IMPACT OF NUTRITION MODELS IN THE DAIRY INDUSTRY

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INTRODUCTION

For some years now, it has been evident that dairy cow nutrition models are vital to the continued success of the dairy industry. This is especially true as we recognize the importance, for example, of ruminal microbes and metabolism in body tissues to nutrient requirements. In addition, our production emphasis has shifted from only milk volume and fat to include milk protein percentage and yield. Mathematical models of nutrition have been in use for over three decades and have stimulated improvement in feeding cattle. However, more complete data sets available in recent years combined with more precise mathematical approaches have now allowed us to improve models of nutrient use tremendously. They will be used more frequently in the future for support of decisions not only on the nutrition of cattle, but for other aspects including farm economics and environmental impact.

DAIRY NUTRITION MODELS: THEIR FORM AND ROLE

Nutritional models vary in complexity according to objectives. A typical scheme of model levels needed to represent a system is found in Table 1. Information about a system must be at least one level below the system explored with the model. Thus, models describing herds operate at the animal level or below, those describing animals require details at the organ level and lower and so on.

Table 1. Model levels[a].

Level	Description of level
i + 1	Collection of organisms (herd, flock, crop)
i	Organism (Animal, Plant)
i-1	Organs
i-2	Tissues
.....	Cells
.....	Organelles

a. Adapted From France and Thornley (1984).

In practice, models only need details that have significant bearing on consequences of changes arising from inputs to the system (Production Model) or as much detail as is necessary to explore the system in new and different ways (Scientific Model). Salient properties of production and scientific models are presented in Table 2.

Table 2. Properties of production and scientific models

Feature	Production Model	Scientific Model
Purpose	Predict response	Understand process
Form	Response surface equations	Differential equations (state equations)
Parameters	Polynomial coefficients derived from data fitting	Biochemical reaction properties
Aggregation step	None; model derived from aggregated experiments	Chemical processes aggregated to organ and animal level functions
Solution process	Simple explicit solution of equations	Complex systems of differential equations requiring special software
Outputs	Computed indicators of adequacy of inputs and production cost measures	Steady state solutions to transactions in terms of scientifically significant indicators
Character	Empirical and static	Dynamic and Mechanistic

Scientific Models

Scientific models are usually developed upward from basic experimental data pertaining to metabolic processes. Scientific models assume that a living system can be described in terms of a set of ‘critical’ metabolic transactions encapsulated in organs. The goal is to translate in vitro experimental data into chemical reactions representing the essential metabolic processes. Differential equations of the mass balance and Michaelis Menten forms are used to describe substrate level changes as the system equilibrates to a (new) steady state because of nutritional and digestive inputs. Implicit to these models are two basic assumptions: firstly, that in vivo metabolic pathways can be represented using the critical transactions modeled from in vitro experimental data, and secondly, that cellular level metabolic processes can be aggregated to the organ level to effectively model whole animal function. Baldwin at the University of California and his colleagues (Baldwin et al. 1987a,b,c) have produced a comprehensive integrated model that describes digestion and metabolism of the dairy cow with dynamic, mechanistic equations of physiological processes.

Production Models

Production models are primarily used to portray animal responses to different inputs. They are usually created from collections of response surface models that are developed from animal or herd level experiments. Thus, these models are developed downward. They are valid within the domain of data underpinning the individual response surfaces and are as accurate as the response models themselves.

A theme for the development, refinement and deployment of empirical production models is seen in the development and implementation the of the National Research Council dairy cow models (NRC 1978, 1989, 2001). In 1978, response equations were used to predict crude protein and energy needs of the dairy cow. The 1989 model used a system of protein utilization that partitioned dietary protein into rumen degradable and rumen undegradable fractions (NRC 1985). Growth of microorganisms in the rumen was driven by energy intake (TDN, NEL). In 2001, the National Research Council released a new dairy cow model that contains some of the mechanistic approaches in the CNCPS/CPM-Dairy that are described below.

Other empirical production models include the DVE/OEB (Dutch, Tamminga et al. 1994), AFRC (British, AFRC 1990, 1992), CSIRO (Australian, CSIRO 1990) and INRA (French, INRA 1989) systems. These early production models stimulated more precise thinking and experimentation. Better data were incorporated into newer versions of models.

THE CORNELL NET CARBOHYDRATE AND PROTEIN SYSTEM (CNCPS)

The need for more accurate models to define ruminal bacteria and whole animal requirements, to assess feed utilization and to predict production responses led to the development of the CNCPS (Fox et al. 1992; O'Connor et al, 1993; Russell et al. 1992; Sniffen et al. 1992). The CNCPS is a mix of empirical and mechanistic approaches that describe feed intake, ruminal fermentation of protein and carbohydrate, intestinal digestion and absorption, excretion, heat production, utilization of nutrients for maintenance, growth, lactation and pregnancy, and nutrient excretion. The system can be applied at the farm level because diets are characterized according to fractions that are measured in most feed analyses laboratories. The system is valuable for estimating ruminal degradability of dietary protein and in determining whether ruminal microbes are provided with proper types and amounts of carbohydrates and nitrogenous nutrients (i.e. ammonia, peptides). The system is also useful in balancing rations based on amino acids.

Separate sub-models (Table 3) were developed to describe inputs (animal, environment and ration) and calculate digestion (rumen and intestine), nutrient (energy, protein and essential amino acid) metabolism and requirements, ration evaluation, manure production and nitrogen and phosphorus excretion.

Table 3. Sub-models used in the Net Carbohydrate and Protein System[a].

Sub-model	Function
	Inputs
Animal	Describe age, weight, body condition, days in milk, stage of gestation, milk yield and composition
Environment	Describe wind, temperature, humidity, heat stress, night cooling, hair coat
Ration	Describe feeds, their composition and amounts in diets
	Calculations
Dry matter intake	Determines expected dry matter intake based on inputs
Rumen	
Rate of passage	Calculates rate of passage of as function of dry matter intake, body weight and forage in ration.
Degradation and escape	Calculated on the basis of pool sizes, degradation rates of protein and carbohydrate fractions and rate of passage
Bacterial growth	Calculates yield of FC and NFC bacteria on the basis of rate of carbohydrate fermentation with adjustments for ruminal pH
Intestinal	Calculates digestion of protein, amino acids, carbohydrates, fats and ash in rumen escape feed fractions and from bacteria
Metabolic	Calculates utilization of absorbed energy, protein and amino acids
Tissue	Calculates ME, protein and essential amino acid requirements for maintenance, growth, gestation and milk production
Fecal	Calculates undigested feed and bacterial residues in feces
Metabolizable protein and energy	Calculates MP and TDN, ME, NEL, NEM and NEG on individual ingredients and on the ration
Ration evaluation	Compares performance based on metabolizable energy, metabolizable protein and essential amino acids to targeted performance
Nutrient excretion	Predicts manure production and N and P excretion

a. Adapted from Fox et al. (1991).

APPLICATION OF THE CORNELL NET CARBOHYDRATE AND PROTEIN SYSTEM

Application of the CNCPS also includes application of CPM-Dairy. The CNCPS is the core dairy cow model in CPM-Dairy developed for consulting dairy nutritionists through a collaborative effort by scientists at Cornell University, the University of Pennsylvania and the Miner Institute (Boston et. 2000; Chalupa et al. 2006).

When the CNCPS was evaluated with data from individual dairy cows where the appropriate inputs were measured and changes in energy reserves were accounted for, the CNCPS accounted for 90% of the variation in actual milk production of individual cows with a 1.3% bias (Fox et al. 2004). Using the same data base to evaluate CPM-Dairy (Chalupa et al. 2006), the correlation coefficient between observed and model-predicted milk production was 0.94 without a significant mean bias (0.11%; $P = 0.90$). Based upon the statistical evaluations performed, the CNCPS and CPM-Dairy models adequately predict milk production at the farm level.

The CNCPS and CPM Dairy computer programs are being routinely used by both nutritional consultants and feed companies. The CNCPS and CPM-Dairy also have been used as a teaching tool to improve skills of students, to evaluate the interactions of feed composition, feeding management and animal requirements and to design and interpret experimental results.

AUTO-BALANCING RATIONS

Auto-balancing of rations is a useful aid in dairy nutrition programs, especially when a large number of ingredients are available. The popularity of the Spartan system (VandeHar et al. 1992) demonstrated the degree to which users appreciated the inclusion of auto-balancing facilities within ration management software.

The usual objective of auto-balancing is to produce an “optimal ration” at the lowest cost. Constraints (minimum and maximum amounts) are set for both nutrients and feed ingredients. Nutritional constraints are based upon application of the factorial approach to describe the requirements of cows to perform specific or multiple functions (maintenance, growth, lactation and pregnancy). Nutritional constraints include dry matter intake, energy (metabolizable and net), protein (crude, soluble, bypass, absorbed or metabolizable), carbohydrates (fiber and non-fiber), fat, minerals and in the case of newer models like the CNCPS and CPM-Dairy, amino acids and rumen available nitrogen (peptides and ammonia). Feed ingredients are selected on the basis of the major nutrients that they provide (i.e. fiber from forages, non-fiber carbohydrates from grains, protein from oil-seed meals). Feed constraints are set based on a knowledge of the availability of purchased ingredients and inventory of ingredients on the farm or contracted for purchase. The amount of an ingredient specified is often adjusted by the formulator to take into account a minimum amount that the formulator feels rations should contain or the maximum amount that the formulator feels can be tolerated by the animal. The amount of a feed ingredient should not be limited by high cost because optimization programs will control the inclusion of expensive feeds. Thus, the auto-balancing (optimization) task is to find the least cost combination of feed ingredients within their minimum and maximum constraints that provide nutrients that are within the specified minimum and maximum ranges. When the foregoing is achieved, the auto-balancing process has provided a solution to the specifications defined by the formulator.

Ration formulators often are discouraged when the optimization process does not give a solution as defined above. This simply means that a combination of feed ingredients in amounts within the minimum and maximum ranges cannot provide nutrients within the specified ranges. To find a solution, the formulator should either expand (relax) the feed ingredient and nutrient constraints or include additional ingredients that are good sources of limiting nutrients. Older optimization methods simply indicated that there was “no feasible” solution. This provided no direction to obtaining a solution. Newer optimization methods provide direction by listing nutrient constraints that are not met.

Linear Programming

Linear programming is used for auto-balancing in most nutrition models (Tedeschi et al. 2000). In fact, ration formulation was one of the first applications of linear programming. Not only could solutions be found in seconds, but building on Danzig’s (1955) contributions to operational research, we also were able to derive an array of other very helpful economic properties (shadow prices) relating to our optimal solution. For example, we could discover over what cost ranges feeds within the optimal ration remained there, as well as which amongst the feeds not selected in the optimal ration were candidates for inclusion if cost decreased.

The suitability of linear programming for optimization depends on the linearity of the problem. That is, the objective and nutrient supply must be expressible as linear functions. Clearly, the objective function and feed cost are linear functions of feed amounts. In both empirical models and in the CNCPS and CPM-Dairy, nutrients like crude protein, fat, carbohydrates (fiber and non-fiber) and minerals are constant proportions of the ingredient regardless of the amount of feed consumed. Thus, supply of these nutrients is a linear function of intake. In empirical dairy cow models, absorbable (metabolizable) protein and energy (metabolizable and net) values also are not affected by intake and thus are constant.

Nonlinear Programming

The CNCPS and CPM-Dairy has a mechanistic rumen sub-model wherein the passage rate of feeds (determined mainly by feed intake but also adjusted by ration forage content and particle size) determines the outflow of nutrients from the rumen system. Thus, nutrients like metabolizable protein, metabolizable energy, amino acid content of metabolizable protein, and rumen available nitrogen (peptides and ammonia) are not constant but vary according to feed consumption and ration ingredients. These features of mechanistic digestion models, together with the fact that novel nonlinear mathematical techniques are needed to bridge non-overlapping digestive model components from different dairy research centers, mean that the problem of dairy cow ration optimization is no longer the province of the linear programming package. In CPM-Dairy (Boston et al. 2000), we demonstrated that by using the ‘Forward Sequential Quadratic Programming’ approach (Zhou and Tits, 1997), the problems alluded to above can be effectively resolved without serious loss of computational efficiency.

Implementing constrained, nonlinear optimization is not without problems. If the nutrition model contains discontinuous (break-point) functions, continuous mathematical models must be developed to describe the discontinuous functions (Boston et al. 2000).

Finally, a linear programming optimization problem has just one solution. This is not so for nonlinear optimization. The entire field of biomathematics is still under investigation. Never-the-less a number of points are clear: (1) the era of the linear program as the exclusive tool for dairy cow ration optimization has ended; (2) the use of nonlinear optimization techniques has been shown to be not only feasible but also practical in the field; (3) work needs to be continued to explore the array of properties of the final nonlinear ration optimization solution which may provide similar information to the optimizer use as did opportunity prices, and shadow prices in the linear programming context; (4) feed cost is a sensible objective for ration formulation; (5) with legislative imposition on dairymen to be mindful of the environment, and with health and fitness promoters seeking milk with special nutritional qualities, broadening the focus of optimization to nutrient excretion and milk components may be desirable.

Linear and nonlinear optimization methods are powerful tools for assisting the formulator in obtaining least cost combinations of feed ingredients to meet nutrients required for maintenance and productive functions like growth, lactation and pregnancy. Solutions obtained are based on constraints for feed ingredients and nutrients selected by the formulator. Rations obtained by optimization should always be assessed by a trained nutritionist before they are implemented.

SUMMARY

Nutrition models are a vital tool for maximizing dairy farm profitability, improving animal health and minimizing potential adverse affects of cattle operations on the environment.

Dairy advisors, educators and researchers could not operate without nutrition models. This applies to consulting nutritionists as well as those in nutrient management, in the feed industry, in governmental organizations and in academia.

The CNCPS was the first nutrition model to apply principles of cattle biology at the farm level. Components of the CNCPS were included in the latest NRC nutrient requirements for dairy cattle and for beef cattle. It is likely that the principles of the CNCPS will be incorporated into other nutrition models.

We never have “the final model.” Models are continually evolving as new data becomes available. There are two main reasons for developing new models. Better prediction of the responses of dairy cattle production is obvious. Not as obvious is that new models may more precisely describe the biology of the dairy cow.

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