead to low LCT values, which are not compatible with known effects of environment on the performance of Holsteins in warm climates. Equations were developed to present TI as a function of body weight, improving prediction of TI for animals of similar age but differing in body weight. An equation was developed to predict rate of decrease of TI at ambient temperatures above LCT. Nonlinear equations were developed that account for wind effects as boundary layer insulation effects dependent on body weight and air velocity. Published data were used to develop adjustments for hair coat effects on EI in Holstein cows. While by NRC equations, wind has negligible effects on heat loss, the recalculated effects of air velocity on heat loss were consistent with published effects of forced ventilation on the responses of the Holstein cow. The derived LCT was higher by 10 to 20°C than that calculated by NRC (2001) and accounted for known Holstein performance in temperate and warm climates. These equations pointed to tentative significant effects of cold (–10°C) on energy requirements (7 Mcal/d) further increased by 1 m/s wind (15 Mcal/d), even in high-producing cows. Needs for increased heat dissipation and estimating heat stress development at ambient temperatures above the LCT are predicted. These equations can be used to revise NRC equations for heat exchange.

(**Key words:** Holstein cow, thermal insulation, energy requirement, heat stress)

Abbreviation key: BI = boundary layer insulation, CI = hair coat insulation, CNCPS = Cornell Net Carbohydrate and Protein System, EI = external insulation, Hex = excess heat, HP = metabolic heat production, INS = body insulation, LCT = lower critical temperature, SA = surface area, Ta = ambient temperature, TI = maximal tissue insulation, TIs = submaximal tissue insulation.

INTRODUCTION

The exchange of heat between the body and its environment is determined by thermal insulation and water evaporation. Thermal insulation is composed of tissue insulation (TI) and external insulation (EI). The rate of increase of metabolic heat production below the lower critical temperature (LCT) is affected by EI and the maximal value of TI. The TI represents the resistance to heat flow from body core to skin, and would therefore be expected to be proportional to body diameter. The latter is relative to body mass and may be estimated by $a \cdot BW^{0.33}$, an equation true for bodies of similar proportions and of different mass (Bruce and Clark, 1979).

An interspecies equation for maximal TI [$0.619 \cdot BW^{0.33} \text{ } ^\circ\text{C}/\text{m}^2 \text{ d Mcal}$ (where BW is in kg)] has been suggested because closely similar values were obtained for baby pigs weighing 1.5 kg, sows weighing 168 kg, and cattle weighing about 450 kg (Bruce and Clark, 1979). This equation for maximal TI has been adopted in thermal exchange models for cattle, sheep, and pigs (McGovern and Bruce, 2000; Turnpenny et al., 2000). In contrast, in the NRC (2001) maximal TI is a function of chronological age and of BCS. The latter values for maximal tissue insulation are considerably higher than those suggested by the interspecies equation.

The EI is the resistance to heat flow from the skin to the air. The EI values used in the NRC (2001) as well as in the Cornell Net Carbohydrate and Protein System (CNCPS; Fox et al., 2000) originate from 2 studies (Blaxter and Wainman, 1961; Webster et al.,

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Table 1. Maximal tissue insulation (TI) in the studies on which the NRC (2001) equation is based (no. 1 to 4) and in two additional studies (no. 5 to 6), the animals examined, the mean BW, and TI values in these studies and the respective TI values calculated by the NRC (2001) equation.

No.	Source	Animals	Mean BW	TI	NRC
1	Blaxter and Wainman (1961)	Mature steers	515	8.1	9.7
2	Blaxter and Wainman (1964)	Mature steers	343	7.8	7.0
3	Webster (1970)	Beef calves	240	7.4	7.0
4	Webster et al., (1970)	Beef calves	228	7.7	7.0
5	Young (1975)	Beef cows	529	11.9	9.7
6	McLean et al., (1984)	Beef cows	522	4.8	9.7

1970). These studies were carried out on animals of beef breeds in Canada and Scotland, in which rather harsh winter climates prevail. The EI is determined by coat depth, hair weight per unit area, hair diameter, and air velocity (Bennett, 1964). The diameter of hair fibers, hair weight per unit surface, and coat depth are affected by the breed of cattle (Turner and Schleger, 1960), by seasonal changes in photoperiod, as well as by regional differences in climate (Berman and Volcani, 1961). It is therefore not obvious that the EI values used in the NRC (2001) and CNCPS (Fox et al., 2000) also are typical for Holstein cattle in climates that are milder than winters in Scotland and Canada.

Metabolic heat production (**HP**) is well known to increase when ambient temperatures decrease. The rate at which HP increases at decreasing ambient temperatures is determined by body insulation (**INS**), the sum TI, and EI. The ambient temperature at which HP stabilizes is the LCT, at which the combined convective and radiant heat loss equals the metabolic HP. The latter is determined by the maintenance HP, the heat increment of lactation, and/or the HP associated with gestation. The ambient temperature representing the LCT of a dairy cow is thus determined by the HP and by the INS.

At ambient temperatures above the LCT, the metabolic HP is larger than the amount of heat required for body temperature maintenance. The difference between the metabolic HP and the combined convective and radiant heat loss is an excess heat (**Hex**) that has to be dissipated to avoid positive heat balance. Thermal insulation determines the rate at which Hex develops at ambient temperatures above the LCT. The ambient temperature beyond which body temperature starts increasing is thus determined by the maximal evaporative capacity of the animal and its INS. Thermal insulation, therefore, is an important determinant of energy requirements in the cold, of the LCT and of the thermal comfort ambient temperature range.

This paper examines published maximal TI and EI values, the experimental evidence supporting their use for Holstein cows, their effects on the estimation of LCT, on the prediction of energy requirements at ambient

temperatures below the LCT and on the development of Hex at ambient temperatures above the LCT.

MATERIALS AND METHODS

Published values TI and EI were examined for their sources, the extent to which they deviate from each other, the animals on which they were determined, and the ambient conditions to which the animals were exposed. Elements that determine insulation values were examined. Equations were developed for the prediction of insulation values most appropriate for the Holstein dairy cow, the most important producer of milk. Sub-maximal TI values, and their relationship to ambient temperature, were calculated from published data on heat exchange at ambient temperatures above the LCT.

The surface area (**SA**) was calculated according to 2 equations: one, namely $0.09 \cdot \text{BW}^{0.67}$, suggested by Mitchell (1928) and presently used in NRC (2001) equations; the other equation, $0.14 \cdot \text{BW}^{0.57}$ (Brody, 1945) was suggested as preferable for estimating SA in Holstein cattle (Berman, 2003). In both formulas, BW is in kilograms.

Maximal TI estimates. In the NRC (2001) nutritional model, maximal TI values are specified by age classes until 1 yr of age, and at later ages TI is affected by BCS. An interspecies equation for prediction of maximal TI according to BW of animal, based on data from pigs and cattle, has been suggested, in which $\text{TI} = 0.434 \cdot \text{BW}^{0.33}$ (Bruce and Clark, 1979). Another equation, based on dairy and beef cattle data, in which $\text{TI} = 0.351 \cdot \text{BW}^{0.41}$ has also been suggested (Ehrlemark and Sallvik, 1996). The values produced by the 2 equations are closely similar; those of the first equation are about 0.5 TI units higher over the 100- to 650-kg BW range. In both equations, changes in TI with BW are practically linear within the 100- to 700-kg BW range. This BW range excludes young, preruminant calves from the prediction equation.

The values of maximal TI in NRC (1981, 2001) represent composite data from Webster (1974) and Blaxter (1977). The data cited by Webster (1974) are a composite of 2 studies also made in Canada on animals of beef

Table 2. Published equations for prediction of maximal tissue insulation (TI) according to BW (W), the animals on which they are based, their mean BW, and the predicted TI for a 500 kg BW animal (TI₅₀₀).

Source	Animal	BW	Regression eq.	TI ₅₀₀
Webster (1970)	Beef calves	240	TI = 5.5 + 0.018*W	14.5
Webster et al. (1970)	Beef calves	228	TI = 2.2 + 0.029*W	16.7
Webster (1974)	Beef calves	235	TI = 2.3 + 0.008*W	6.3
Ehrlemark and Sallvik (1996)	Cattle	350	TI = 0.351*W ^{0.41}	4.5
Bruce and Clark (1979)	Pigs, cattle		TI = 0.619*W ^{0.33}	4.7

breeds (Webster, 1970; Webster et al., 1970). The data from Blaxter (1977) on adult animals comprise 2 studies carried out in Scotland on mature steers of beef breeds (Blaxter and Wainman, 1961; 1964). The mean TI of measurements carried out below 0°C in those studies, as well as in 2 later studies (Young, 1975; McLean et al., 1984) were calculated (Table 1) and compared to the TI estimated according to NRC (2001) for animals with BCS 6 on a 1 to 9 score scale.

The means of maximal TI on which the NRC (2001) is based are quite close to each other (studies 1 to 4, Table 1). The maximal TI means of beef cows (Young, 1975; McLean et al., 1984), not included in the formation of the NRC (2001) estimate (studies 5 and 6, Table 1), differ distinctly from each other, and from the NRC, although the animals experienced similar cold exposures. One mean is distinctly higher (11.9) and the other distinctly lower (4.8) than the NRC (2001) maximal TI estimate.

Empirical equations for the prediction of maximal TI according to BW are compared (Table 2) at a 500-kg BW. The first 2 equations, upon which the NRC (2001) estimate is partly based, produced the higher estimates for TI, two- to threefold higher than the other estimates. The high intercept in the first equation might be due to the small range of BW in this study. The third equation (Webster, 1974) is based on the pooled data of the 2 earlier studies with beef calves (Webster, 1970; Webster et al., 1970). The TI estimates produced by it are similar to those of the last 2 equations. The fourth equation is based on pooled data of beef animals (Blaxter and Wainman, 1961; Webster et al., 1970; Webster, 1974) and of Jersey, Holstein, and Brown Swiss dairy cows (Thompson et al., 1952). The fifth equation is based on data of baby pigs (Mount, 1968) and sows (Hovell et al., 1977) and on the pooled data of beef calves (Webster, 1974).

The last 3 equations produce similar estimates of TI, although they are based on different experimental data, including pigs, beef cattle, and dairy cattle. It seems therefore justified to estimate maximal TI on the basis of all available information on cattle, by an equation based on the mean of the outputs of the equations of Webster (1974), Ehrlemark and Sallvik (1996), and

Bruce and Clark (1979). On this basis, maximal TI, with SA by the equation of Mitchell (1928), may be estimated with high accuracy over the range of BW relevant to dairy cattle (100 to 750 kg) by a linear equation relating it to BW (kg):

$$TI = 2.4 + 0.0054 * BW \quad (R^2 = 0.99) \quad [1]$$

For animals weighing 200, 300, 400, 500, and 600 kg, maximal TI values would be 3.5, 4.1, 4.7, 5.2, and 5.7, respectively. These estimates are body mass dependent only and are not supposed to be modified by the BCS of the animal.

Submaximal TI estimates. Maximal TI represents heat transfer to body surface in the absence of vasodilatory episodes. At ambient temperatures above the LCT, the frequency of such episodes increases to finally stabilize in a state of continuous vasodilation (Berman et al., 1984). These are generally accepted views, but apparently there has been no attempt to quantify these changes in TI in relation to ambient temperature. Published data on responses of cattle, weighing 500 kg and more, were further analyzed for this purpose (Table 3), to equate TI at ambient temperatures above the LCT (TIs).

The change in TIs per °C change in ambient temperature (Ta) was also estimated from 2 additional studies in lactating Holstein cows. In one study, an incremental change in Ta from 18 to 28°C was associated with a reduction in TIs of 0.14°C m² d/Mcal per °C increment in Ta (Kibler et al., 1965). In another study, a seasonal change in mean daily temperature from 17 to 32°C was associated with a reduction in TIs of 0.1°C m² d/Mcal per °C increase in temperature (Berman, 1971). These, taken as a whole, suggest that ambient temperatures rise above the LCT are associated with declines in TI of the order of 0.12°C m² d/Mcal per °C increment in Ta.

EI estimates. According to NRC (1996, 2001) and the CNCPS (Fox et al., 2000), the equation for estimation of EI, is:

$$EI = ((7.36 - (0.296 * \text{WindSpeed}) + (2.55 * \text{HairDepth})) * \text{Coat}) * 0.8,$$

Table 3. Regression equations of changes in tissue insulation (TIs, °C m² d/Mcal) at ambient temperatures (Ta) increasing above the lower critical temperatures. Analysis of data presented in studies on responses of cattle weighing 500 to 650 kg.

Source	Animals	Regression eq.	R ²
Blaxter and Wainman (1961)	Mature beef steers	TIs = 8.0 – 0.22*Ta	0.99
Blaxter and Wainman (1964)	Mature beef steers	TIs = 8.2 – 0.19*Ta	0.84
McLean et al. (1984)	Beef cows	TIs = 3.4 – 0.12*Ta	0.99
Kibler et al. (1970)	Lactating Holstein	TIs = 4.3 – 0.10*Ta	0.97

where

$EI = ^\circ C/m^2 \text{ d Mcal}$; WindSpeed = kph; HairDepth = 0.63 cm in summer, 1.27 cm in winter; and Coat = coat condition, 1.0 to 0.2, mostly dependent on presence of mud or snow in it.

By this approach, EI is estimated by an equation in which the effects of air velocity, coat depth, and hide condition are multiplied by a coefficient and deducted from a fixed value, equivalent to an intercept. The grounds for including the 0.8 coefficient is not detailed in the NRC (2001) documentation. The 0.8 coefficient presumably corrects for the proportion of HP dissipated via the respiratory tract, hence not passing from skin to air, i.e., about 15% of total heat production (Blaxter and Wainman, 1961). The EI data upon which the equation is based (Blaxter and Wainman, 1964; Webster et al., 1970, Webster, 1970) represent heat loss from skin. Hence, in the calculations presented here the 0.8 coefficient was discarded wherever EI was calculated according to the NRC (2001).

The intercept present in this equation, namely 7.36°C m² d/Mcal, equals the EI produced by a 10-mm deep coat at a wind speed of 0.44 m/s, where body surface area is estimated by $SA = 0.09 \cdot W^{0.67}$ (NRC, 1981). Therefore, this intercept does not estimate the EI when coat and wind effects are nil. Also, air velocity effects are presented as linear effects. The high intercept value may be a by-product of the nature of the data, e.g., data in which coat is thick, and with little variation in its thickness may produce regressions with a large intercept. The value of EI in NRC (1996, 2001) and CNCPS (Fox et al., 2000) is derived from NRC (1981), and the latter is based on 3 studies (Blaxter and Wainman, 1964; Webster et al., 1970, Webster, 1970). In one of these, a study conducted on mature steers (Blaxter and Wainman, 1964) coat depth varied between 4 and 31 mm. In another study, using growing beef calves in winter (Webster, 1970), coat depth varied between 19 and 25 mm. In the third study (Webster et al., 1970), also conducted using growing beef calves during an exceptionally cold winter, coat depth was between 10 and 20 mm, and the coat depth term effect on EI was small and statistically insignificant. The 3 studies may

thus represent a particular case of high EI values of beef cattle acclimatized to the rather harsh winter conditions in Scotland (Blaxter and Wainman, 1964) and Canada (Webster, 1970; Webster et al., 1970). The equations that estimate EI in the aforementioned studies, as well as the EI estimated for wind speed of 0.5 m/s and coat depth of 5 mm are presented (Table 4). The mature steer data (Blaxter and Wainman, 1964) were analyzed by multiple regression, with coat depth, wind, animal, and interactions as variance factors ($R^2 = 0.88$; $P < 0.01$). The equation for EI is presented in Table 4 for the respective study.

These equations might be seen with some reservations concerning the nature of the equations describing the effects of wind and coat on EI, the type of animals on which they were examined, and the climate to which these animals were exposed. In one study (Blaxter and Wainman, 1964), the animals were exposed to air velocities of 0.18 and 0.71 m/s. In the other 2 studies (Webster, 1970; Webster et al., 1970), apparently based on very similar data, the animals were exposed to air velocities of 0.17, 3.6, and 5.3 m/s. The lower air velocities (0.17 to 0.71 m/s) are between those of free convection and those of the lower range of forced convection. The higher air velocities range might be in the range that disturbs the insulation of the coat. This distribution of air velocities makes it difficult to estimate whether the relationship between air velocity and EI is linear or non-linear.

This difficulty may be solved by following a different approach, considering that EI has 2 components: the insulation of the coat (**CI**) and the boundary layer insulation (**BI**) of air surrounding the animal. Each of these is independent of the other, and they are best examined separately. The first 2 terms in the NRC (2001) equation for EI represent in fact the BI. As long as the coat is not disturbed, air velocity affects only the insulation of the boundary layer. Within the air velocities range (0.5 to 3 m/s), that comprises situations most commonly experienced by dairy cattle in modern dairy farm systems, air velocity effects on insulation are related to the square root of air velocity (Monteith, 1973). It is mostly at air velocities above 3 to 4 m/s, that flowing air penetrates into the coat and reduces its insulation

Table 4. The studies of external insulation (EI, °C m² d/Mcal), the predicting equations for EI, and the EI predicted for wind speed of 0.5 m/s (1.8 kph) and coat depth of 5 mm. (V = air velocity, m/s; D = hair coat thickness, mm).

Source	Equation	Predicted ¹
NRC (2001)	$(7.36 - 1.07*V + 0.26*D)*0.8$	8.3
Blaxter and Wainman (1964) ²	$7.3 - 4.50*V^{0.5} + 0.33*D$	5.8
Webster (1970)	$11.8 - 3.80*V^{0.5} + 0.24*D$	9.1
Webster et al. (1970)	$11.1 - 3.44*V^{0.5} + 0.22*D$	9.8
Webster (1971) cow model (no coat)	$10.4 - 3.80*V^{0.5}$	7.8

¹The 0.8 coefficient was excluded in the calculation. The basis for this is given in the text.

²The mature steers data analyzed by multiple regression, with coat depth, wind, animal, and interactions as variance terms ($R^2 = 0.88$; $P < 0.01$).

properties (Ames, 1974; Gebremehdin et al., 1983; Arkin et al., 1991), so that the relationship between air velocity (range 0.1 to 4 m/s) and EI may become linear. The effects of air velocity on EI therefore include nonlinear BI effects (at air velocities less than 3.5 m/s) as well as linear effects on coat insulation (at air velocities larger than 4 m/s), whereas in the NRC (2001) equation for EI, the relationship is presented as linear. Also, after adjusting the EI for the effects of air velocity and coat depth, it may be expected that the value of the intercept would be close to the insulation of still air, but it is 7.4 instead of 19.4°C m² d/Mcal (Monteith, 1973). As on the body surface of dairy cattle air velocities generally are less than 4 m/s, a more detailed examination of nonlinear air velocity effects on BI seems indicated.

BI estimates. The effect of air velocity on the BI is affected by the curvature of the surface, i.e., the diameter of the body. The EI of the bovine body has been examined on cow models made of cylinders representing the trunk and extremities. In one study the orientation of wind relative to model was not specified, and the model was left uncovered by a hide (Webster, 1971) so that EI represents BI. Dimensions of model components were not specified, except that the model had the shape and size of a 250-kg calf. Dimensions might thus be inferred, but not conclusively assessed. The equation relating air velocity and insulation reflects some experimental and/or analytical difficulties, as insulation values do not approach the insulation of still air at air velocities below 0.1 m/s. The other study was carried out on a hide-covered cow model, and full details were given on its dimensions (Wiersma and Nelson, 1967). The data on the relationship between air movement (V, m/s) and BI determined on parts of the model in the latter study had been further parameterized to include dimension effects (McArthur, 1987), related to body diameter (D, m) and expressed as:

$$BI = 3.46*D^{0.47}*V^{-0.53} \quad [2]$$

For this equation to be used in cattle varying in size, their mean body diameter needs to be estimated. It was presumed that the mean diameter of the trunk estimates the mean of minimal and maximal diameters of the trunk, and that these are best estimated at the level of the heart and last costal rib, i.e., using heart girth and paunch girth data. In 2 models of thermal balance of cattle (Ehrlemark, 1988; McGovern and Bruce, 2000), the diameter of dairy cattle was estimated by $D = 0.06*BW^{0.39}$. This equation estimates the mean diameter of the trunk and does not account for the contribution of body appendages to the mean diameter of the body, as indicated by the values produced by it. To estimate this contribution, it was presumed that mean diameter of the appendages is represented by shinbone diameter, and that appendages comprise 20% of total body surface (Johnson et al., 1961). Heart girth (HG) to BW (W) relationship was estimated according to published equations (Heinrichs et al., 1992). In mature Holstein cows, paunch girth was 123% of heart girth according to 2 sources (Brody, 1945; Batra and Touchberry, 1974), as well as from additional measurements carried out in Israel (Solomon and Berman, 2003, unpublished data). Shinbone diameter was estimated from the relationship between shinbone circumference and BW, calculated from published data (Brody, 1945). Equations were developed on this basis for estimating mean diameter (D, m) of the body of Holstein cattle from HG (m) or BW (kg) data:

$$D = 2.89*10^{-2}*HG, \quad [3]$$

where

D = mean body diameter (m); HG = heart girth (m).

$$D = 0.2 + 0.001*BW - 5.85*10^{-7}*BW^2 \quad [4]$$

An equation that allows adjustments for a variable body size as well as for a variable air velocity may be

Figure 1. Boundary layer insulation as estimated by the NRC (2001) equation (open squares; $BI = 7.36 - 1.07 \cdot V$ and as suggested in this study (closed squares) by $BI = (1.68 + 0.003 \cdot W - 1.84 \cdot 10^{-6} \cdot W^2) \cdot V^{-0.53}$, where $BI = ^\circ\text{C m}^2 \text{ d/Mcal}$, $V = \text{air velocity (m/s)}$ and $W = \text{BW}$.

attained by combining equation 2 with equation 3 or 4, so that BI becomes:

$$BI = 3.46 \cdot (2.89 \cdot 10^{-2} \cdot HG)^{0.47} \cdot V^{-0.53}$$

or

$$BI = 3.46 \cdot (0.2 + 0.001 \cdot BW - 5.85 \cdot 10^{-7} \cdot BW^2)^{0.47} \cdot V^{-0.53} \quad [5]$$

$$= (1.68 + 0.003 \cdot BW - 1.84 \cdot 10^{-6} \cdot BW^2) \cdot V^{-0.53} \quad [6]$$

Either equation 5 or 6 seems to offer a solid approximation of BI as the predicted values of BI approach the insulation of still air at low air velocities. Also, the BI predicted by this equation corresponds with that determined by a hot plate technique (Bennett, 1964). The equation may be simplified for classes of BW. For the 200 to 300, 300 to 400, 400 to 500, and 500 to 650 kg BW classes, the value of BI may be predicted as 2.27, 2.43, 2.55, and 2.66, respectively, with discrepancies of less than 5% of the values calculated from respective body dimensions. Equations 5 and 6 differ from that of the NRC (2001) in attributing an exponential instead of a linear relationship between BI and air velocity. The difference between the 2 equations is negligible at very low air velocities and increases gradually to reach a maximum at about 1 m/s air velocity, to slowly decrease thereafter (Figure 1).

Figure 2. Boundary layer insulation for a 200-kg calf (open squares) and a 600-kg cow (closed squares) as estimated by $BI = (1.68 + 0.003 \cdot W - 1.84 \cdot 10^{-6} \cdot W^2) \cdot V^{-0.53}$, where $BI = ^\circ\text{C m}^2 \text{ d/Mcal}$, $V = \text{air velocity (m/s)}$, and $W = \text{BW}$.

The relationship between BI and air velocity was calculated for 200 and 600 kg of BW (Figure 2). For a 200-kg calf, BI is 21% smaller and for a 400-kg cow 7% smaller than that for a 600-kg cow over the whole range of air velocity. The difference in BI due to body dimension is larger at lower wind speeds, but becomes negligible at air velocities of 0.5 m/s and higher. It also is apparent that assuming a linear relationship between air velocity and insulation only may be a satisfactory approximation of BI at air velocities higher than 1 m/s, beyond which insulation changes only to a lesser degree. However, at 10 to 30 cm over the surface of cows, air velocity is 0.15 and 0.5 m/s is frequently found, even in open shelter systems in which horizontal forced ventilation is produced by fans (Berman, unpublished data).

CI estimates. The estimate of the effect of coat depth on EI in NRC (2001) for dairy cattle is based on mature steers and growing calves of beef breeds in a harsh winter in Canada (NRC, 1981). These EI values may be applied to mature dairy cattle in temperate and warmer climates if hair coat insulation is similar in the beef animals and the target dairy animal cattle.

In cattle coats, CI was correlated ($P < 0.01$) with coat depth, hair weight per unit area, hair density, and hair diameter (Berry and Shanklin, 1961; Bennett, 1964; Gebremehdin, 1983). Hair fiber diameter, weight per unit surface, and coat depth are all affected by both seasonal photoperiod changes and regional differences in temperature (Berman and Volcani, 1961). The EI data derived from studies in which animals were acclimatized to temperature for short periods may not represent a steady state, as in mature cows hair weight per unit surface continued to decline even at 9 wk after

cows were transferred from 18 to 29°C (Kibler et al., 1965). More representative information may be obtained from studies of seasonal changes in coat, which are free of these limitations.

Weight of hair in Holstein cows in midwinter in Israel was 1.3 g/100 cm² (Berman and Volcani, 1961), 0.9 g/100 cm² in Holstein calves in the United States (Berry and Shanklin, 1961), and 1.5 g/100 cm² in Friesian calves in New Zealand (Holmes et al., 1980). These contrast the hair weights of 10 g/100 cm² in Hereford and Angus cattle in midwinter in Canada (Gilbert and Bailey, 1991).

Hair diameter in Holstein cows in warm environments was reported as 79 microns (Gutierrez et al., 1984), with seasonal changes ranging from 46 to 70 microns in India (Govindaiah and Nagaroenkar, 1983) and 82 to 123 microns in Israel (Berman and Volcani, 1961). These contrast hair diameter values of 76 microns for guard hairs and 34 microns for the undercoat hair, the latter constituting about 63% of midwinter hair coat of Hereford and Angus cattle in Canada (Gilbert and Bailey, 1991).

Coat depth in Holstein cows in warm environments was reported as 2.8 mm (Pinheiro and Silva, 1998). Summer to winter seasonal changes ranged from 2.5 to 3.5 mm in India (Govindaiah and Nagaroenkar, 1983) and 1.8 to 6.3 mm in Israel (Berman and Volcani, 1961). These contrast hair coat depth values for dairy cattle given by the NRC (2001), 6.3 mm for summer coat depth and 12.7 mm for winter hair depth. The latter are close to the respective values reported for beef breeds (Blaxter and Wainman, 1964; Webster et al., 1970; McLean et al., 1984).

Thus it appears that hair coat characteristics of the cattle on which the NRC (2001) EI equation is based differ from those typical for Holstein cattle, and more so from those of Holstein cattle in warmer climates. Values typical for Holstein cattle should be used, to obtain more adequate external insulation estimates.

Coat depth effects on insulation may be estimated from CI per millimeter of coat depth. Coat insulation values would be best estimated when air velocity is below that at which wind penetrates the coat and disturbs its insulation properties, i.e., below 3 to 4 m/s. In such conditions, CI per millimeter coat depth was about 1.25°C m² d/Mcal in Aberdeen Angus steers (Blaxter and Wainman, 1961) and mature beef cows exposed to a harsh winter climate (McLean et al., 1984), 0.84 when the latter cows were acclimatized to 18°C, 0.66 in beef calves in Canada (Webster et al., 1970), 0.62 in British beef breeds in Australia (Bennett, 1964), 0.36 in Ayrshire Shorthorn cross steers (Blaxter and Wainman, 1964), 0.18 and 0.33 in summer and 0.44 in winter in Israeli Holstein cows (Arkin et al., 1991; Berman, 1971).

In Holstein cows in the United States, CI (coat depth not specified) declined from 4.0 to 1.0°C m² d/Mcal during acclimatization to air temperatures gradually increasing from -17 to 28°C (Ehrlemark, 1988). The latter is close to the CI for Holstein cows in Israel. It seems therefore that a value of 0.30°C m² d/Mcal per millimeter coat depth would be an acceptable estimate for Holstein hair coat insulation. This estimate is different from that in the NRC (2001) equations, though not markedly so. The major difference is in the coat depth assumed to prevail in dairy cattle in both summer and winter.

INS estimates. At this stage, it seems that total INS may be best estimated for Holstein cattle by:

$$\text{INS} = \text{TI} + \text{EI} = \text{TI} + (\text{BI} + \text{CI}) \quad [7]$$

$$= (2.4 + 0.0054 \cdot \text{BW}) + (1.68 + 0.003 \cdot \text{BW} - 1.84 \cdot 10^{-6} \cdot \text{BW}^2) \cdot \text{V}^{-0.53} + 0.3 \cdot \text{D}.$$

LCT estimates. The LCT is estimated by the equation (Blaxter, 1961; NRC, 2001):

$$\text{LCT} = 39 - (\text{INS} \times \text{HP} \times 0.85),$$

where

LCT = lower critical temperature (°C),

INS = tissue insulation + external insulation (°C/m² d Mcal),

HP = metabolic heat production (Mcal/m² d), and

0.85 = proportion of metabolic heat production lost via the skin.

Heat production at different milk yields was calculated in this study according to NRC (2001): maintenance heat production as 0.080 Mcal/kg BW^{0.75}, milk NE_L concentration = 0.36 + [0.0969(fat%)], and efficiency of dietary metabolic energy use for milk energy production as 64%. The effects of suggested changes in TI, BI, and CI and the EI estimation on LCT were examined for a 600-kg BW cow yielding 0 to 45 kg/d milk of 3.5% fat, exposed to air velocities of 0.2 and 1.0 m/s. The lower velocity represents situations in which air movement around the animals is low, e.g., high animal density, confined environments, and periods of low winds. The higher air velocity represents air velocities present in well-ventilated environments and shelters in which forced ventilation is used.

Energy cost of cold. The additional energy cost of nonevaporative heat loss due to exposure to ambient temperatures below the LCT (H_{cs}) was estimated by the equation (NRC, 2001):

$$H_{cs} = SA \cdot (LCT - T_a) / INS \quad [8]$$

where

H_{cs} = Mcal/d,

SA = body surface area, $SA = 0.09 \cdot BW^{0.667}$ according to Mitchell (1928), and

T_a = air temperature ($^{\circ}C$).

The effects of suggested changes in TI , BI , and CI and the EI estimation on the H_{cs} was calculated for a 600-kg BW cow producing 35 kg/d of 3.5% milk and exposed to 0.2 and 1 m/s air velocity at ambient temperatures below the LCT . Winter coat thickness was varied at the 2 wind velocities.

Excess heat estimates. The approach used for the prediction of nonevaporative heat loss from the body at ambient temperatures below the LCT was extended in a novel approach for the prediction of the heat that needs to be dissipated from the body to prevent a rise in body temperature. This is defined by the excess heat, Hex , estimated by the difference between nonevaporative heat loss and heat production. The rate at which the Hex increases is a reciprocal of INS . The INS is the sum of TI , CI , and BI . The BI depends on air velocity, CI is constant over periods of 1 to 2 mo, and TI declines at ambient temperatures above the LCT (Berman et al., 1984). The estimate of the increment in heat loss requirement thus needs to be modified by accounting for changes in TI . The Hex was estimated at temperatures above the LCT by the equation:

$$Hex = SA \cdot (T_a - LCT) / (INS - 0.12 \cdot (T_a - LCT)), \quad [9]$$

where Hex = heat excess, Mcal/d.

In the forementioned equation, INS was reduced by 0.12 units per $^{\circ}C$ increase of the T_a above the LCT , to account for the decline in TI at such conditions as presented in the respective section. The Hex was calculated for a 600-kg cow producing 35 kg/d of 3.5% fat, having a 0.3 or 0.6 cm thick coat and exposed to 0.2 and 1 m/s air velocities in summer. The calculations were conducted according to the NRC (2001) model and by the model suggested here.

RESULTS

LCT estimates. The impact of the suggested TI , BI , and CI and the EI estimation on LCT was examined (Table 5). The estimates were calculated as suggested by NRC (2001) and as suggested in this study (equation 7). In both models, when calculating EI and of LCT , it is presumed that 85% of total heat production is dissipated via body surface and 15% via the respiratory tract

Table 5. Estimates of lower critical temperatures ($^{\circ}C$) for a 600 kg cow yielding 0 to 45 kg/d milk, 3.5% fat, exposed to 0.2 and 1.0 m/s air velocities. Estimates calculated as suggested in NRC (2001) and as suggested in this study (ADJ), with summer coat thickness as 6.3 mm and 3 mm, respectively.

Yield (kg/d)	Air velocity 0.2 m/s		Air velocity 1.0 m/s	
	NRC	ADJ	NRC	ADJ
0	25.6	30.8	26.2	32.8
10	16.0	24.9	17.0	28.3
20	6.4	19.0	7.9	23.8
30	-3.3	13.1	-1.3	19.3
35	-8.1	10.2	-5.9	17.1
40	-12.9	7.2	-10.5	14.9
45	-17.7	4.2	-15.1	12.6

(Blaxter and Wainman, 1961). In the NRC (2001), the 0.8 (or 0.85) coefficient is used twice, as 0.80 in the EI equation and as 0.85 in the LCT equation. The duplication of the coefficient has the effect of artificially increasing the LCT values in the NRC (2001) model. Wherever calculating by the NRC model in the present study, the 0.85 factor was only used in the LCT equation. At the lower air velocity, estimated INS values are practically identical in both calculation models and at the higher velocity differences in INS between the 2 models are maximal.

In the LCT equation, the product of multiplying insulation by heat production is deducted from a fixed value. Therefore, the effect of a changing either heat production or insulation would have a multiplicative effect on LCT . At a low milk production, i.e., low HP , differences in LCT between the 2 modes of calculation are least, and they increase with increasing milk production (Table 5). Similarly, the differences in LCT between the modes of calculation of LCT are smaller at the lower air velocity. Alternatively, the impact of the equations used to estimate LCT increases with increasing milk production and air velocities up to 1 m/s. By the NRC (2001) equations, for a cow producing 45 kg/d at 3.5% fat, increasing air velocity from 0.2 to 1.0 m/s air velocity affects the LCT by 1 to $2^{\circ}C$. In contrast, by the equations suggested here, increasing air velocity from 0.2 to 1.0 m/s increases LCT by about $8^{\circ}C$. At a daily milk production of 45 kg at 3.5% fat and 0.2 m/s air velocity, the LCT is estimated at -17.7 and $4.2^{\circ}C$ by the NRC (2001) model and by the model suggested here (equation 7), respectively, and that is a $21.9^{\circ}C$ difference between the 2 models. For the same milk production but at 1.0 m/s air velocity, the respective LCT estimates become -15.1 and $12.6^{\circ}C$, respectively, a $27.7^{\circ}C$ difference.

Energy cost below the LCT . Metabolic heat production increases at ambient temperatures below the LCT . This energy cost, the H_{cs} , depends on both the LCT and the INS . The LCT determines the ambient temperature

Figure 3. Estimates of energy cost (Mcal/d) at temperatures below the LCT at 0.2 and 1.0 m/s air velocities (closed and open symbols, respectively) calculated according to NRC (2001) and as suggested in this study (■ and ▲, respectively), for a cow producing 35 kg/d at 3.5% fat. Coat thickness was set as 12.7 mm (and 6 mm at 1.0 m/s air velocity, ○) in estimates made according to NRC (2001) and as 6 mm for calculations made as suggested in this study.

below which energy requirements start rising. Total insulation modifies the rate at which Hcs increases when ambient temperatures decline below the LCT. The Hcs was calculated with the NRC (2001) equations and those suggested here (equation 7). Winter coat thickness varied in the 2 models. In the NRC (2001) model, winter coat thickness is set as 12.7 mm, and Hcs was calculated accordingly. In the calculations made by the model suggested here, a 6-mm coat thickness was used as the data presented suggest it as a closer estimate of coat thickness in Holstein cows in winter. The Hcs was calculated for both coat depths at 0.2 and 1.0 m/s air velocity at ambient temperatures below their respective LCT (Figure 3). Reducing coat thickness from 12.7 to 6 mm at 1.0 m/s air velocity only increased the Hcs calculated by the NRC (2001) model by 1.5 Mcal/d. The difference in INS between the 2 modes of calculation is small at 0.2 m/s and is maximal at the 1 m/s air velocity. The Hcs estimates suggest that the effect of wind on heat loss is very small by the NRC (2001) equations. Also suggested by these estimates is that the energy cost of low temperatures at 1 m/s air velocity by the NRC (2001) equation is very small relative to that expected by the equations suggested here.

Heat stress development above the LCT. The Hex gradually increases as ambient temperatures increase beyond the LCT. The Hex needs to be dissipated by reducing TI and increasing evaporative heat loss if body temperature is to be maintained. This study indicated that it is possible to estimate this rate of decrease in TI for cattle.

Figure 4. Estimated requirements for evaporative heat loss – excess heat- (Mcal/d) at temperatures above the lower critical temperature (LCT) at 0.2 and 1.0 m/s air velocities (closed and open symbols, respectively) calculated according to NRC (2001) and as suggested in this study (■ and ▲, respectively). Coat thickness was set as 6.3 and 3 mm in estimates made according to NRC (2001) and as suggested in this study, respectively. Rate of decline of TI at temperatures above the LCT estimated as $0.12^{\circ}\text{C m}^2 \text{ d/Mcal per } ^{\circ}\text{C increment in } T_a$.

The LCT and INS were estimated (Figure 4) according to the NRC (2001) and the equations suggested here (equations 7 and 9) for a cow exposed to summer. Coat thickness was set as 6.3-mm when calculating Hex by the NRC (2001) model and as 3-mm when calculating by the model suggested here. Assuming a 3-mm thick coat in NRC (2001) model calculations produced little, if any, change in Hex estimates. When calculated by the NRC (2001) model, the increase in Hex started at lower temperatures and rose at a slower rate than that predicted by the model suggested here. By the NRC (2001) approach for INS, air velocity had little effect on the estimated Hex. However, if INS was calculated as suggested in this study, increasing air velocity from 0.2 to 1.0 m/s shifted by 10°C the ambient temperature at which Hex started to increase. The effect of air velocity on Hex declined with rising ambient temperatures by the estimation mode suggested here. This is expected as effects of air velocity on heat loss are proportional to the difference between skin and air temperatures, and are thus expected to decline with increasing ambient temperature.

DISCUSSION

This study examined the assumptions and experimental evidence underlying the estimates of TI and EI suggested in nutritional models (NRC, 1981, 1996, 2001; Fox et al., 2000). In these models, the TI is based on the chronological age up to 1 yr of age, and in mature

cows it is modified by the BCS of the animal. In the model suggested here, TI is a function of the BW of the animal. The maximal TI value estimated by this function for a 600-kg cow is not far from that of mature beef cows of similar weight (McLean et al., 1984) but is markedly lower than the 9.7 value estimated for a cow in moderate to good body condition (BCS 6 on a 1 to 9 scoring system) according to the NRC (2001). If the TI value estimated according to the NRC (2001) is not adjusted for body condition, the NRC estimate of TI for such a cow would be 5.2, close to that estimated by the equation suggested here. An equation based on BW seems advantageous over age-based estimates, as BW within age is modified by nutritional state.

In the NRC (2001), TI is also modified according to BCS of the animal. No grounds are given, however, for modifying TI according to BCS. The BCS of the animal reflects accumulation of fat in layers underlying the skin, i.e., subcutaneous fat. Its sparing effect on heat loss to the environment has been the focus of scientific interest owing to its critical role in survival of aquatic and terrestrial mammals in cold climates. More recently, interest shifted to gender differences in thermoregulation related to body composition and distribution of adipose tissues in the human body as well as to the significant role played by muscle tissue in body insulation (Anderson, 1999). It has been demonstrated in man that alterations in muscle blood flow provide the bulk of limb insulation (Veicsteinas et al., 1982). The subcutaneous fat layer may be crossed by blood vessels conveying heat to the skin, sometimes as countercurrent heat exchange structures sparing heat loss in the cold. In fur-bearing animals, the smaller diameter, insulation, and fat depots of the limbs point to vasomotor control as the main regulator of their heat loss. Information specific for these aspects in the bovine is rather limited. A study carried out in the northern United States indicated that in Angus-Hereford cows of the same lean body mass, but not in Angus-Holstein cows, animals with more fat had a lower daily energy requirement during winter (Thompson et al., 1983). Beef type breeds tend to deposit a smaller proportion of their total fat as abdominal and intermuscular depots, and a larger proportion as subcutaneous fat than dairy breeds (Charles and Johnson, 1976; Kempster et al., 1976; Truscott et al., 1976; Dikeman et al., 1977). It seems therefore that BCS may be a factor modifying TI in beef cattle, but there is no evidence that this may be relevant for Holstein cattle, too.

The TI estimates blood circulation dependent heat loss at ambient temperatures below the LCT. It is well established that heat transfer to body surface is enhanced at higher ambient temperature. To the best of our knowledge there are no published estimates of tis-

sue insulation changes at ambient temperature above LCT in cattle. When calculated from published data at ambient temperatures above the LCT, TI was $5.53^{\circ}\text{C m}^2 \text{ d/Mcal}$ in beef cows at 20°C (Young, 1975). Information on TI in dairy cows at ambient temperatures above the LCT is less available. Mean daily TIs in lactating Holstein cows in Israel (Berman, 1971) were 3.3 and $2.3^{\circ}\text{C m}^2 \text{ d/Mcal}$ at mean daily temperatures of 17 and 32°C , respectively. In Holstein cows transferred from 18 to 29°C for 9 wk, TIs decreased from 3.6 to $2.2^{\circ}\text{C m}^2 \text{ d/Mcal}$ (Kibler et al., 1965). The 2 sets of values, one measured in a near-natural climate and the other in a controlled climate, closely correspond to each other. They indicate that TIs may decline at ambient temperatures above the LCT to less than half maximal TI. This study also indicated, by analyzing published data (Blaxter and Wainman, 1961, 1964; Kibler et al., 1970; McLean et al., 1984) that the rate of decline of TIs as ambient temperatures rise above the LCT may be estimated as $0.12^{\circ}\text{C m}^2 \text{ d/Mcal per } ^{\circ}\text{C}$ increment in ambient temperature. The latter estimate may be used for the prediction of heat loss at ambient temperatures above the LCT.

In the NRC (2001) equation for EI, a 0.8 coefficient is used, but no justification is given for it. It probably is meant to adjust EI for the heat lost via the respiratory tract. The EI data upon which the equation is based (Blaxter and Wainman, 1964; Webster et al., 1970; Webster, 1970) represent heat loss from skin. This coefficient does not appear in other models of nutritional requirements (NRC, 1996; Fox and Tytlutki, 1998; Fox et al., 2000). Unless other reasons are present for the inclusion the 0.8 coefficient, it seems that the EI would be better estimated by excluding this coefficient from its estimation.

In the NRC (1986, 1996, 2001) equation for EI, a fixed value (7.36) is presumed, from which a linear effect of air velocity is deducted and a linear effect for coat thickness is added. The fixed value and the air velocity factor may be seen as representing a BI effect. The boundary layer effect depends, however, on both body mass and air velocity, and both effects are of exponential nature. The BW effect on BI is independent of that of air velocity. The BW effect is not very large, yet not marginal: in 200-, 400-, and 500-kg BW animals, BI would be 23, 7, and 1% smaller than that in a 600-kg BW animal. These indicate that including in the EI equation a function that adjusts it to the BW of the animals would significantly improve its predictive value. The value of the prediction would be significantly improved if the fixed effects were replaced by BW-dependent BI functions.

In the NRC equation, a linear approach is used for estimating the effect of air velocity on EI. This presump-

tion is not consistent with the exponential expression in which this effect is estimated in convective heat transfer (Blaxter, 1962; Monteith, 1980; McArthur, 1987). The discrepancy between the 2 methods of estimation is negligible in still air, increases exponentially with increasing rate of air movement, is maximal at 1 m/s air velocities, and slowly decreases thereafter. The maximal discrepancy is about $4^{\circ}\text{C m}^2 \text{ d/Mcal EI}$ units. Using a linear approach for estimating EI would thus overestimate it by about 25 to 50%, leading to an underestimate of heat loss in cold exposed animals.

The NRC (2001) states "For lactating cows in cold environments, the change in energy requirements is probably minimal because of the normally high heat production of cows consuming large amounts of feed." The data presented here suggest that this statement is based on the assumption that CI values typical for beef cattle breeds in cold regions also are typical for dairy breeds, specifically the Holstein. Experimental evidence presented in this study indicates that the CI values used by NRC (2001) should be modified for them to apply to Holstein cattle in climates warmer than Canada or Scotland. The present study also suggests that it is possible to estimate the development of thermal stress and of the requirements for heat stress relief on the basis of the insulation characteristics of the animals.

Assuming a linear relationship between air velocity and insulation may be a satisfactory approximation of BI only at air velocities higher than 1 m/s, beyond which insulation changes only to a lesser degree. This would, however, necessitate using a different value for the fixed effect for BI. Air velocity usually is about 0.4 m/s in confined housing systems and varies between 0.3 and 2 m/s in open shelters. It should be noted that at 10 to 30 cm above the surface of cows, air velocities in the 0.1 to 0.5 m/s range are frequently found, even in open shelter systems in which horizontal forced air movement is produced by fans (Berman, unpublished data). Air velocities in the immediate environment of the animals thus frequently are in the range that has the largest impact on BI. Using a linear approach for estimating air velocity effects on BI would mask their impact on BI. In contrast, using an exponential approach for estimating BI would open new scopes in the planning of housing and climate sheltering systems for dairy cattle (Berman and Wolfenson, 1992). From the data presented here, it may also be inferred that close to minimal BI is reached at air velocities of 1 m/s. This suggests that air velocities not greater than 1 m/s in the immediate animal environment may be sufficient to reach close to maximal convective and evaporative heat loss from the body surface of the animals.

When cattle are lying, the body surface exposed to the thermal properties (temperature, humidity, flow velocity) of surrounding air is reduced. Also, they rest in lower layers of the air, closer to the ground, in which air flow is slower. In resting cattle, their limbs are folded against the trunk, which practically eliminates their separate presence as small diameter bodies and may thus increase BI by up to 20%. When cattle huddle together in cold and windy situations, their exposed body surface is markedly reduced, and they may be considered as having a larger diameter. All these may be considered as behavioral factors and structural elements that act to increase the BI of the animals. In contrast, the insulation properties of surfaces on which cattle are lying down are lower than that of air: a 20-cm layer of straw and dung has an insulation of about $8^{\circ}\text{C d m}^2/\text{Mcal}$, similar to that of BI at air velocities of 0.5 to 5 m/s, while concrete with some straw on it, asphalt or rubber mats on concrete have insulation values about 1 to $2^{\circ}\text{C d m}^2/\text{Mcal}$ (Bruce, 1979). This suggests that heat loss to the resting surface may be an important factor in heat loss predictions for cattle.

The earlier published figures of LCT for dairy cattle (Webster, 1974) suggested values of -30°C and beyond for animals producing more than 20 kg/d. These figures were difficult to reconcile with the performance of Holstein cattle in warmer climates and their thermal state (Berman, 1967; Berman and Morag, 1971; Folman et al., 1979; Berman et al., 1985). They stem from the insulation values used in these estimations. The present NRC (2001) suggests LCT values of -8 to -5°C for summer-adapted animals yielding 35 kg of milk per day. The rise in skin temperatures and skin water loss and later in body temperatures that occurs at ambient temperatures above the LCT, might serve as an indicator of the proximity of the LCT. Their patterns of change in lactating Holsteins at rising ambient temperatures (Berman, 1967, 1971; Berman and Morag, 1971) suggest that LCT values of Holstein cattle are higher than those suggested by the NRC (2001). Also, the small, almost negligible effect of air velocity on heat loss by the NRC (2001) does not explain the effects forced ventilation had on the thermal balance of lactating Holstein cows (Berman et al., 1985). These effects are, however, expected if LCT and heat excess are estimated as suggested in this study. The LCT and INS values estimated as suggested in this study are therefore supported by the patterns of change in thermal responses as well as by the known performance of Holstein cows in warm regions. It is noteworthy that similar estimates of LCT were arrived at on the basis of thermal responses of lactating Holstein cows in a warm region (Berman and Meltzer, 1973).

Estimating body surface area from the equation of that of Brody (1945) instead of using that of Mitchell (1928), would not affect LCT values. A change in SA has similar but opposite effects on INS and HP estimates so that their product, which determines the LCT, remains the same. A change in estimated SA would, however, affect the estimate of total skin evaporative capacity and thereby affect the ability to cope with the excess heat accumulating in the body with rising ambient temperatures.

Taken as a whole, this study indicates the need for a revision of data and equations on the basis of which heat loss and heat stress are estimated for dairy cattle in the NRC (2001) and in the CNCPS (Fox et al, 2000).

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