Unveiling the Production Efficiency of the Beef Cow: A Systematic Approach using Nutrition Models[1]

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Introduction

The search for ways to select for improved beef cow efficiency has become the *holy grail* of the beef cattle seedstock industry. Increases in beef production have often been possible due to enhancements in the reproduction indexes (e.g. calving frequency, age at first calving, calving interval), nutrition concepts (e.g. strategic supplementation, type of forage as well as quantity and quality), genetic selection (e.g. bull selection, crossbreeding), and (or) ranch management (e.g. matching breeding and calving seasons with availability of forage).

Nonetheless, beef production still is perceived as a relatively inefficient process from the standpoint of energy expenditure. Research has indicated that 70 to 75% of dietary energy expenditure is used for maintenance (Ferrell and Jenkins, 1985), the remaining is used for pregnancy and lactation requirements, and that beef cows are responsible for 60 to 70% of the total of energy expenditure (Johnson, 1984); at least 50% of this energy is expended to maintain the cow.

Ideally, efficient beef cows use less resource to obtain the same outcome in a sustainable environment. There are several indexes used to select efficient beef cows. All of them are based on retaining beef cows that routinely produce a weaned calf with fewer inputs, mainly feed, e.g. the ratio of pounds of calf weaned per unit of forage consumed or the ratio of pounds of calf weaned per pound or number of females exposed to a bull. Additionally, beef cow maturation rate has also been shown to be correlated with production efficiency and may be used to select for efficient cows (Parker et al., 1972; Tedeschi et al., 2000a, b).

A cautionary note in adopting a selection index is that a small-frame cow with low milk producing capability may be apparently more efficient if the calf performance is not taken into account. Additionally, selecting efficient animals may reduce the expression of other traits that are equally important for the beef production process, e.g. reproductive efficiency, maternal ability, etc.

An interesting report that outlined definitions of efficiency for primary and secondary traits for dairy cow efficiency, which also applies to beef cow efficiency, has been produced by the European Association on Animal Production (Ostergaard et al., 1990). They summarized as follows: "*The improvement in biological efficiency is important, and research has to be focused on the underlying processes such as rumen*

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function, utilization of digested and metabolized energy, and the partitioning of feed energy between milk and body tissue. Knowledge about genetic variation between animals for these different biological processes is very limited, and should be studied in relation to the composition of feed ration, the feeding strategy and the physiological state of the animal".

The principal objective of this article is to present a mathematical model being developed to estimate the ratio of energy required (metabolizable energy – ME, Mcal) by a cow to pounds (or kilos) of weaned calf (energy efficiency index – EEI, Mcal/lb or Mcal/kg); the lower the better. A second objective is to compare each EEI to the range of expected EEI using Monte Carlo simulation to identify the upper and lower cutoff EEI. A third objective is to present advanced topics on the identification and selection of mitochondrial DNA (mtDNA) mutants that have higher energy efficiency.

A brief description of the mathematical model

Several models have been developed to simulate cow/calf production systems have been made in the past (Boyd, 1977; Fox et al., 1988; Long, 1972; Miller et al., 1980; Naazie et al., 1997; Notter et al., 1979a, b, c). Fox et al. (1988) developed a model to simulate the interactions of a cow/calf herd with beef production environment that would assist matching cattle to the forage management system to enhance profitability of the herd. Their model computes a balance between energy requirements for maintenance, pregnancy, lactation, and tissue mobilization and energy available from the forage; thus, allowing one to match availability of forage with periods of higher energy demand by the cow and calf. Our current model is based on the model described by Fox et al. (1988) with some modifications.

Our current model computes energy requirement for maintenance based on body weight adjusted for conceptus weight, environment (climate effects), physical activities, and physiological stage (dry vs lactation) as recommended by the NRC (2000). Additionally, smooth curve adjustments using the cubic spline technique are provided to be used during transition phases since this is a time-dependent model. DiConstanzo et al. (1990) found that among non-pregnant non-lactating Angus cows of similar fat masses, those with larger protein masses had higher energy requirements for maintenance because the ME required to maintain 1 kg of protein was 9.3 times higher than fat (192.9 ± 24.8 vs 20.7 ± 21.5 kcal, respectively). Therefore, the composition of the body is also important in computing ME requirement for maintenance as we have shown for growing/finishing animals (Tedeschi et al., 2004).

Energy for pregnancy is based on the NRC (2000) recommendations that uses days pregnant to derive energy concentration of the conceptus. The model assumes a fixed calving interval of 365 d.

The energy requirement for lactation is computed based on NRC (2000) and Fox et al. (2004). Milk composition is used to compute net energy of the milk, which drives

the energy requirement for lactation. A fixed value of 5.29 Mcal of ME/kg of milk DM basis is assumed to compute intake of ME by the calf. The peak milk is used to plot the lactation curve, which predicts the daily amount of milk available for calf feeding.

The model uses Abdelsamei's data (1989) to estimate forage intake of the calf. In his experiment, the *ad libitum* intake of chopped alfalfa of 40 Holstein calves fed 5 leves of milk production (peak milk at 59.5 DIM: 2.72, 5.44, 8.16, 10.88, and 13.6 kg) was measured for 200 d. We used this data to derive five multiple regression equations to estimate forage intake for the pre-peak milk phase as shown in Table 1.

Table 1. Regressions to estimate forage intake by nursing calves for five milk levels before peak milk is reached.

Variables	Peak Milk, kg				
	2.72	5.44	8.16	10.88	13.6
Calf BW, kg	-0.008	0.025	0.004	-0.004	-0.001
DIM, d	-0.019	0.221	0.108	-0.023	-0.002
Calf BW × DIM	0.000	-0.005	-0.002	0.000	0.000
Cow milk, kg	-1.272	0.496	-0.423	0.031	0.033
Calf BW × Cow milk	0.010	-0.008	0.007	0.001	0.000
DIM × Cow Milk	0.027	-0.226	-0.066	0.006	-0.002
Calf BW × DIM × Cow milk	0.000	0.005	0.001	0.000	0.000
Peak milk, kg	0.595	-1.147	-0.196	0.183	0.025

The intake of forage (kg/d) for the post-peak milk phase is computed using the multiple regression ($R^2 = 98.6\%$, N = 394, RMSE = 281.24) listed below.

Forage intake = 30.313×Calf BW – 753.76×Cow Milk – 11.704×Calf BW×Cow Milk -190.316×Peak milk + 0.499 ×Calf BW×Peak milk + 112.106×Cow milk×Peak milk -0.085×Calf BW×Cow milk×Peak milk

Figure 1 shows the magnitude of the influence of the factors used to estimate forage intake by the calf. Clearly, cow milk and peak milk have a negative correlation whereas calf BW has a positive correlation with forage intake.

It is well documented that BCS has an important role in beef production and (or) reproduction efficiency (Houghton et al., 1990; Mortimer et al., 1991). In our model, tissue mobilization is used to compute energy available/required for body reserves based on BCS changes (this feature is currently not implemented).

Figure 2 depicts the scheme of the current model developed to estimate energy requirement of the beef cow and the interactions between lactation and weaning weight (WW) of the calf.

The application of this model is two fold: (1) to estimate the weaning weight of the calf given the information available and compare performance of different cows, and (2) to identify efficient cows by changing the peak milk until the WW predicted by the model matches the observed WW, then computing the EEI of the cow as the ME requirement divided by the WW.
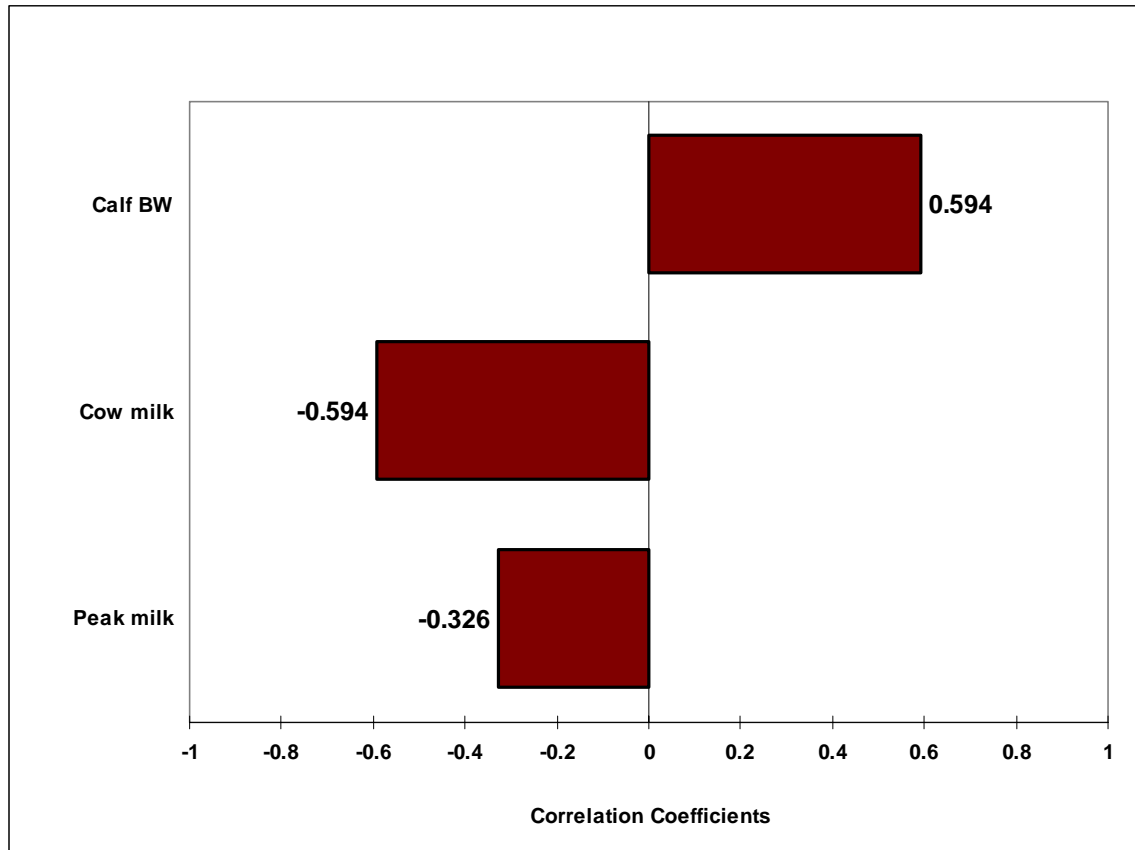

Figure 1. Correlation of the most influential factors to predict forage intake.

An evaluation of the model

Figure 3 shows the comparison of weaning weight and EEI of two cows (small and large) with five peak milk levels. Birth weight was assumed to be 6.5% of the mature weight of the cow. As peak milk increases, WW increases almost linearly and the difference in the calf WW between small and large cows seems to increase (Figure 3A).

Consistently, as peak milk increases, the energy efficiency index (amount of ME requirement per WW) decreases exponentially (Figure 3B). It is also clear that the higher the peak milk, the smaller is the difference between small and large cows. This is likely due to the effect of milk on available energy for maintenance and growth of the calf and the effect of BW on forage intake of the calf, since at lower peak milk calves from the large size cows will be heavier and will consume more forage than the calves of the small size cows. Therefore, the higher the milk production of the cow, the more difficult it is to

select for efficient cows because of the dilution effects of maintenance over the lactation energy requirements and the impact of milk on calf growth. The only way the larger cow could be more efficient than a smaller one is if their metabolic efficiency of energy was different. However, there are data indicating that cow size (BW) does not influence the efficiency of energy use (Ferrell and Jenkins, 1984a, b); therefore, the larger the cow, more is the energy (ME) that is required for maintenance.
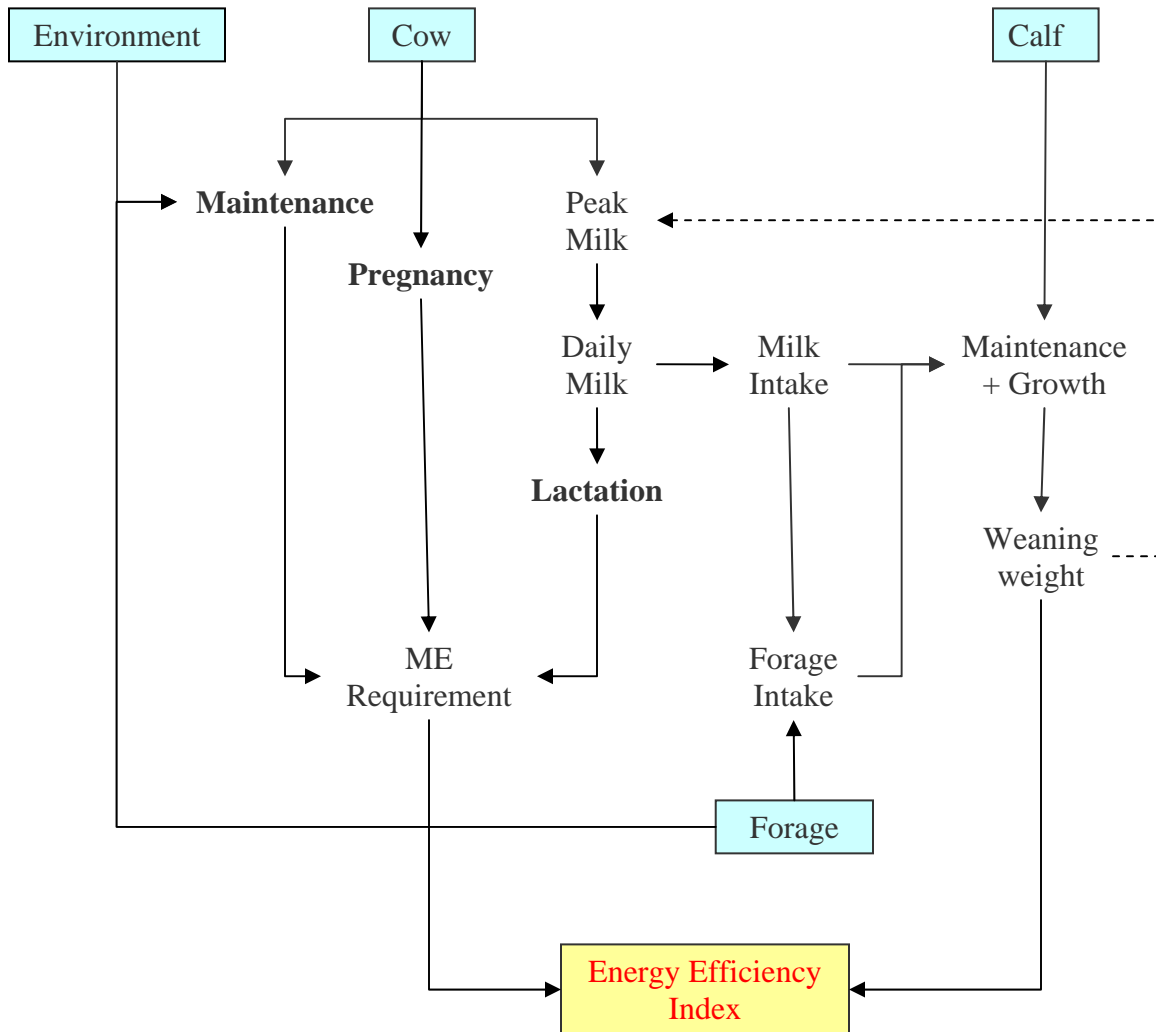
Figure 2. Flowchart of the mathematical model to predict energy efficiency index.

These findings are in agreement with those reported by Davis et al. (1983b). They've shown that smaller cows can wean more pounds of calf per pound of feed than larger cows. In another study, Davis et al. (1983a) reported that feeding larger cows a higher-energy diet did not increase the number and total weight of calves weaned to offset the higher level of energy intake. Therefore, larger animals can wean a larger calf

as depicted in Figure 3A. Our simulation indicated that differences in energetic efficiency due to cow size becomes smaller as milk production increases as shown in Figure 3B.

Cows selected for improved efficiency in a certain environment may not express their efficiency in another environment (Ferrell and Jenkins, 1985). When forage is available, larger animals may be able to offset their inefficiency by weaning a heavier calf. However, when forage is limited, larger animals may not be as efficient as smaller ones.
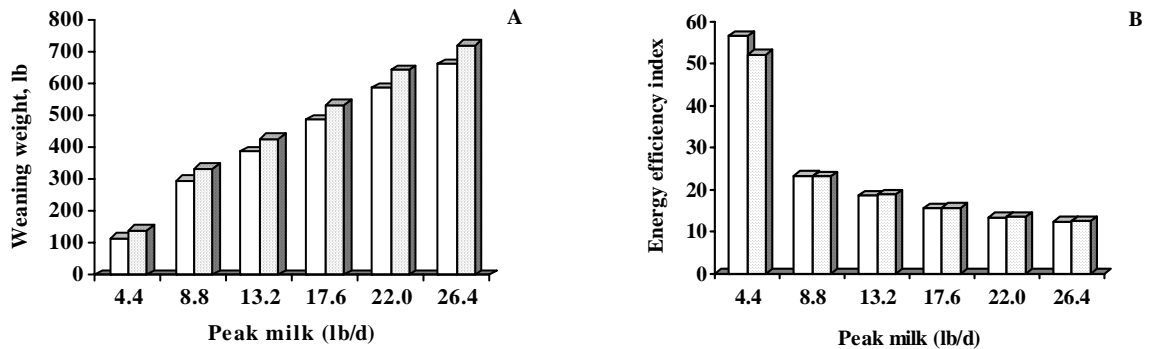

Figure 3. Comparison of weaning weight (A) and energy efficiency index (B) of two-cow sizes (990 lb – open bars and 1166 lb – dotted bars) at five peak milks.

Milk production is also a determinant of calf WW and efficiency of the cow. The higher the milk production, the chance of producing a heavier calf is increased (Clutter and Nielsen, 1987; Lewis et al., 1990). However, it is well known that high-milking cows have lower energy efficiency (ME efficiency) because the internal organs are larger and they have a faster metabolism compared to the low-milking cow (Ferrell and Jenkins, 1984a, b, 1985). This means that higher-milking cows spend more energy for maintenance; therefore, they require more energy per pound of BW than lower-milking cows (Montano-Bermudez and Nielsen, 1990), but the EEI maybe offset by the weaning weight of the calf, which may yield the same EEI for small and large cows. Compensatory growth may also play a key role in the growth of the lighter calves. In fact, Lewis et al. (1990) found that post-weaning effects of increased WW on ADG due to the cow's higher milk yield were small. In addition, they reported that only calves from the low-milking group (5.6 kg/d) showed compensatory growth.

In contrast with our findings, Montano-Bermudez and Nielsen (1990) found out that lower-milking cows were more efficient producers to weaning than high-milking cows. Additionally, the authors reported the calves retained this efficiency advantage through the feedlot. On the other hand, Miller et al. (1999) reported no effect of milk yield on biological efficiency of Hereford, Charolais x Simmental x Maine-Anjou, and Tarentaise x Pinzgauer x Gelbvieh x Angus calves from calving to slaughter. Our

simulation indicated that differences in EEI between small and larger cows and between peak milk levels decreases as peak milk increases.

A practical application of the model

The mathematical model described in Figure 2 may be used as a decision support system tool by farmers to assist in genetic selection programs. Using Monte Carlo simulation (Winston, 1993), one can simulate the expected outcomes of the EEI given the distribution, mean, and variability of the parameters used by the model.

Figure 4 shows a simulation with cow BW, peak milk, and forage quality. It indicated that for that scenario, cows that had EEI lower than 13.9 or higher than 17.24 Mcal/lb are within the 10% more and less efficient cows, respectively. Therefore, one could select for cows having less than 13.9 Mcal/lb to increase the efficiency of the herd, or conversely, one could cull those cows having EEI higher than 17.24 Mcal/lb.
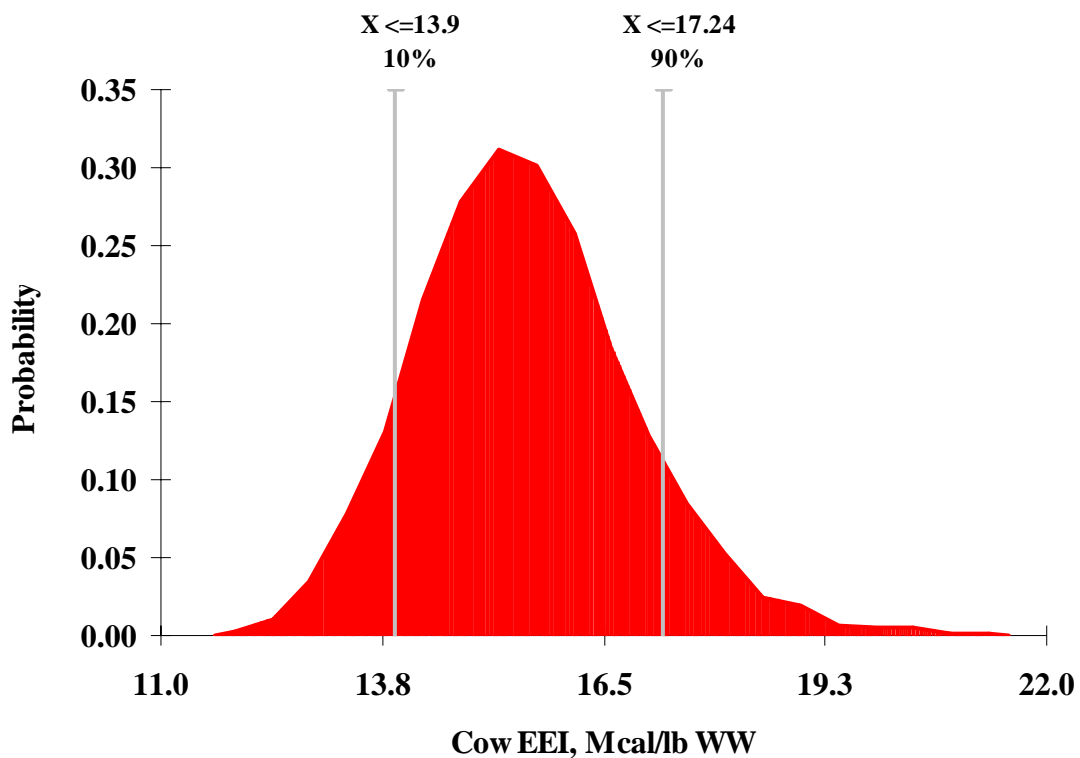

Figure 4. Monte Carlo simulation.

Another application of the model is the simulation of availability and quality of forage (Figure 5) throughout the year relative to forage requirements for different cattle types in the hear to evaluate and improve the energy balance for the annual production cycle (Figure 6).

Figure 5 shows the forage energy content for each month following the distribution of the TDN and its variability for each month and Figure 6 shows the energy balance (requirement minus supply) for the same period. It is clear that a strategic supplementation program should take place during the months of July thru December.
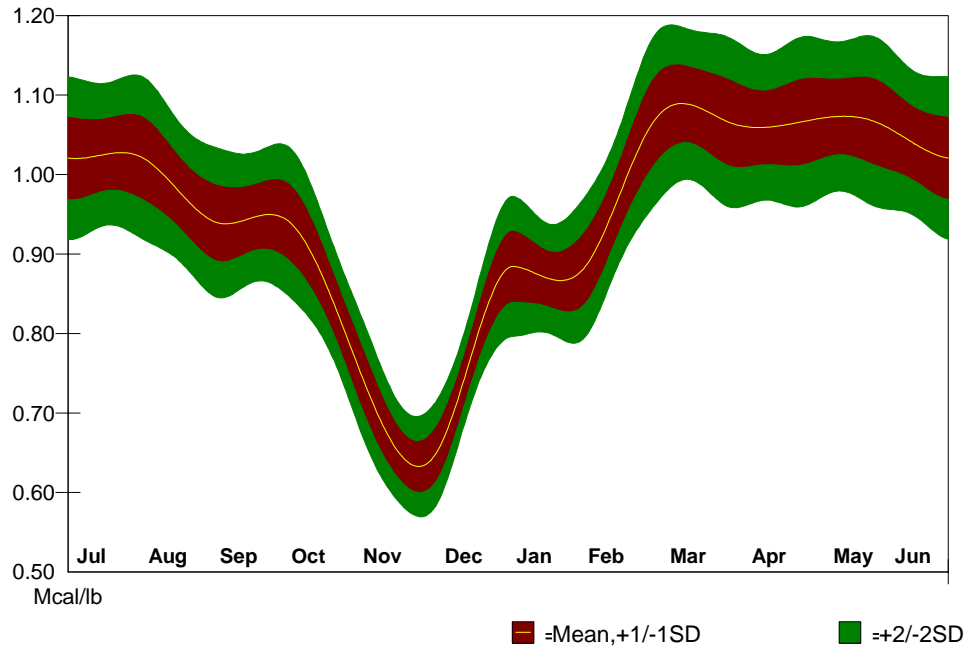

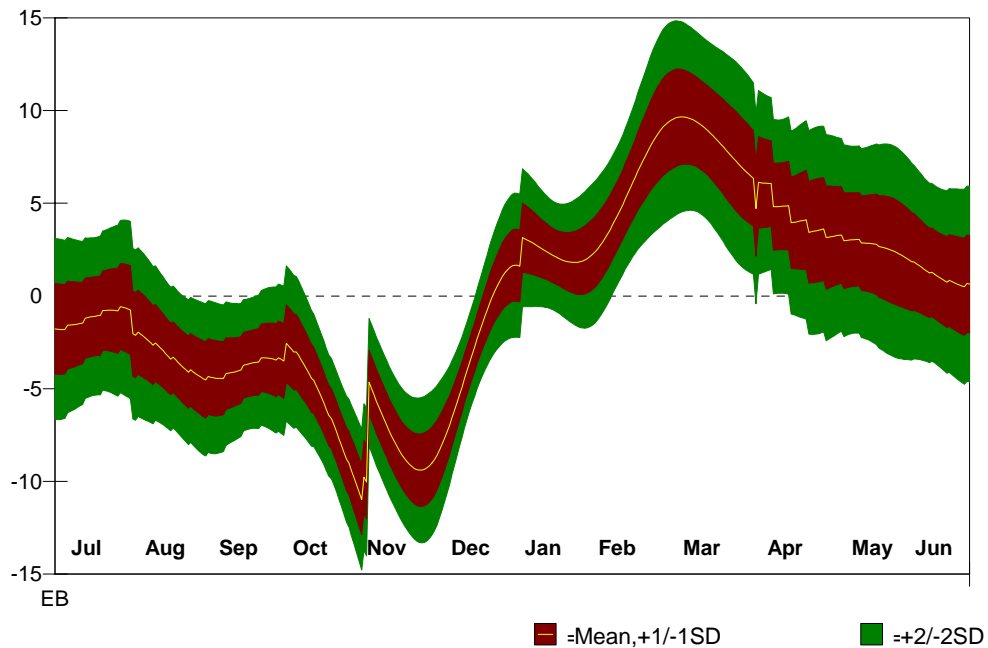Figure 5. Forage energy content throughout the production cycle.

Figure 6. Energy balance throughout the production cycle.

A glance of the future

The scientific efforts in the development of an EPD for efficiency have gained some attention by the breed associations in the US as an additional decision-making tool for purchase and evaluation of sires. Australian scientists have used the residual feed intake (RFI) analysis to select efficient bulls (Archer and Bergh, 2000; Archer et al., 2001; Archer et al., 1999). The main problems with this technique are the need for measurement of individual intake and the tendency to select for leaner animals as an undesirable consequence. We are currently working on evaluating a mathematical model (Cornell Value Discovery System – CVDS; Tedeschi et al., 2004) that estimates required intake given animal's performance and adjusts gain and intake for body composition (degree of maturity) to rank the estimates of feed efficiency of individual animals. This model is currently available for growing/finishing animals and may be downloaded at http://www.cncps.cornell.edu. The current model will also be used to estimate EPD for beef cow efficiency to assist genetic selection programs.

We are also working on a genomic-modeling project that involves the mapping and identification of mitochondrial DNA mutants that are more energetically efficient. The presence of maternal genetic effects has long been hypothesized to have an effect on economical traits of cattle. However, little support has been found in the common statistical analysis of genetic breeders (Gibson et al., 1997). Mitochondria are a likely source of some of this "unexplained" variation since they contain their own DNA and are only maternally inherited. It is well known that mtDNA variation may cause bias in the estimation of variance components (Boettcher et al., 1996b). Therefore, a positive mitochondrial effect is desirable for dams of cows, but not for dams of sires, since they are not passed onto male progeny.

Mitochondrial DNA has been extensively used in phylogeny to identify cattle lineages using DNA displacement loop sequence variation (Bradley et al., 1996; Loftus et al., 1994). Additionally, mtDNA has also been used to characterize substitutions that could be responsible for several economical traits, including meat quality (Mannen et al., 2003), milk production and animal health (Boettcher et al., 1996a; Boettcher et al., 1996c; Schutz et al., 1994).

The basic hypothesis is that a lineage of cattle that is more energetically efficient might exist due to certain arrangements in the mtDNA that permit the mitochondria to be more efficient. This energetic efficiency of the mitochondria is reflected in the bioenergetics of the whole animal and is responsible for some variation found among progeny of the same sire but different dams. External effects that might regulate mitochondria efficiency have also been reported, such as acetyl-L carnitine (Iossa et al., 2002) and fatty acids (Clarke et al., 2000; Jezek et al., 1998; Schrijver and Privett, 1984).

In broilers, low feed efficiency is related to defects in electron leak in muscle mitochondria (Bottje et al., 2002). In plants, ATP Synthase is a key enzyme in providing energy since it uses a transmembrane electrochemical proton gradient to drive synthesis of ATP. The enzyme complexes function as miniature rotary engines, ensuring energy

coupling with very high efficiency (Bunney et al., 2001). In rats, a low mitochondrial proton leak rate may partially explain the abnormally lower heat production and bioenergetics efficiencies of the obese Zucker rat (21% lower than leaner animals) as reported by Ramsey et al. (1996).

Mitochondrial proton leak may be responsible for at least 20% of the resting oxygen consumption in mammals (Ramsey et al., 2001). It is also documented that uncoupling protein 1 homologue, UCP3, is responsible for a decrease in efficiency of energy metabolism because of the dissipation of energy as heat due to an uncoupling of adenosine triphosphate (ADP) production from mitochondrial respiration process (Schrauwen, 2002). Therefore; mutants that have a lower mitochondrial proton leak or have lower concentration of UCP3 will be more energetically efficient. We just have to come across them!

Conclusions

Mathematical models can be used to assist in the identification of efficient cows and simulation of different scenarios of production to identify optimum management systems for beef cows. More work is needed to include protein availability and quality to the current model. Once this is attained, this model can also be applied to select best strategy for forage management and supplementation to minimize costs and environment impacts of N.

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