

Development of Mathematical Models to Estimate Animal Performance and Feed Biological Values ¹

Luis Orlando Tedeschi, Texas A&M University, College Station, TX 77843

Danny G. Fox, Cornell University, Ithaca, NY 14853

James B. Russell, U.S. Plant, Soil and Nutrition Laboratory, ARS/USDA, Ithaca, NY 14853

Introduction

Mathematical models can be used to integrate our knowledge of feed, intake, and digestion and passage rates upon feed energy values, escape of dietary protein, and microbial growth efficiency. They can be valuable tools for estimating animal requirements and nutrients derived from feeds in each unique farm production scenario, and thus can have an important role in providing information that can be used in the decision-making process to enhance the feeding system (Tedeschi et al., 2005b). By accounting for farm-specific animal, feed, and environmental characteristics, more accurate prediction of dietary nutrient requirements for maintenance, growth and milk production of cattle and nutrient excretion in diverse production situations is possible (Fox et al., 2004).

In the United States, livestock farms are under increasing pressure to reduce nutrient accumulation on the farm and manure nutrient excretions in order to meet environmental regulations (Fox et al., 2006). The Natural Resources Conservation Service (**NRCS**), an office of the United States Department of Agriculture (**USDA**), has identified the need to improve feed management in concentrated animal feeding operations (**CAFO**) to reduce manure nutrients. The USDA-NRCS has developed a national conservation practice standard for feed management (#592; USDA-NRCS, 2003) to be used as part of the nutrient management (#590; USDA-NRCS, 2006) planning process. The purpose of a feed management plan is (1) to supply the quantity of available nutrients required by livestock while reducing the quantity of nutrients excreted, and (2) to improve net farm income by feeding nutrients more efficiently.

The development of feeding and nutrient management plans is complex and requires the integration of a large amount of research and knowledge information. Therefore, mathematical nutrition models can be used to assist in the deployment of governmental regulations by facilitating the application and development of site-specific plans. Mechanistic models more accurately account for animal and crop requirements, and manure and soil management than fixed, tabular guidelines because they can be customized and calibrated for site-specific characteristics and recommendations (Tedeschi et al., 2005a; Tedeschi et al., 2005b).

The identification of cattle requirements and formulating diets to meet those requirements more accurately is the best current strategy to minimize nutrient output per kg of meat or milk produced. The terms *precision feeding* and *phase feeding* have been widely used to describe nutrient management practices that result in reduced excretion of nutrients by CAFO. Both terms refer to a more precise nutrition system, where nutritionists meet cattle nutritional needs without

¹ Tedeschi, L. O., D. G. Fox, and J. B. Russell. 2007. Development of mathematical models to estimate animal performance and feed biological values. Pages 223-252 in International Symposium of Advances in Research Techniques for Ruminant Nutrition, 1, Pirassununga, SP, Brazil. Studium 5D Marketing e Comunicação.

supplying nutrients in excess, reducing outputs and inputs. *Phase feeding of protein* or *protein withdrawal* is a systematic method that applies precision feeding concepts to different phases of animal growth to accurately meet their nutrient requirements during the feeding period. Phase feeding involves formulating and providing more specific rations during growth-specific periods as the animal matures (Vasconcelos et al., 2007).

Developing Nutrition Models to Manage Nutrient Accountability

A nutrition model can be defined as an integrated set of mathematical equations and transfer coefficients that describe the various animal physiological functions (Gill et al., 1989). The integrated model is then used to predict the response of each animal physiological function to a variable or combination of variables. Included are predictions of tissue requirements (maintenance, growth, pregnancy, lactation and tissue reserves), and animal digestion and metabolism of nutrients consumed to meet requirements. The level of aggregation of equations depends on the data available to develop and test them, and the objective of the model (i.e. to understand and describe how the biological system works vs. the development of a model for on farm application). Most nutrition models use a combination of mechanistic and empirical approaches to represent the aggregated response of whole physiological functions to the variables (Tedeschi et al., 2005b).

The Cornell Net Carbohydrate and Protein System (**CNCPS**) is a mechanistic nutrition model (Fox et al., 2004) that was first published in 1992 and 1993 in a series of four papers (Fox et al., 1992; O'Connor et al., 1993; Russell et al., 1992; Sniffen et al., 1992), and the model has been continually refined and improved over the last 15 years (Ainslie et al., 1993; Fox et al., 1995; Fox and Tylutki, 1998; Fox et al., 2002; Fox et al., 1999; Klausner et al., 1998; Lanzas, 2006; Lanzas et al., 2007a; Lanzas et al., 2007b; Lanzas et al., 2007c; Pitt et al., 1996; Seo et al., 2006a; Seo et al., 2006b; Tedeschi et al., 2002a; Tedeschi et al., 2002b; Tedeschi et al., 2006a; Tedeschi et al., 2000a; Tedeschi et al., 2005a; Tedeschi et al., 2002c; Tedeschi et al., 2000b; Tedeschi et al., 2000c; Tedeschi et al., 2003; Tedeschi et al., 2001; Tedeschi et al., 2006b; Tylutki and Fox, 1997; Tylutki et al., 1994; Tylutki et al., 2007).

Predicting the Requirements of Energy and Protein by Physiological Stages

The CNCPS has separate sub-models with distinctly different levels of aggregation. Some sub-models are relatively mechanistic while others are primarily empirical. Steady state conditions are assumed for the whole model and its components. The CNCPS submodels can be classified by physiological function: (1) maintenance, (2) growth, (3) pregnancy, (4) lactation, (5) reserves, (6) feed intake and composition, (7) rumen fermentation, (8) intestinal digestion, (9) metabolism, and (10) nutrient excretion (Fox et al., 2004).

Maintenance

Energy available for productive functions depends on the proportion of energy consumed that must be used for meeting maintenance (**NE_m**) requirements, and therefore is considered first in evaluating a diet and animal performance. Maintenance requirements in the CNCPS are

determined by accounting for breed, physiological state, activity, urea excretion, heat or cold stress and environmental acclimatization effects (Fox et al., 1992; Fox and Tylutki, 1998). The CNCPS model estimates the cost of metabolizable energy (**ME**) to synthesize urea N from protein in excess of requirements (7.3 kcal/g of N).

The Beef Cattle National Research Council (NRC, 2000) increased the maintenance energy requirement for bulls by 15% and decreased the NEm by 10% for all types of *Bos indicus* cattle breeds. However, in a recent evaluation of three comparative slaughter experiments with Nellore cattle fed high forage diets, Tedeschi et al. (2002b) reported the NEm of bulls (n = 31) and steers (n = 66) were similar, about 77.2 kcal kg^{-0.75} empty body weight (**EBW**). For this reason, the CNCPS does not increase the NEm requirement for bulls, or reduce the NEm requirement for Nellore fed high forage diets.

The CNCPS assumes that protein requirements for maintenance are the sum of scurf protein, urinary protein, and metabolic fecal protein (NRC, 1984; 1985; 1989; 2000; 2001). Metabolic fecal protein is currently calculated as 9% of indigestible dry matter (**DM**; i.e. 100 - digestible DM).

Growth

Energy and protein requirements for growth include adjustments for the effects of body weight, rate of body weight gain, chemical composition of gain, and mature weight (Fox et al., 1992; Fox et al., 1999; Tedeschi et al., 2002b; Tylutki et al., 1994), as adapted by the NRC (2000; 2001). A size scaling system based on the ratio of current weight to mature weight is used to predict the composition of gain. The net energy for gain (**NEg**) is based on empirical relationships described by the NRC (2000). Equivalent empty body weight (**EqEBW**) is 0.891×Equivalent shrunk body weight (**EqSBW**), and empty body gain (**EBG**) is 0.956×shrunk body gain (**SBG**). Across all beef cattle types, these equations accounted for 94% of the variation in energy and 91% of the protein retained with a 2% bias (NRC, 2000). Similar results were obtained with Holstein heifers (Fox et al., 1999).

Recent research indicates that the growth rate for dairy herd replacement heifers affects first lactation milk production (Fox et al., 1999; NRC, 2000; 2001; Van Amburgh et al., 1998). The dairy NRC (2001) adopted the CNCPS approach of using target weights and daily gains to compute requirements for average daily gain (**ADG**) for cattle of any mature weight (Fox et al., 1999). Coefficients to estimate the target weights are based on Gregory et al. (1992), Van Amburgh et al. (1998) and NRC (2000).

Pregnancy

The CNCPS computes pregnancy requirements and weight gain from growth of the gravid uterus based on expected calf birth weight and day of gestation (Bell et al., 1995; NRC, 2000; 2001). For pregnant heifers, weight of fetal and associated uterine tissue is deducted from EqEBW to compute energy and protein requirements for growth, but conceptus growth then is added to ME- and metabolizable protein- (**MP**) allowable ADG to compute target ADG for comparison with observed ADG.

Body Reserves

The CNCPS reserves model uses BCS rather than body weight (**BW**) to compute energy reserves because most beef and dairy producers monitor body condition score (**BCS**) to manage energy reserves (Tedeschi et al., 2006b). The CNCPS uses the reserves model developed for the NRC (2000) and adapted for dairy cattle (NRC, 2001) as described by Fox et al. (1999). However, for lactating dairy cows, the CNCPS and NRC (2001) models estimate energy and protein requirements for maintenance and pregnancy, and the amount remaining above intake is used to estimate ME- and MP-allowable milk production, respectively. The changes in BCS are not accounted for in predicting ME and MP balances. Therefore, adjustments for ME- and MP-allowable milk for changes in BCS were developed (Tedeschi et al., 2006b). The authors concluded that both models adequately predicted the first limiting ME- or MP-allowable milk after adjusting for changes in BCS.

Lactation

Energy and protein required for lactation are calculated from actual milk production and components. Metabolizable energy required for lactation is computed from milk energy with an efficiency of 64.4% (Moe, 1981). Metabolizable protein requirements are computed from milk yield and milk protein content and MP is converted to milk protein with an efficiency of 65% (NRC, 1985). Since actual milk production of beef cows usually is not measured, their lactation requirements are estimated from age of cow, time of lactation peak, expected peak milk yield based on breed and calf weaning weights, day of lactation, duration of lactation, milk fat content, milk solids not fat, and protein as described by NRC (2000).

Requirements for Amino Acids

Equations used to compute amino acid requirements were described and discussed by Fox and Tedeschi (2003). Amino acid requirements are based on (1) the amino acid composition of tissue, milk, and ruminal bacteria, recommended ratios of methionine and lysine for milk production, and (2) the efficiencies of utilization of amino acids for each physiological stage. The coefficients for the efficiency of individual amino acids use for lactation were calculated from summarized data for uptake/output of individual amino acids by the mammary gland in experiments using dairy cattle (Cant et al., 1993; Clark et al., 1977; Erickson et al., 1992; Guinard and Rulquin, 1995; Hanigan et al., 1992; Lykos and Varga, 1997; Mackle et al., 2000; Metcalf et al., 1996; Spires et al., 1975). Amino acid requirements for gain or milk production are compared to amino acids that would be supplied from the chemical and physical characteristics of the feed, the amino acid composition of the insoluble protein that escapes the rumen, the amino acid composition of bacterial protein and efficiency of use (NRC, 2000; 2001; O'Connor et al., 1993; Rulquin and Vérité, 1993).

Predicting the Supply of Energy and Nutrients

The CNCPS v. 5 has two levels of solution to accommodate the needs of different types of users. Level 1 is intended for conditions in which feeds cannot be characterized well or the

user is not knowledgeable enough to use the CNCPS rumen model with confidence. Level 2 is intended for users who have adequate information on feed composition and DM intake (**DMI**) and an understanding of how to use the level 2 rumen model (Fox et al., 2004).

Level 1 computes total digestible nutrients (**TDN**) and MP values for feeds with empirical equations (Table 12) based on those developed by Weiss et al. (1992), Weiss (1993; 1999) and NRC (2001). Once the TDN is computed at a maintenance level of intake (Eq. 1, Table 12), it is adjusted for other levels of intake (Tedeschi et al., 2005a). The MP from microbial protein is calculated as 13% of TDN times 64% efficiency, which assumes microbial protein is 64% true protein; this is the same equation as is used in level 1 of the beef NRC (2000). The TDN discounted for level of DMI is used by NRC (2001) and CNCPS level 1, whereas NRC (2000) level 1 uses undiscounted TDN. Undegraded protein from feed is calculated from CP intake and undegraded CP (%UIP) and has an intestinal digestibility of 80%.

In level 2 of the CNCPS, ruminally available TDN and MP are derived mechanistically from digestion (**Kd**) and passage (**Kp**) rates (Russell et al., 1992; Sniffen et al., 1992) using the simple relationship $Kd/(Kd + Kp)$. Feeds not digested in the rumen pass undegraded to the intestines where it may or may not undergo further digestion. Each feed component (neutral detergent fiber (**NDF**), crude protein (**CP**), soluble CP, NDF insoluble protein (**NDIP**), and acid detergent fiber (**ADF**) insoluble protein (**ADIP**), lignin, fat, and ash) is assigned its own Kd, and this value can be modified to accommodate variations in feed processing. The Kp values depend on factors such as intake, particle size, lignification and the ratio of forage to concentrate. Sugars usually have a high Kd (> 60%) and are almost completely digested in the rumen, but many carbohydrates and proteins (e.g. B fraction components) have a low Kd and are not completely digested by ruminal microorganisms. This system of calculating ruminal disappearance assumes that: (1) Kd rate is a simple first order rate, (2) each feed component operates as a single pool, (3) ruminal microorganisms are always in excess, (4) there is no lag-time before the initiation of fermentation, and (5) Kp depends only on intake and physically effective NDF.

The accuracy of predicting ruminal digestibility of feeds depends on accurate determinations of passage rates. Seo et al. (2006a) developed empirical equations using external markers and random coefficient models to identify key independent predictor variables for passage rates of forage, concentrate, and liquid. The equations developed were:

$$Kp \text{ forage} = (2.365 + 0.0214 \times FpBW + 0.0734 \times CpBW + 0.069 \times FDMI) / 100$$

$$Kp \text{ concentrate} = (1.169 + 0.1375 \times FpBW + 0.1721 \times CpBW) / 100$$

$$Kp \text{ liquid} = (4.524 + 0.0223 \times FpBW + 0.2046 \times CpBW + 0.344 \times FDMI) / 100$$

Where Kp is the passage rate, h⁻¹; FpBW the forage DMI as a proportion of BW, g/kg; CpBW the concentrate DMI as a proportion of BW and FDMI is the forage DMI, kg.

These Kp equations for forages, concentrates, and liquid explained 87%, 95% and 94%, respectively of the variation in passage rates in the database used in equation development after adjustment for random study effect (Seo et al., 2006a). Several attempts have been done to derive empirical equations to determine passage rate of solids and liquids (Fox et al., 2004; Lescoat and Sauvant, 1995; NRC, 2000; 2001). These studies have similarly concluded that empirical models have limitations in predicting passage rate and a maximum of 40% of the variation can be explained (Seo et al., 2006a); therefore, other types of modeling approaches are needed (Ellis et

al., 1994). Seo et al. (2007a; 2007b) have developed a mechanistic, dynamic model to predict solid and liquid passage rates based on physiological and anatomical description of the rumen, animal information, and physicochemical characteristics of the feeds. They concluded the model was able to describe the factors that affect the dynamics of liquid and solids flow out of the rumen in dairy cattle. More work is needed for beef cattle and other ruminant species.

Physically Effective Neutral Detergent Fiber (peNDF)

When cattle are fed diets deficient in fiber and rich in grain, ruminal pH can decline significantly. Davis et al. (1964) noted that cows fed grain-based diets produced less saliva than those fed forage, and other workers have shown that they often have a slower dilution rate (Allen, 1997). If the fluid dilution rate is rapid, volatile fatty acids (VFA) can pass out of the rumen in the fluid phase and be absorbed from the abomasum where the pH is lower and passive diffusion is more rapid, but this avenue of VFA removal is depressed in animals fed grain-based rations (Russell, 2002). The effectiveness of the NDF in stimulating saliva flow and ruminal fluid dilution rate is manifested in its ability to stimulate chewing, rumination and rumen motility. The CNCPS currently uses the NDF content of the ration and the physical properties of the NDF to predict ruminal pH and the impact of acidic pH on ruminal fermentation (Table 14). The peNDF is the percent of the NDF that is retained on a 1.18 mm screen as described by Mertens (1997).

Zebeli et al. (2006) compared peNDF values retained on a 1.18 mm screen or 19- and 8-mm Penn State Particle Separator screens (Kononoff et al., 2003; Lammers et al., 1996). The $\text{peNDF}_{>1.18}$ indicated the requirement for pef in high-producing dairy cows fed TMR is about 19% of DM. This value is very close to the current value adopted by the CNCPS of 20% (Fox et al., 2004). They concluded that peNDF measured using the 1.18 mm sieve provided a satisfactory measure of mean ruminal pH (r^2 of 0.67) and NDF digestibility (r^2 of 0.56), poorly correlated with daily chewing (r^2 of 0.17), and rumination (r^2 of 0.24). They found that milk parameters (fat and protein) had even lower sensitivity to $\text{peNDF}_{1.18}$.

Recent evaluations using the Z-Box method to evaluate the physically effective fiber (pef) (Cotanch and Grant, 2006; Grant and Cotanch, 2005) indicated the following procedures would be necessary three 50-g sample size, different sieves depending on type of forage (3.18 mm for corn silage, 4.76 mm for haycrop silage, and 2.38 or 3.18 mm for total mixed ration), vigorous vertical shaking (20-25 cm up/down and 50 shakes), and compute pef as the cumulative retained grams divided by the cumulative initial grams.

Feed Characterization

In level 2 of the CNCPS 5.0, carbohydrates are defined as fiber carbohydrates (FC) or non-fiber carbohydrates (NFC). The FC is equal to the NDF and NFC is total DM minus NDF (adjusted for NDIP), CP, fat, and ash. Carbohydrates (CHO) are further categorized into A, B1, B2 and C fractions. The CHO A fraction is a very rapidly fermented, water soluble pool that is largely composed of sugars although it also contains organic acids and short oligosaccharides. The CHO B1 fraction, with a slower Kd than CHO A, is primarily starch and pectin. The CHO B2 pool is composed of available NDF. The CHO C pool is an indigestible fraction, and it is computed as $\text{NDF} \times \text{Lignin} \times 2.4$ (% DM). The assumption that the CHO A fraction is largely sugar is an oversimplification, and does not account for the fact that forages and silages can have

a significant amount of organic acids. Organic acids are not utilized as efficiently for microbial growth as sugars (Doane et al., 1997a; Molina, 2002).

Recently, Lanzas et al. (2007b) indicated several limitations of this scheme have become apparent because not all of these fractions are precisely defined or analyzed. It does not account for all the variability observed in NFC digestibility when various processing treatments are applied (Offner and Sauvant, 2004). In addition, the description and ruminal digestibility of the fraction containing starch and soluble fiber were highlighted as an area that needed further improvement to accurately predict ruminal VFA production and pH (Pitt et al., 1996). Figure 1 depicts the carbohydrate fractionation based on Fox et al. (2004) and Lanzas et al. (2007b).

Figure 1. Comparison of carbohydrate fractionations.

Lanzas et al. (2007b) reported this new carbohydrate fractionation scheme predicts a lower microbial CP production. The Predicted ruminal NFC digestibility remained similar. They concluded the new carbohydrate fractionation scheme provides a more appropriate feed description to account for variation in changes in silage quality and diet NFC composition.

Protein fractions (as a percentage of the CP) are described using a scheme similar to that used for carbohydrates. Protein fraction A (PROT A) of CP is NPN that enters the ruminal ammonia pool directly. PROT B1 is true protein that has a rapid Kd and is nearly completely degraded in the rumen. The PROT C fraction is acid detergent insoluble protein (**ADIP**) and is assumed to be unavailable. The PROT B3 or slowly degraded protein fraction is determined by subtracting the value determined for ADIP from the value determined for neutral detergent insoluble protein (**NDIP**). The PROT B2 fraction, which is partly degraded in the rumen, is then estimated as the difference between CP and the sum of soluble + B3 + C where the soluble

protein equals A + B1. Intestinal digestibility of the amino acids is assumed to be 100% for B1 and B2 and 80% for B3 protein pools, as described by O'Connor et al. (1993).

The assumption that PROT A fraction protein is NPN that enters the ruminal ammonia pool directly can be a problem with high quality alfalfa silages (Aquino et al., 2003; Makoni et al., 1997; Ross and Van Amburgh, 2003). As much as two-thirds of the NPN can be peptides and amino acids that are forms of nitrogen that stimulate the growth of NFC bacteria to a greater extent than ammonia (see microbial growth below). If the alfalfa silage is high quality and has been ensiled properly, as much as 2/3 of the NPN should be included in the PROT B1 fraction.

Lanzas et al. (2007c) conducted a sensitivity analysis of the protein fractionation schemes of the CNCPS 5.0 (Fox et al., 2004) and found out that The rumen-undegradable protein (RUP) flows were sensitive to ruminal degradation rates of the B2 protein fraction for protein supplements, energy concentrates, and forages. Absorbed Met and Lys flows were also sensitive to intestinal digestibility of RUP. The CNCPS model was sensitive to acid detergent insoluble crude protein (ADICP or ADIN) and its assumption of complete unavailability. Neither the intestinal digestibility of the RUP nor the protein degradation rates are routinely measured. The authors suggested (1) a different protein fractionation was needed to account for their variability and (2) better methods for measuring pool sizes and ruminal digestion rates for protein fractionation systems was required. Based on these recommendations Lanzas (2006) proposed a different protein fractionation as shown in Figure 2.

Estimates of Kd values for common feeds were developed (Sniffen et al., 1992) and have been expanded to over 150 feedstuffs (Fox et al., 2003; Tedeschi et al., 2002c; Tedeschi et al., 2001). The Kd values were in most cases extrapolated from in vitro studies or in situ experiments. Protein Kd degradation rates have also been estimated from enzymatic studies. Many of the values in the original feed library (Sniffen et al., 1992) have been updated for the current feed library (Fox et al., 2003), based on recent studies with the gas production system (Molina, 2002; Pell et al., 1998; Pell and Schofield, 1993; Schofield, 2000; Schofield and Pell, 1995a; b; Schofield et al., 1994; Stefanon et al., 1996), including the evaluations of Doane et al. (1997b), Chen et al. (1999), Juarez Lagunes et al. (1999), Cerosaletti (1998), Kolver et al. (1998), Tedeschi et al. (2002c) and Lanzas (2007a). The use of the terms A, B and C to describe feed carbohydrate and proteins is a convenient method of classification, but it does not circumvent the need for independent measurements of Kd. Some organic acids have a slow Kd and can also escape the rumen (Doane et al., 1997a; Molina, 2002). Recent modifications to the rate of degradation of carbohydrate and protein fractions proposed in Figure 1 and 2 and methods to measure them are discussed elsewhere (Lanzas, 2006; Lanzas et al., 2007b; Lanzas et al., 2007c).

Microbial Growth

In level 2 of the CNCPS, ruminal microorganisms are categorized as bacteria that ferment FC and NFC (NRC, 2000; Russell et al., 1992). Generally, FC bacteria degrade cellulose and hemicellulose, grow more slowly, and utilize ammonia as their primary nitrogen source for microbial protein synthesis. The NFC bacteria that utilize starch, pectin, and sugars usually grow more rapidly than the FC bacteria and can utilize ammonia or amino acids as nitrogen sources. The rate of NFC and FC bacterial growth (μ) is dictated by the amount of carbohydrate that is digested in the rumen and the rate of carbohydrate digestion (Kd) so long as adequate nitrogen sources and other essential nutrients are available. The CNCPS assumes that bacterial growth

rate (μ) is proportional to K_d , and this assumption is, in turn, based on the idea that the rumen operates as a substrate-limited, enzyme (microbial mass) excess system.

The CNCPS assumes that NFC and FC bacteria both have a theoretical maximum growth yield (Y_g) of 50 g cells per 100 g of carbohydrate fermented, a value that is identical to that reported by Isaacson et al. (1975) for continuous cultures of mixed ruminal bacteria. The CNCPS uses the double reciprocal plot of Pirt (1965) to correct the yield (Y , g bacteria/g fermented carbohydrate) for maintenance energy (k_m , g carbohydrate/g bacteria/h): $1/Y = k_m/k_d + 1/Y_g$. The CNCPS assigns different maintenance coefficients to the FC and NFC bacteria (0.05 and 0.15 g of carbohydrate/g of bacteria/h, respectively). The maximum yield (Y_g , g bacteria/g carbohydrate) is assumed to be 0.4 for both FC and NFC bacteria. Figure 3 depicts a relationship between FC and NFC bacteria yield and rate of degradation (k_d) of carbohydrate. The FC bacteria would have a greater yield at the same k_d due to the lower maintenance requirement. Nonetheless, in practical conditions, usually the NFC k_d is smaller than the FC k_d , resulting in a greater yield for NFC bacteria than FC bacteria.

Figure 2. Comparison of protein fractionations.

It has long been recognized that bacteria must devote a fraction of their ATP to non-growth functions, and this expenditure is analogous to the maintenance energy of animal cells (Russell and Wallace, 1997). Because bacteria must use energy to maintain cell integrity, yield declines particularly at slow growth rates. In recent years, it has become apparent that most bacteria have another avenue of non-growth energy dissipation that is distinctly different from maintenance energy, and this dissipation has been called "energy spilling" (Russell and Cook, 1995). The impact of maintenance on yield is most apparent when energy is limiting, but bacteria are more apt to spill energy when it is in excess. The energy status of bacteria can be envisioned as a balance of anabolic and catabolic rates, and most bacteria grow twice as fast if they are

supplied with preformed amino acids. The CNCPS does not have an energy spilling function per se, but it has a peptide stimulation algorithm that increases yield by as much as 18% if peptides and amino acids are available (Russell and Sniffen, 1984).

The rumen sub-model was constructed before the isolation and characterization of obligate amino acid (OAA) fermenting bacteria (Paster et al., 1993). These bacteria ferment amino acids, but not carbohydrates, and can contribute significantly to the ammonia production of cattle fed forage (Rychlik and Russell, 2000; Yang and Russell, 1993). The OAA fermenting bacteria violate the assumption that all ruminal bacteria need carbohydrates (or possibly organic acids) in order to grow, but they have very low growth yields and contribute little bacterial protein to the animal. The OAA fermenting bacteria are currently part of the NFC bacterial pool, a categorization that is not ideal. They are more sensitive to ionophores than true NFC bacteria that can also deaminate amino acids.

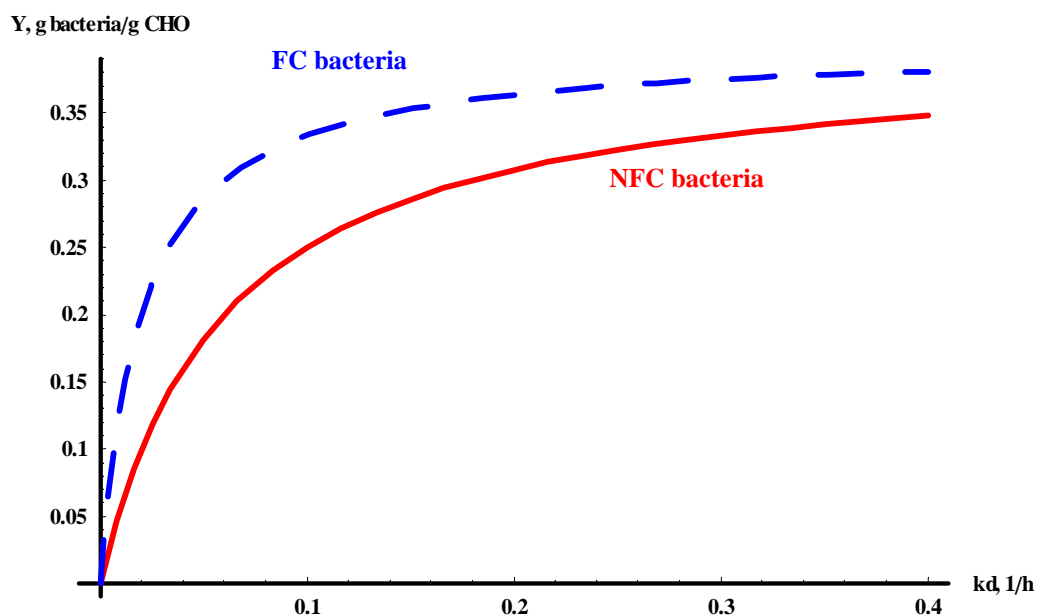


Figure 3. Relationship between bacteria yield (g bacteria/g fermented carbohydrate) of fiber-fermenting (FC, dashed line) and non-fiber-fermenting (NFC, solid line) bacteria and rate of degradation (kd, 1/h) of carbohydrates.

The CNCPS 4.0 and subsequent releases account for the effects of ruminal nitrogen deficiency (Tedeschi et al., 2000b; Tedeschi et al., 2000c). Fiber digestion rate and microbial yield are reduced proportionally to the ammonia deficiency. If the rumen N balance is negative, microbial yield and fiber escaping the rumen are adjusted as follows: (1) the sum of rumen available peptides and ammonia is divided by microbial N content to determine the N allowable microbial growth, (2) this value is subtracted from the energy allowable total microbial growth to obtain the reduction in yield, (3) this yield reduction is allocated between FC and NFC bacteria based on their proportions in the energy allowable total bacterial growth, and (4) the loss in fiber digested is computed as the loss in FC yield divided by its growth rate, which is added to the FC escaping the rumen. These calculations do not account for the loss of ruminally degraded dietary N that is not captured by the rumen bacteria. In the NRC (2001) this inefficiency is addressed by

assuming bacteria capture 85% of ruminally-degraded N; however, they do not account for N supplied to the rumen from recycling. In the current version of the CNCPS, the NRC (1985) equation is used to estimate recycled N added to the rumen supply of N to account for the effects of this inefficiency. Further improvements in accuracy of predicting recycled N are needed to predict N needed in the diet to meet microbial N requirements. Lanzas (2006) recently developed a mechanistic model for this purpose.

Intestinal Digestion

The CNCPS uses experimentally measured digestibility coefficients to predict intestinal digestibilities and fecal losses (Knowlton et al., 1998; Sniffen et al., 1992). The accuracy of these estimates depends on how well ruminally undegraded carbohydrate and protein fractions are predicted. For most feeds, over 75% of total tract digestion occurs in the rumen. The small intestine is assumed to lack the enzymes to digest cellulose and hemicellulose, but the colon has fibrolytic bacteria. To account for hindgut fiber digestion, intestinal digestion of CHO B2 is assigned a digestibility of 20%, based on Sniffen et al. (1992). Intestinal CHO B1 digestibility depends on type of grain, degree and type of processing, and level of intake above maintenance (Knowlton et al., 1998; Sniffen et al., 1992).

Adequacy of the CNCPS Model in Predicting Milk Production

For a model to be useful on farms, the combination of model equations must accurately predict animal responses. Tedeschi (2006) discussed several techniques for evaluating model predictions, which were used in evaluations of the CNCPS model with data from several countries. In the studies of Kolver et al. (1998), the CNCPS underpredicted ME allowable milk by 2.5% and 6.8% in TMR and pasture fed groups, respectively. In a study on 10 dairy farms in the UK, ADAS (1998) reported that the CNCPS predicted milk yield when either ME or MP was limiting to within 2.5% and 5%, respectively, using actual DMI; these differences were not statistically different from actual milk yields. The CNCPS intake model predicted DMI to within 2% of actual values. Fox et al. (2004) evaluated the ability of the CNCPS to predict the performance of individual animals. When nearly all of the CNCPS inputs were measured (Ruiz et al., 2002; Stone, 1996), the CNCPS accounted for 88% of the variation in milk production with a mean bias of 1.8 kg d⁻¹ or 5.5%. When energy was first limiting for high producing cows, the r² was 76% and the mean bias was 3 kg d⁻¹ (8% underprediction bias). If protein was first limiting, the r² was 84% and the mean bias was -0.2 kg d⁻¹ (1.1% overprediction bias; Table 18). When the CNCPS reserves model (Tedeschi et al., 2006b) was used to adjust supply of energy to account for changes in BCS, the model accounted for 90% of the variation in milk production with a mean bias of 1.3%.

Similarly, an experiment conducted at the Brazilian Agricultural Research Corporation (EMBRAPA in Coronel Pacheco, MG, Brazil) using lactating Holstein cows (Fernando C. F. Lopes, unpublished) was used to test the adequacy of the CNCPSv6 for tropical conditions. In this experiment, fourteen lactating Holstein cows in late lactation were maintained in free-stall and individual DMI was recorded with Calan gates. Cows were milked twice daily (0600 and 1400 h) and fed corn silage and mineral salt *ad libitum*, and concentrate (4.08 to 8.16 kg/d) according to the milk production level. Milk production and composition data were collected

daily for five consecutive days, and analyzed for fat, protein, and total solids. Initial and final full BW and BCS were recorded. Feed samples were collected, dried using forced air ventilation system at 55°C for 72 h, ground using Willey-type mill to pass through a 1-mm screen, and analyzed for DM, ash, nitrogen, NDF, ADF, lignin, ether extract, and in vitro digestibility of DM. Figure 4 depicts the relationship between observed and model-predicted milk production after an adjustment for changes in BCS. The model predictions had low mean bias (3.2%), great CCC (0.9; due to a high accuracy, C_b of 0.98), and low MSEP (4.58 kg/d). The precision of the predictions was high (r^2 of 0.85).

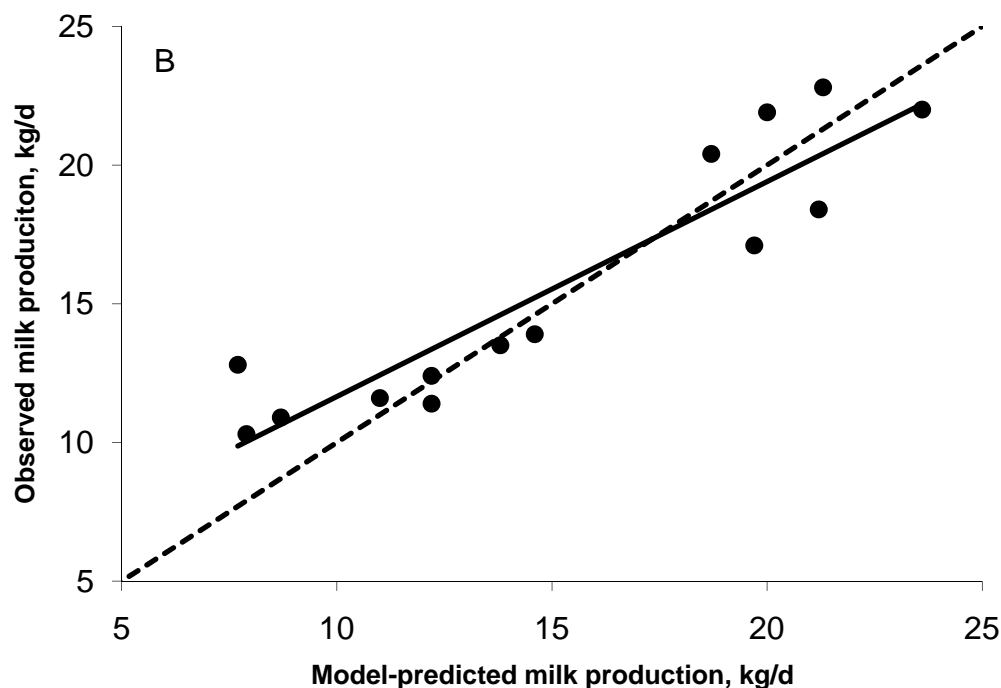


Figure 4. Relationship between observed and model-predicted first-limiting metabolizable energy- or metabolizable protein-allowable milk production of a tropical experiment with lactating Holstein cow with adjustment for changes in body condition score.

Future Research

The next generations of mathematical nutrition models have to improve their accuracy in formulating diets, including energy, protein (i.e. N), and macro- and micro minerals; and provide means for site-specific optimization. Optimization is an important tool in assisting feed and nutrient management; therefore, contributing to improved accuracy of implementing the precision and phase feeding techniques. The foremost goal of model optimization is the ability to provide producers, consultants, and researchers with tools to assist in complex problem solving and decision-making processes.

The rumen plays an important role in transforming feed components before the host animal can digest and absorb the dietary nutrients; therefore, accounting for the processes inside the rumen is crucial to meet animal requirements and environmental guidelines. Ruminal pH affects fiber digestibility and microbial CP production dramatically. It is well documented that factors other than fiber particle size may have a more systematic and predictive role in determining ruminal pH. Such factors include starch processing (Yang et al., 2001), water intake, and saliva flow that dictate the amount of ruminal VFA that is washed out of the rumen (Allen, 1997). Improving VFA models will allow consultants and nutritionists to more accurately predict the energy derived from a diet and maximize fiber digestibility.

Furthermore, the prediction of methane (CH_4) and nitrous oxide (N_2O) production by cattle is important due to the greenhouse effect of these gases. In the rumen, H^+ is produced during the anaerobic fermentation of glucose. This H^+ can be used during the synthesis of VFA and microbial organic matter, the preferred pathways environmentally-speaking. But, the excess of hydrogen from NADH is eliminated primarily by the formation of methane by methanogenic bacteria, a non-preferred pathway.

It is critical to accurately predict the route (fecal or urinary) and form (e.g. potentially volatile ammonia) of N excretion. Several approaches have been used to compute metabolic fecal N, but the most common is the regression of apparently digested N on N intake in which the slope indicates the true digestibility of N and the intercept indicates the metabolic fecal N. A more mechanistic hindgut model is required to accurately predict the fermentative processes occurring in the large intestine, including the production and absorption of VFA, the capture of N by hindgut bacteria, the recycling of urea and the absorption of ammonia from the hindgut.

Concurrent to the need of more comprehensive mathematical nutrition models, simplicity of inputs and user-friendly models are needed. Several problems have been identified that restrict the use of decision support systems, including their complexity and the number of inputs and information needed for their execution (McCown, 2002). To offset the challenges of high data requirements and entry, it is necessary to develop input structures that can be used to streamline data inputs. Such techniques (e.g. neural network) are available and have to be incorporated into nutrition models.

Conclusion

Mathematical modeling in nutrition is important because the human mind is able to formulate concepts and hypothesis but lack the ability to track quantitative relationships of complex, nonlinear, and dynamic systems. It provides us with a tool to analyze huge amounts of data and information about nutrition and metabolism and systematically build representations of the real system to conduct virtual and controlled experiments. Through simulation, we can foster our intuition and improve our mental simulation capability. These models can be used on farms to integrate and apply the accumulated scientific knowledge of animal requirements, rumen functions, and digestion and metabolism to further improve feeding systems, decrease environmental pollution, and minimize use of resources to assure the goal of a sustainable agriculture.

Literature Cited

- ADAS. 1998. On farm validation of the Cornell Net Carbohydrate and Protein System. ADAS Bridgets Research Centre Research Report. Martyr Worthy, Winchester, Hampshire, England. p.
- Ainslie, S. J., D. G. Fox, T. C. Perry, D. J. Ketchen, and M. C. Barry. 1993. Predicting amino acid adequacy of diets fed to Holstein steers. *J. Anim. Sci.* 71:1312-1319.
- Allen, M. S. 1997. Relationship between fermentation acid production in the rumen and the requirement for physical effective fiber. *J. Dairy Sci.* 80(7):1447-1462.
- Aquino, D. L., L. O. Tedeschi, C. Lanzas, S. S. Lee, and J. B. Russell. 2003. Evaluation of CNCPS predictions of milk production of dairy cows fed alfalfa silage. Pages 137-150 in Proceedings of Cornell Nutrition Conference for Feed Manufacturers, Syracuse, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Bell, A. W., R. Slepatis, and R. A. Enrhardt. 1995. Growth and accretion of energy and protein in the gravid uterus during late pregnancy in Holstein cows. *J. Dairy Sci.* 78:1954-1961.
- Cant, J. P., E. J. DePeters, and R. L. Baldwin. 1993. Mammary amino acid utilization in dairy cows fed fat and its relationship to milk protein depression. *J. Dairy Sci.* 76:762-774.
- Cerosaletti, P. E. 1998. Application of the Cornell net carbohydrate and protein system on a pasture-based dairy farm. M.S. Thesis, Cornell University, Ithaca, NY.
- Chen, Y. K., A. N. Pell, L. E. Chase, and P. Schofield. 1999. Rate and extent of digestion of the ethanol-soluble and neutral detergent-insoluble fractions of corn grain. *J. Anim. Sci.* 77:3077-3083.
- Clark, J. H., H. R. Spires, R. G. Derrig, and M. R. Bennink. 1977. Milk production, nitrogen utilization, and glucose synthesis in lactating cows infused postruminally with sodium caseinate and glucose. *J. Nutr.* 107:631-644.
- Cotanch, K. W. and R. J. Grant. 2006. Measuring physically effective fiber on-farm to predict cow response. Pages 151-160 in Proceedings of Cornell Nutrition Conference for Feed Manufacturers, Syracuse, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Davis, C. L., R. E. Brown, and D. C. Beitz. 1964. Effect of feeding high-grain restricted-roughage rations with and without bicarbonates on the fat content of milk produced and proportions of volatile fatty acids. *J. Dairy Sci.* 47:1217-1226.
- Doane, P. H., A. N. Pell, and P. Schofield. 1997a. The effect of preservation method on the neutral detergent soluble fraction of forages. *J. Anim. Sci.* 75(4):1140-1148.
- Doane, P. H., P. Schofield, and A. N. Pell. 1997b. Neutral detergent fiber disappearance and gas and volatile fatty acids production during the in vitro fermentation of six forages. *J. Anim. Sci.* 75:3342-3352.
- Ellis, W. C., J. H. Matis, T. M. Hill, and M. R. Murphy. 1994. Methodology for estimating digestion and passage kinetics of forages. Pages 682-756 in Forage quality, evaluation, and utilization. G. C. Fahey Jr., M. Collins, D. R. Mertens and L. E. Moser, ed. American Society of Agronomy, Madison, WI.
- Erickson, P. S., M. R. Murphy, and J. H. Clark. 1992. Supplementation of dairy cow diets with calcium salts of long-chain fatty acids and nicotinic acid in early lactation. *J. Dairy Sci.* 75:1078-1089.
- Fox, D. G., M. C. Barry, R. E. Pitt, D. K. Roseler, and W. C. Stone. 1995. Application of the Cornell net carbohydrate and protein model for cattle consuming forage. *J. Anim. Sci.* 73:267-277.

- Fox, D. G., C. J. Sniffen, J. D. O'Connor, J. B. Russell, and P. J. Van Soest. 1992. A net carbohydrate and protein system for evaluating cattle diets: III. Cattle requirements and diet adequacy. *J. Anim. Sci.* 70:3578-3596.
- Fox, D. G. and L. O. Tedeschi. 2003. Predicting dietary amino acid adequacy for ruminants. Pages 389-410 in *Amino Acids in Animal Nutrition*. J. P. F. D'Mello, ed. CABI Publishing, Cambridge, MA.
- Fox, D. G., L. O. Tedeschi, T. P. Tylutki, J. B. Russell, M. E. Van Amburgh, L. E. Chase, A. N. Pell, and T. R. Overton. 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. *Anim. Feed Sci. Technol.* 112:29-78.
- Fox, D. G. and T. P. Tylutki. 1998. Accounting for the effects of environment on the nutrient requirements of dairy cattle. *J. Dairy Sci.* 81:3085-3095.
- Fox, D. G., T. P. Tylutki, G. L. Albrecht, P. E. Cerasoletti, and L. O. Tedeschi. 2002. Environmental protection and the Cornell University nutrient management planning system: Future perspectives. Pages 79-98 in *Proceedings of Cornell Nutrition Conference for Feed Manufacturers*, Syracuse, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Fox, D. G., T. P. Tylutki, L. O. Tedeschi, and P. E. Cerasoletti. 2006. Using a nutrition model to implement the NRCS feed management standard to reduce the environmental impact of a concentrated cattle feeding operation. Page 15 p. in *Visions for Animal Agriculture and the Environment*, Kansas City, MO. Department of Animal Science at Iowa State University.
- Fox, D. G., T. P. Tylutki, L. O. Tedeschi, M. E. Van Amburgh, L. E. Chase, A. N. Pell, T. R. Overton, and J. B. Russell. 2003. The Net Carbohydrate and Protein System for evaluating herd nutrition and nutrient excretion: Model documentation. Mimeo. No. 213. Animal Science Dept., Cornell University, Ithaca, NY. p.
- Fox, D. G., M. E. Van Amburgh, and T. P. Tylutki. 1999. Predicting requirements for growth, maturity, and body reserves in dairy cattle. *J. Dairy Sci.* 82:1968-1977.
- Gill, M., D. E. Beever, and J. France. 1989. Biochemical bases needed for the mathematical representation of whole animal metabolism. *Nutrition Abstract Review.* 2:181-200.
- Grant, R. J. and K. W. Cotanch. 2005. Physically effective fiber for dairy cows: Current perspectives. Pages 61-70 in *Proceedings of Cornell Nutrition Conference for Feed Manufacturers*, Syracuse, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Gregory, K. E., L. V. Cundiff, and R. M. Koch. 1992. Composite breeds to use in heterosis and breed differences to improve efficiency of beef production. U.S. Department of Agriculture, Washington, DC. p.
- Guinard, J. and J. Rulquin. 1995. Effects of graded amounts of duodenal infusions of methionine on the mammary uptake of major milk precursors in dairy cows. *J. Dairy Sci.* 78:2196-2207.
- Hanigan, M. D., C. C. Calvert, E. J. DePeters, B. L. Reis, and R. L. Baldwin. 1992. Kinetics of amino acid extraction by lactating mammary glands in control and sometribove-treated Holstein cows. *J. Dairy Sci.* 75:161-173.
- Isaacson, H. R., F. C. Hinds, M. P. Bryant, and F. N. Owens. 1975. Efficiency of energy utilization by mixed rumen bacteria in continuous culture. *J. Dairy Sci.* 58:1645-1659.
- Juarez Lagunes, F. I., D. G. Fox, R. W. Blake, and A. N. Pell. 1999. Evaluation of tropical grasses for milk production by dual-purpose cows in tropical Mexico. *J. Dairy Sci.* 82:2136-2145.

- Klausner, S. D., D. G. Fox, C. N. Rasmussen, R. E. Pitt, T. P. Tylutki, P. E. Wright, L. E. Chase, and W. C. Stone. 1998. Improving dairy farm sustainability I: An approach to animal and crop nutrient management planning. *Journal of Production Agriculture*. 11(2):225-233.
- Knowlton, K. F., B. P. Glenn, and R. A. Erdman. 1998. Performance, ruminal fermentation, and site of starch digestion in early lactation cows fed corn grain harvested and processed differently. *J. Dairy Sci.* 81:1972-1984.
- Kolver, E. S., L. D. Muller, M. C. Barry, and J. W. Penno. 1998. Evaluation and application of the Cornell Net Carbohydrate and protein system for dairy cows fed diets based on pasture. *J. Dairy Sci.* 81:2029-2039.
- Kononoff, P. J., A. J. Heinrichs, and D. R. Buckmaster. 2003. Modification of the Penn State forage and total mixed ration particle separator and the effects of moisture content on its measurements. *J. Dairy Sci.* 86:1858-1863.
- Lammers, B. P., D. R. Buckmaster, and A. J. Heinrichs. 1996. A simple method for the analysis of particle sizes of forage and total mixed rations. *J. Dairy Sci.* 79:922-928.
- Lanzas, C. 2006. Models to Predict Ruminal Carbohydrate and Nitrogen Supply and Nitrogen Excretion in Cattle. Ph.D. Dissertation, Cornell University, Ithaca, NY.
- Lanzas, C., D. G. Fox, and A. N. Pell. 2007a. Digestion kinetics of dried cereal grains. *Anim. Feed Sci. Technol.*:(In press).
- Lanzas, C., C. J. Sniffen, S. Seo, L. O. Tedeschi, and D. G. Fox. 2007b. A feed carbohydrate fractionation scheme for formulating rations for ruminants. *Anim. Feed Sci. Technol.*:(In press).
- Lanzas, C., L. O. Tedeschi, S. Seo, and D. G. Fox. 2007c. Evaluation of protein fractionation systems used in formulating rations for dairy cattle. *J. Dairy Sci.* 90:507-521.
- Lescoat, P. and D. Sauvant. 1995. Development of a mechanistic model for rumen digestion validated using the duodenal flux of amino acids. *Reproduction, Nutrition, Development*. 35:45-70.
- Lykos, T. and G. A. Varga. 1997. Varying degradation rates of total nonstructural carbohydrates: Effects on nutrient uptake and utilization by the mammary gland in high producing dairy cows. *J. Dairy Sci.* 80:3356-3367.
- Mackle, T. R., D. A. Dwyer, K. L. Ingvarsen, P. Y. Chouinard, D. A. Ross, and D. E. Bauman. 2000. Effects of insulin and postruminal supply of protein on use of amino acids by the mammary gland for milk protein synthesis. *J. Dairy Sci.* 83:93-105.
- Makoni, N. F., G. A. Broderick, and R. E. Muck. 1997. Effect of modified atmospheres on proteolysis and fermentation of ensiled alfalfa. *J. Dairy Sci.* 80:912-920.
- McCown, R. L. 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agric. Syst.* 74:179-220.
- Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. *J. Dairy Sci.* 80:1463-1481.
- Metcalf, J. A., D. Wray-Cahen, E. E. Chettle, J. D. Sutton, D. E. Beaver, L. A. Crompton, J. C. MacRae, B. J. Bequette, and F. R. C. Backwell. 1996. The effect of dietary crude protein as protected soybean meal on mammary metabolism in the lactating dairy cow. *J. Dairy Sci.* 79:603-611.
- Moe, P. W. 1981. Energy metabolism of dairy cattle. *J. Dairy Sci.* 64:1120-1139.
- Molina, D. O. 2002. Prediction in intake of lactating cows in the tropics and of the energy value of organic acids. Ph.D. Dissertation, Cornell University, Ithaca, NY.

- NRC. 1984. Nutrient Requirements of Beef Cattle (6th ed.). National Academy Press, Washington, DC.
- NRC. 1985. Ruminant Nitrogen Usage. National Academy Press, Washington, DC.
- NRC. 1989. Nutrient Requirements of Dairy Cattle (6th ed.). National Academy Press, Washington, DC.
- NRC. 2000. Nutrient Requirements of Beef Cattle (updated 7th ed.). National Academy Press, Washington, DC.
- NRC. 2001. Nutrient Requirements of Dairy Cattle (7th ed.). National Academy Press, Washington, DC.
- O'Connor, J. D., C. J. Sniffen, D. G. Fox, and W. Chalupa. 1993. A net carbohydrate and protein system for evaluating cattle diets: IV. Predicting amino acid adequacy. *J. Anim. Sci.* 71:1298-1311.
- Offner, A. and D. Sauvant. 2004. Comparative evaluation of the Molly, CNCPS, and LES rumen models. *Anim. Feed Sci. Technol.* 112:107-130.
- Paster, B., J. B. Russell, C. M. J. Yang, J. M. Chow, C. R. Woese, and R. Tanner. 1993. Phylogeny of ammonia-producing ruminal bacteria, *Peptostreptococcus anaerobius*, *Clostridium sticklandii* and *Clostridium aminophilum* sp. nov. *Int. J. Sys. Bacteriol.* 43:107-110.
- Pell, A. N., R. E. Pitt, P. H. Doane, and P. Schofield. 1998. The development, use and application of the gas production technique at Cornell University, USA. In *in vitro* Techniques for Measuring Nutrient Supply to Ruminants. No. 22. British Soc. Anim. Sci., Penicuik, U.K. p.
- Pell, A. N. and P. Schofield. 1993. Computerized monitoring of gas production to measure forage digestion *in vitro*. *J. Dairy Sci.* 76:1063-1073.
- Pirt, S. J. 1965. The maintenance energy of bacteria in growing cultures. *Proceedings of the Royal Society of London, Ser. B.* 163:224-231.
- Pitt, R. E., J. S. Van Kessel, D. G. Fox, A. N. Pell, M. C. Barry, and P. J. Van Soest. 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. *J. Anim. Sci.* 74(1):226-244.
- Ross, D. E. and M. E. Van Amburgh. 2003. Amino acid composition of ruminant feeds and feed fractions. *J. Anim. Sci.* 81 (Suppl. 1):217 (Abstr.).
- Ruiz, R., L. O. Tedeschi, J. C. Marini, D. G. Fox, A. N. Pell, G. Jarvis, and J. B. Russell. 2002. The effect of a ruminal nitrogen (N) deficiency in dairy cows: evaluation of the Cornell net carbohydrate and protein system ruminal N deficiency adjustment. *J. Dairy Sci.* 85:2986-2999.
- Rulquin, H. and R. Vérité. 1993. Amino acid nutrition of dairy cows: productive effects and animal requirements. Pages 55-77 in *Recent Advances in Animal Nutrition*. P. C. Garnsworthy and D. J. A. Cole, ed. Nottingham University Press.
- Russell, B. J. 2002. *Rumen Microbiology and Its Role in Ruminant Nutrition*, Ithaca, NY.
- Russell, J. B. and G. M. Cook. 1995. Energetics of bacterial growth: balance of anabolic and catabolic reactions. *Microbiological Reviews.* 59(1):48-62.
- Russell, J. B., J. D. O'Connor, D. G. Fox, P. J. Van Soest, and C. J. Sniffen. 1992. A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. *J. Anim. Sci.* 70:3551-3561.
- Russell, J. B. and C. J. Sniffen. 1984. Effect of carbon-4 and carbon-5 volatile fatty acids on growth of mixed rumen bacteria *in vitro*. *J. Dairy Sci.* 67:987-994.

- Russell, J. B. and R. J. Wallace. 1997. Energy yielding and consuming reactions. Pages 246-282 in *The Rumen Microbial Ecosystem*. P. N. H. a. C. S. Stewart, ed. Blackie Academic & Professional, London, England.
- Rychlik, J. L. and J. B. Russell. 2000. Mathematical estimations of hyper-ammonia producing ruminal bacteria and evidence for bacterial antagonism that decreases ruminal ammonia production. *FEMS Microbiology Ecology*. 32:121-128.
- Schofield, P. 2000. Gas production methods. Pages 209-232 in *Farm Animal Metabolism and Nutrition*. J. P. F. D'Mello, ed. CAB International, Wallingford, Oxon, U.K.
- Schofield, P. and A. N. Pell. 1995a. Measurement and kinetic analysis of the neutral detergent-soluble carbohydrate fraction of legumes and grasses. *J. Anim. Sci.* 73:3455-3463.
- Schofield, P. and A. N. Pell. 1995b. Validity of using accumulated gas pressure readings to measure forage digestion *in vitro*: A comparison involving three forage. *J. Dairy Sci.* 78:2230-2238.
- Schofield, P., R. E. Pitt, and A. N. Pell. 1994. Kinetics of fiber digestion from *in vitro* gas production. *J. Anim. Sci.* 72:2980-2991.
- Seo, S., C. Lanzas, L. O. Tedeschi, and D. G. Fox. 2007a. Development of a mechanistic model to represent the dynamics of liquid flow out of the rumen and to predict rate of passage of liquid in dairy cattle. *J. Anim. Sci.* 90:840-855.
- Seo, S., C. Lanzas, L. O. Tedeschi, A. N. Pell, and D. G. Fox. 2007b. Development of a mechanistic model to represent the dynamics of particle flow out of the rumen and to predict rate of passage rate of particles in dairy cattle. *J. Dairy Sci.*:(Submitted).
- Seo, S., L. O. Tedeschi, C. G. Schwab, and D. G. Fox. 2006a. Development and evaluation of empirical equations to predict feed passage rate in cattle. *Anim. Feed Sci. Technol.* 128:67-83.
- Seo, S., L. O. Tedeschi, C. G. Schwab, and D. G. Fox. 2006b. Evaluation of the passage rate equations in the 2001 Dairy NRC Model. *J. Dairy Sci.* 89:2327-2342.
- Sniffen, C. J., J. D. O'Connor, P. J. Van Soest, D. G. Fox, and J. B. Russell. 1992. A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. *J. Anim. Sci.* 70:3562-3577.
- Spires, H. R., J. H. Clark, R. G. Derrig, and C. L. Davis. 1975. Milk production and nitrogen utilization in response to postruminal infusion of sodium caseinate in lactating cows. *J. Nutr.* 105(1111-1121).
- Stefanon, B., A. N. Pell, and P. Schofield. 1996. Effect of maturity on digestion kinetics of water-soluble and water-insoluble fractions of Alfalfa and Brome hay. *J. Anim. Sci.* 74:1104-1115.
- Stone, W. C. 1996. Applied topics in dairy cattle nutrition: 1. Soyhulls as either a forage or concentrate replacement in early lactation Holstein dairy cattle, 2. Evaluation of the Cornell Net Carbohydrate and Protein System's metabolizable protein requirement as supply in Holstein dairy cattle, 3. In vitro effects of lipids on fermentation systems. Ph.D. Dissertation, Cornell University, Ithaca, NY.
- Tedeschi, L. O. 2006. Assessment of the adequacy of mathematical models. *Agric. Syst.* 89:225-247.
- Tedeschi, L. O., M. J. Baker, D. J. Ketchen, and D. G. Fox. 2002a. Performance of growing and finishing cattle supplemented with a slow-release urea product and urea. *Can. J. Anim. Sci.* 82:567-573.

- Tedeschi, L. O., C. Boin, D. G. Fox, P. R. Leme, G. F. Alleoni, and D. P. D. Lanna. 2002b. Energy requirement for maintenance and growth of Nellore bulls and steers fed high-forage diets. *J. Anim. Sci.* 80:1671-1682.
- Tedeschi, L. O., D. G. Fox, M. J. Baker, and D. P. Kirschten. 2006a. Identifying differences in feed efficiency among group-fed cattle. *J. Anim. Sci.* 84:767-776.
- Tedeschi, L. O., D. G. Fox, L. E. Chase, and S. J. Wang. 2000a. Whole-herd optimization with the Cornell net carbohydrate and protein system. I. Predicting feed biological values for diet optimization with linear programming. *J. Dairy Sci.* 83:2139-2148.
- Tedeschi, L. O., D. G. Fox, and P. H. Doane. 2005a. Evaluation of the tabular feed energy and protein undegradability values of the National Research Council nutrient requirements of beef cattle. *Professional Animal Scientist.* 21:403-415.
- Tedeschi, L. O., D. G. Fox, A. N. Pell, D. P. D. Lanna, and C. Boin. 2002c. Development and evaluation of a tropical feed library for the Cornell Net Carbohydrate and Protein System model. *Scient. Agric.* 59(1):1-18.
- Tedeschi, L. O., D. G. Fox, and J. B. Russell. 2000b. Accounting for ruminal deficiencies of nitrogen and branched-chain amino acids in the structure of the Cornell net carbohydrate and protein system. Pages 224-238 in *Proceedings of Cornell Nutrition Conference for Feed Manufacturers*, Rochester, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Tedeschi, L. O., D. G. Fox, and J. B. Russell. 2000c. Accounting for the effects of a ruminal nitrogen deficiency within the structure of the Cornell net carbohydrate and protein system. *J. Anim. Sci.* 78:1648-1658.
- Tedeschi, L. O., D. G. Fox, R. D. Sainz, L. G. Barioni, S. R. Medeiros, and C. Boin. 2005b. Using mathematical models in ruminant nutrition. *Scient. Agric.* 62(1):76-91.
- Tedeschi, L. O., D. G. Fox, and T. P. Tylutki. 2003. Potential environmental benefits of ionophores in ruminant diets. *J. Environ. Qual.* 32:1591-1602.
- Tedeschi, L. O., A. N. Pell, D. G. Fox, and C. R. Llamas. 2001. The amino acid profiles of the whole plant and of four residues from temperate and tropical forages. *J. Anim. Sci.* 79:525-532.
- Tedeschi, L. O., S. Seo, D. G. Fox, and R. Ruiz. 2006b. Accounting for energy and protein reserve changes in predicting diet-allowable milk production in cattle. *J. Dairy Sci.* 89:4795-4807.
- Tylutki, T. P. and D. G. Fox. 1997. Application of the Cornell Nutrient Management Planning System: Optimizing herd nutrition. Pages 54-65 in *Proceedings of Cornell Nutrition Conference for Feed Manufacturers*, Rochester, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Tylutki, T. P., D. G. Fox, and R. G. Anrique. 1994. Predicting net energy and protein requirements for growth of implanted and nonimplanted heifers and steers and nonimplanted bulls varying in body size. *J. Anim. Sci.* 72:1806-1813.
- Tylutki, T. P., D. G. Fox, V. M. Durbal, L. O. Tedeschi, J. B. Russell, M. E. Van Amburgh, T. R. Overton, L. E. Chase, and A. N. Pell. 2007. Cornell net carbohydrate and protein system; A model for precision feeding of dairy cattle. *Anim. Feed Sci. Technol.*:(Accepted).
- USDA-NRCS. 2003. Conservation Practice Standard. Feed Management 592. Available: <http://www.nrcs.usda.gov/technical/Standards/nhcp.html>.
- USDA-NRCS. 2006. Conservation Practice Standard. Nutrient Management 590. Available: <http://www.nrcs.usda.gov/technical/Standards/nhcp.html>.

- Van Amburgh, M. E., D. M. Galton, D. E. Bauman, R. W. Everett, D. G. Fox, L. E. Chase, and H. N. Erb. 1998. Effects of three prepubertal body growth rates on performance of Holstein heifers during first lactation. *J. Dairy Sci.* 81:527-538.
- Vasconcelos, J. T., L. O. Tedeschi, D. G. Fox, M. L. Galyean, and L. W. Greene. 2007. A review: Feeding nitrogen and phosphorus in beef cattle feedlot production to mitigate environmental impacts. *Professional Animal Scientist*. 23:(In press).
- Weiss, W. P. 1993. Predicting energy values of feeds. *J. Dairy Sci.* 76:1802-1811.
- Weiss, W. P. 1999. Energy prediction equations for ruminant feeds. Pages 176-185 in *Proceedings of Cornell Nutrition Conference for Feed Manufacturers*, Rochester, NY. New York State College of Agriculture & Life Sciences, Cornell University.
- Weiss, W. P., H. R. Conrad, and N. R. St. Pierre. 1992. A theoretically-based model for predicting total digestible nutrient values of forages and concentrates. *Anim. Feed Sci. Technol.* 39:95-110.
- Yang, C. M. J. and J. B. Russell. 1993. The effect of monensin supplementation on ruminal ammonia accumulation in vivo and the number of amino acid-fermenting bacteria. *J. Anim. Sci.* 71:3470-3276.
- Yang, W. Z., K. A. Beauchemin, and L. M. Rode. 2001. Effects of grain processing, forage to concentrate ratio, and forage particle size on rumen pH and digestion by dairy cows. *J. Dairy Sci.* 84:2203-2216.
- Zebeli, Q., M. Tafaj, H. Steingass, B. Metzler, and W. Drochner. 2006. Effects of physically effective fiber on digestive processes and milk fat content in early lactating dairy cows fed total mixed rations. *J. Dairy Sci.* 89:651-668.