DEVELOPMENT OF THE CNCPS AND CPM MODELS: THE SNIFFEN AFFECT

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This paper will describe the contributions of Dr. Charles Sniffen to the development of the Cornell Net Carbohydrate and Protein System and CPM-Dairy.

THE BEGINNING

Danny Fox and Charlie Sniffen joined the faculty of the Animal Sciences Department at Cornell University in 1977 and 1978, respectively. Danny had considerable modeling experience and, with Dr.Roy Black, had developed a beef cattle management model at Michigan State University (Fox and Black, 1984). The Michigan State University model was later programmed into Basic for a Radio Shack TRS 80 and became Cornell Cattle System 1. Charlie had little modeling experience, but always had an appreciation for the value of computers in solving complex mathematical problems as evidenced by the acquisition at the University of Maine of a computer from the nose cone of a Trident missile (Hoover, 2003).

These men recognized that current ruminant nutrition models, such as the NRC models, lacked integration between the animal and its environment and lacked integration between physiological functions and metabolic processes.

THE FIRST ATTEMPT

In 1980, Dr. David Mertens took a sabbatical leave from the University of Georgia and came to Cornell University to work with Dr. Tony Oltenacu on modeling lactation curves. Dave, with Dr. Lane Ely, had previously published a rumen digestion model (Mertens and Ely, 1979) and Dave began work on a dynamic mass action model of the dairy cow. Charlie became aware of what Dave was doing when Dave presented a NY-PA farmer seminar (Mertens, 1981). Dave and Charlie became modeling teammates.

The model grew and eventually consisted of over 1600 equations and 800 variables. According to Dave, it wasn't much of a whole animal model because there was a large rumen and very small organs (intestines, liver, muscle and mammary gland). Everything was going well until Dave decided to add protozoa to the rumen. The model would run well with the starting parameters, but if any inputs were changed even slightly, protozoa would grow to the point where they would have a greater mass than the entire cow. Dave and Charlie had demonstrated "chaotic behavior" in a dynamic system. That is, once a dynamic system gets complex with first and second order mass action equations, slight perturbations in coefficients or starting values can result in totally unexpected and random behavior.

While this first attempt might be considered a failure, it was a success in that concepts such as carbohydrate and protein fractions, rates of ruminal degradation of feed fractions and microbial pools are what make the CNCPS/CPM-Dairy models unique.

TOWARDS A SUCCESSFUL MODEL

After Dave returned to the University of Georgia, he, Charlie and Jim O'Connor (who had been hired by Dave as a programmer) continued to interact. This impacted the philosophy of what the CNCPS should be and programming platforms for the CNCPS evolved.

The Philosophy

Charlie and Danny proposed that accurate descriptions of nutritional requirements and nutrient supplies coupled with careful descriptions of the animal, its environment and its management would allow nutritionists to identify more of the sources of variation in cattle performance than less comprehensive nutrition models.

Criteria used for the development of the CNCPS included (1) Inputs needed by the model should be routinely available on the farm or through analyses for nutrient fractions in feed testing laboratories, (2) the model would be based on documented research, (3) the model could be modified as new information became available, and (4) the output from the model should help producers improve their feeding programs.

Table 1. Model Levels[1].

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

1. Adapted From France and Thornley (1984).

A key challenge in model development is determining the appropriate level of aggregation. Nutrition 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.

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[1]

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

1. Adapted from Boston et al. (2000).

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 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 portray animal responses to alternating competing 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. 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. 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 calculates ruminal degradation of dietary protein by an aggregated dynamic model.

The CNCPS is a combination of empirical and mechanistic approaches that describe (1) feed intake, (2) ruminal fermentation of protein and carbohydrate, (3) intestinal digestion and absorption, (4) utilization of nutrients for maintenance, growth, lactation and pregnancy, (5) reserves, and (6) nutrient excretion.

Programming Platforms

After using languages like Fortran and Pascal on IBM, Apple and Compaq microcomputers, it was decided to use spreadsheet technology. Spreadsheets are useful in the initial development of models and indeed were used in early releases of the CNCPS. However, there are limitations in what can be done in spreadsheets, especially in developing user-friendly models.

Development of the CNCPS

Danny Fox set about to develop the nutrient requirement side of the CNCPS. Important components of the sub-model were the impacts of environment, management and body reserves on nutrient requirements (Fox et al. 1988).

In cattle, ruminal bacteria and their products of fermentative digestion and feed fractions that escape fermentative digestion provide nutrients for maintenance and productivity. Thus, a system was needed to describe feed nutrient fractions and their degradation in the rumen and this needed to be coupled with a model of bacterial growth.

Dr. Peter Van Soest joined the team and suggested that the detergent system could be used to partition protein fractions as well as carbohydrate fractions (Figure 1, Tables 2 and 3). He also suggested using the kinetic approach described by Waldo et al. (1972) to describe the fermentative digestion of a nutrient pool as the pool*$(k_d/(k_d+k_p))$

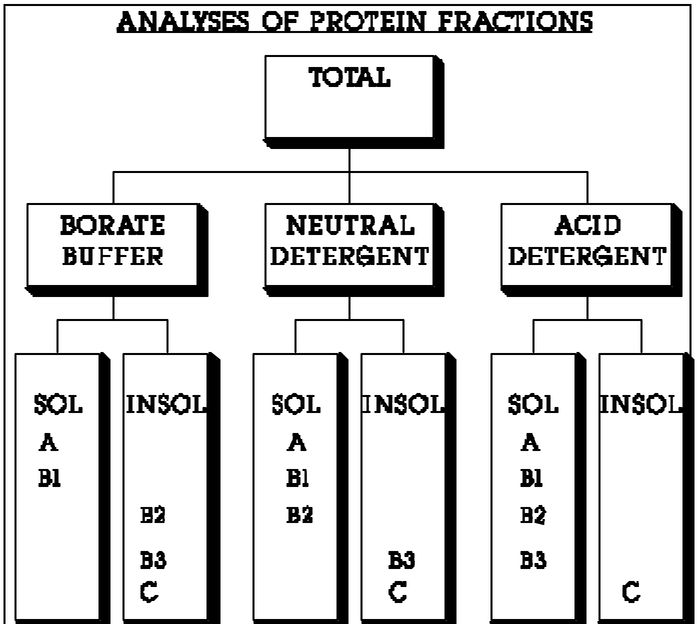

Figure 1. Protein fractions in feeds

where k_d is the rate of digestion (%/h) and k_p is the rate of passage (%/h). Digestion rates were obtained by applying curve-peeling techniques to enzymatic, *in vitro* and *in situ* derived time-course data. Originally, rates of passage were estimated from tabular values but then the equations of Sauvant and Archimede from INRA were used (Chalupa et al. 1991).

Table 3. Composition and digestion of protein fractions in the CNCPS and CPM-Dairy

Fraction	Composition	Digestion Rumen (%/h)	Digestion Intestinal (%)[1]
A	NH_3, NO_3, AA peptides	Instantaneous	100
B_1	Globulins Some albumins	200-300	100
B_2	Most albumins Glutelins	5-15	100
B_3	Prolamins Extensin proteins Denatured proteins	0.1-1.5	80
C	Maillard products N bound to lignin	0	0

1. Digestibility of the rumen escape fraction

Table 4. Composition and digestion of carbohydrate fractions in CNCPS/CPM-Dairy

Model		Composition	Digestion	
CNCPS CPM V 2	CPM V3		Rumen (%/h)	Intestine (%)[1]
A	A_1	Silage Acids	1-2	100
A	A_2	Sugars	100-300	100
B_1	B_1	Starch	10-40	75
B_1	B_2	Soluble Available Fiber Pectins *B* Glucans	40-60	75
B_2	B_3	Insoluble Available Fiber Cellulose Hemicellulose	2-15	20
C	C	Unavailable Fiber Lignin Fiber associated with lignin	0	0

1. Digestibility of the rumen escape fraction

The missing link at this point was a model of bacterial growth. Most nutrition models grew ruminal bacteria as a function of consumed TDN or energy. This approach completely ignored the dynamics of bacterial growth. Dr Jim Russell developed a simple yet brilliant model of bacterial growth. In this model, bacteria have a maintenance energy requirement and grow at rates in accordance with the rate of carbohydrate fermentation. Partition of ruminal bacteria into fiber digesters and non-fiber digesters allows for application of biological differences in growth characteristics of these two categories of bacteria. Fiber digesters have a lower maintenance requirement but grow slower than non-fiber digesters. Fiber digesters only use ammonia as a nitrogenous nutrient whereas growth of non-fiber digesters is enhanced if peptide nitrogen is available. On the basis of lower bacterial growth in cattle fed low forage rations and lower *in vitro* growth yield in cultures incubated at pH 5.7 vs. 6.7, the efficiency of bacterial growth was discounted when ration peNDF fell below 20%.

Danny Fox then undertook the arduous task of validating the CNCPS.

During development, the CNCPS was presented at symposia and nutrition conferences (Fox et al. 1982, 1987; Sniffen et al. 1987; Van Soest et al. 1982). The first complete publication of the CNCPS was as an experiment station bulletin (Fox et al. 1990; O'Connor et al. 1990). The initial three refereed articles described the CNCPS in terms of ruminal fermentation (Russell et al. 1992), carbohydrate and protein availability (Sniffen et al. 1992) and cattle requirements and diet adequacy (Fox et al. 1992). A year later, a factorial-based amino acid sub-model was published (O'Connor et al. 1993). Subsequently, the ideal protein method of Rulquin and Verite (1993) was added.

To date, there have been five releases of the CNCPS: version 1 in 1991, version 2 in 1993, version 3 in 1994, version 4 in 2000 and version 5 in 2003. Each version contained updates on the mathematical descriptions of cattle biology, environment and management to improve the accuracy of the model and in the user interface to improve user friendliness of the software. Versions 1, 2 and 3 were programmed in spreadsheets, initially Lotus 123 and later in Excel. Versions 4 and 5 were written in Visual Basic. The first two implemented the CNCPS model for diet evaluation on a single group basis only while the last three versions were designed to evaluate whole herd nutrient management and excretion. The reader is directed to Fox et al. (2000) and the CNCPS (2003) web site for further details on model development and publications.

CPM-DAIRY

By 1987, the CNCPS had moved to a point were it could be used in the field. Early spreadsheets like Lotus 123 had limitations and the model could only handle nine feed ingredients. Dr. Bill Chalupa and colleagues at the University of Pennsylvania moved the dairy cattle part of CNCPS (lactating cows, dry cows and replacement heifers) into the Quatro Pro spreadsheet. This allowed for the use of more feed ingredients and provided a platform for auto-balancing rations. This was the beginning of the CPM-Dairy project.

CPM-Dairy was a joint software development by scientists at Cornell University, the University of Pennsylvania and the Miner Institute. CPM-Dairy was intended for those wanting to use the CNCPS to evaluate and formulate rations for dairy cattle. A primary goal of the CPM-Dairy project was to convert a large-scale scientific model into a user-friendly commercial product (Boston et al. 2000). A secondary goal was to improve auto-balancing of rations.

The CNCPS is inherently non-linear in the way that digesta flow affects nutrient yield from feed fractions. Feed ingredients and amount of feed consumed have impacts on rates of passage and consequently on extent of fermentative digestion and bacterial growth. Thus, feed ingredients have variable metabolizable protein and metabolizable energy values. We used the optimization scheme of Zhou and Tits (1997) that employed a forward sequential quadratic programming approach. Unfortunately some of the yield equations in the CNCPS depended on discontinuous functions. The science within CNCPS emanated from different research centers where non-overlapping experimental boundaries meant that gaps existed in the knowledge. To deal with this problem we developed two approaches: replacing the piece-wise segments of two models with smooth nonlinear functions (where adjoining models had sensible intersections), and building transition functions to smoothly fill gaps between published reports (Boston et al. 2000).

CPM-Dairy version 1.0 was programmed in Microsoft C. Rations were evaluated and formulated according to a modified NRC model (MNRC) and to an up-dated version 3 of the CNCPS. Release of version 1.0 was in October 1998.

CPM-Dairy versions 2 and 3 are 3 still in extensive beta testing. Release is expected by the end of 2003. They are written in Microsoft Visual Basic 6.0 (for the User

Interface) and Microsoft C++ 6.0 (for the calculations and optimizations) with a Microsoft Access 2000 database to store default and current feed dictionary values. Nutrient supplies and requirements are calculated according to the CNCPS version 5. An NRC or modified NRC option is not provided. CPM-Dairy version 3 has expanded carbohydrate fractions, a lipid sub-model and incorporates NRC (2001) mineral requirements. Auto balancing has been expanded to include minerals and vitamins.

APPLICATION OF THE CNCPS AND CPM-DAIRY

There is and will continue to be much discussion and revision of the equations in the models. However, the models have gained international acceptance. They are used throughout the world by nutrition advisors to evaluate and formulate rations. Many researchers, including graduate students, have used the models to design experiments and evaluate results. The CNCPS was selected as an option in the latest NRC beef cattle model (NRC, 1996).

Perhaps the most important aspect of the CNCPS and CPM-Dairy is that the models have stimulated thought processes. Descriptions of the biology of cattle are moving from empirical and static mathematical equations to mechanistic and dynamic mathematical equations. New assays are being developed to better describe nutrient fractions and their rates of ruminal fermentation. This, of course, is what Charlie Sniffen and Danny Fox envisioned in 1978.

SUMMARY OF DR. SNIFFEN'S CONTRIBUTIONS

Charlie Sniffen and Danny Fox are indeed the fathers of the successful CNCPS/CPM-Dairy projects, but we should not forget the early contributions of Dave Mertens. These men had vision but small egos. They recognized their limitations and brought a cadre of scientists into the project.

As noted by Hoover (2003), Charlie can generate ideas faster than they can be implemented. We cannot enumerate the number of phone calls and e-mails that we've received over the years with excellent suggestions for the improvement of CPM-Dairy.

Model development has "fun parts" and "dog parts." A "dog part" has been development and update of the feed dictionaries. No one really wanted to undertake that task. Charlie has been the leader of the feed dictionary effort. Initially, he took the few values that were available and, based on his knowledge of protein and carbohydrate fractions, "radiated out" to construct values for an array of feed ingredients. As new information became available, values were modified. His most intense approach was the recent effort with Kurt Contach of the Miner Institute to update the feed dictionaries for CPM-Dairy version 3. Edits were based on data from over 10,000 feed ingredients.

Charlie has an infectious enthusiasm for ideas and innovations to help the dairy producer. When Charlie is convinced that developing an idea into a product would assist the dairy industry, he makes sure that no unreasonable impediment interferes with implementing that idea.

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