The Cornell Net Carbohydrate and Protein System version 7: What is Taking So Long?

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Introduction

The development of the Cornell Net Carbohydrate and Protein System (CNCPS) has been discussed in many previous conference proceedings. The intent of this paper and presentation is to provide a description of the latest updates to the model, specifically regarding version 7, and to provide a timeline for the launch of this project into the industry. As with all things related to model development, there are many aspects which can impact the speed with which developers build, evaluate, modify, and publish the equations or processes within the system to ensure it provides appropriate and useful answers when determining what nutrient(s) are limiting productive functions in growing heifers or high producing lactating cattle. With the release of the eighth edition of the nutrient requirements of dairy cattle from the National Academies of Sciences, Engineering and Medicine (NASEM) committee (NASEM, 2021), the dichotomy between how a NASEM publication and model is developed and how the CNCPS has been approached is more apparent. Because the committee evaluates nearly all supplies of nutrients, and nutrient updates from other sources are limited, the NASEM updates provide relevant information to be included in future CNCPS updates, particularly in the areas of vitamins and minerals, fatty acids, and water intake. Nevertheless, differences in the modeling process exists and are discussed within this paper.

There are three distinct differences between the development of a new edition for the NASEM model and updates made toward the CNCPS which greatly impacts the speed with which updates are released. The first is the NASEM is comprised of a committee where each member is assigned to one or two topics to review the current literature, compile relevant data, assess, modify, and/or develop new equations while writing their assessment in book chapters. Each committee member brings expertise that is complimentary and slightly unique to ensure an effective and comprehensive assessment and update to nutrient requirements and supply. There are managers, timelines and support staff that contribute to the success of the NASEM effort. Upon the conclusion and publication of these updates, the committee provides their updated recommendations to nearly all relevant nutrients that are formulated in a dairy diet and will concomitantly describe research ‘areas of opportunity’ for the industry to focus their efforts on before the next committee is convened. The development process for the CNCPS involves efforts by graduate students, postdoctoral associates and visiting faculty, with the help of interested faculty within, and beyond, the Department of Animal Sciences. As with the NASEM process, there is a reliance on literature data, data base construction and statistical evaluation, but it is usually in the context of another project or hypothesis. These researchers typically have a specific area of nutrition that they study, whereby they evaluate current literature to understand limitations in the data, perform experiments aimed at providing new and relevant information to lessen these limitations, and integrate these findings by assessing, modifying, and/or developing new equations within the model structure. An exception to this process in the last 12 years was the graduate program of Dr. Ryan Higgs, where his program support allowed for a focused effort on updating version 6 which, after realizing the need to redesign the calculation process of the CNCPS due to limitations in disaggregating feed and microbial nutrient supplies, provided for the translation of version 6.5 and development of it into version 7 (Higgs and Van Amburgh, 2016).

One of the shortcomings of the NASEM process is that once the publication and its associated model is released, the committee is disbanded, and updates are only made when the next committee is convened. Given the rate of newly published research in the field it can be difficult to create model which provides robust predictions with an evolving knowledgebase. As such, the frequency of which a model should be updated should reflect the needs of the industry and their understanding of nutrition. The disbandment of the committee can also be problematic from the sense that there is minimal testing and evaluation of the system in prospective animal studies. This process is left to the users, other academics, and future committees, leaving little opportunity to modify and update what the committee developed outside of literature data, compiled datasets, and statistical evaluation. Over the last few iterations of the NRC/NASEM, the published models have essentially started over with new data, a new approach and generally improved statistical approaches when analyzing current literature datasets. This leads to two distinct differences compared to the development of the CNCPS. First, the architectural and computational structure of the CNCPS model has been conserved for from the model's inception in 1990 (Fox et al., 1992, Russell et al., 1992, Sniffen et al., 1992, O'Connor et al., 1993) to 2015 (Van Amburgh et al., 2015a, Van Amburgh et al., 2015b), a 25-year period where incremental changes (Van Amburgh et al., 1998, Fox et al., 2004, Lanzas et al., 2007, Tylutki et al., 2008) were made to predictive equations of both cattle requirements and nutrient supplies through the rumen and gastro-intestinal tract, as well as refinements and additions to the model's feed library. These updates to the model have been more frequent throughout these 25 years and the methodical updating of equations based on model performance feedback and new data have allowed for the refinement of equations that have not predicted well, resulting in a more robust prediction and reconciliation of nutrient supply and requirements for cattle. This refinement in the model can be a slow, painstaking at times, process; however, it is important to note that in an integrated model, one permutation in an equation or system usually illuminates an offset in the next system or set of equations. This process of working through updated and new equations can turn into a proverbial game of "whack-a-mole", where each update leads to another unveiling of an offset which requires more work and time. This becomes more of an issue with models that exhibit greater complexity, as demonstrated in version 7, where more time is warranted, relative to v.6.5.5, to ensure that accurate predictions relative to observed data.

Given the use and distribution of the model throughout the industry, this group has felt obligated to evaluate the predictions of CNCPS v.7 in several prospective cattle studies to ensure that the predictions of requirements and supply are consistent with observed cattle performance. These observations are in no way a means of validating the systems predictions, rather this deviation from previous versions of the model require a series of evaluations to ensure that predictions are within an acceptable range for accuracy and precision. One technique of model evaluation involves boundary testing to understand the model's limitations and if the predictions are true and consistent with higher yielding cattle than what might be found in the literature used to build the model. This boundary testing has resulted in several revisions, and subsequent delays, of version 7 due to the elucidation of biases involving rumen protozoal flows and subsequent microbial interactions. Further, the testing of boundaries for a new concept for metabolizable amino acid requirements, related to the supply of metabolizable energy, has required extensive vetting to understand how energetic efficiency impacts nitrogen and amino acid metabolism when cattle are lactating. Lastly, the procurement of time and resources to design, program, and deploy a packaged architecture for this new version that allows for a smooth integration of version 6 and version 7 systems in an industry setting has been challenging as our group looks to revamp the system of deployment and updates to users of the model.

The focus of this paper will highlight changes in supply predictions that are significantly different than v6.5.5, discuss the boundary testing which provided additional revisions to version 7, and outline the steps our group has taken to deploy this version in an appropriate timeframe. For a more mechanistic review of CNCPS v7, please refer to Higgs and Van Amburgh (2016).

Updated Nutrient Supply Predictions

Nutrient supply predictions within the updated version of CNCPS build upon ruminal and intestinal transactions that are reported in previous model versions and further describe their dynamic flow starting at the mouth, ending at the rectum, and providing pool size and flux predictions for the rumen, omasum, and small and large intestines (Table 1). This disaggregation of compartmental modeling will utilize a similar feed fractionation scheme, with a greater description of fiber carbohydrates and revisions on how intestinal digestibility of protein in feeds which contain little to no fiber are calculated. A more descriptive report becomes useful during formulation as it will allow the user to understand total tract digestibility of fiber and if feed inventory and costs allow, make modifications to enhance digestibility and energy availability. This will also provide useful information about ruminal digestibility of aNDFom as its digestion will be explicitly quantitative. The total tract digestibly estimations have been tested on four prospective studies, three of which were formulated to North American specifications and one using an Irish grazing system. On average, the resolution of predicted aNDFom total tract digestibility was within 7%, or 2.9 units, of observed total tract digestibility. This group will continue to use future studies to evaluate the accuracy of this predictions and will modify equations when biases present themselves under varying fiber feeding conditions.

Table 1. Intake, degradation, digestion and excretion by digestive compartment of carbohydrate pools from both forage and concentrate sources according to CNCPS v7 calculations.

	Digestion by compartment[1] (g/d)					
				Neutral Detergent Fiber		
	Sugar	Starch	Soluble Fiber	Fast Degrading	Slow Degrading	Undegradable
Proportion of diet, % DM	4.2	30.5	3.7	18.5	5.0	7.1
Forage ingredients, g						
Intake	181	6212	424	3481	1122	1629
Rumen degraded	105	5037	340	2954	615	0
Rumen pool[2]	15	488	35	1241	1193	3802
Rumen passage	76	1175	84	528	507	1629
Small intestine digested	76	877	0	0	0	0
Small intestine passed	0	298	84	528	507	1629
Large intestine degraded	0	207	57	226	71	0
Fecal excretion	0	91	27	302	437	1629
Apparent total tract digestion, %	100	98.5	93.7	91.3	61.1	0
Concentrate ingredients, g						
Intake	998	3078	626	1706	283	358
Rumen degraded	730	2116	445	1290	172	0
Rumen pool	50	329	62	821	216	709
Rumen passage	269	961	180	416	110	358
Small intestine digested	269	754	0	0	0	0
Small intestine passed	0	208	180	416	110	358
Large intestine degraded	0	120	107	131	22	0
Fecal excretion	0	88	73	285	88	358
Apparent total tract digestion, %	100	97.2	88.3	83.3	68.8	0

[1] Cattle consumed an average of 28.0 kg of DMI from this diet .
[2] Defines the residual quantity of each carbohydrate fraction which resides in the rumen and has not been degraded or passed.

There are two aspects to this pool size data on aNDFom which will become relevant to the user as the steady state rumen pool size of the potentially digestible aNDFom and the uNDF will be a determinant of potential dry matter intake (DMI) for the animal (Table 2). This approach is meant to complement existing equations provided within previous versions of the CNCPS, in addition to equation published in the NASEM (2021) model, providing users with an additional tool to troubleshoot and reconcile predicted and observed DMI on farm. The recommended intake and rumen fill values are based on the work conducted at Miner Institute, University of Bologna and Cornell University (Cotanch et al., 2014) using the intake metrics developed by Mertens (2010). This information was one of the outcomes of the Informal Fiber Working Group that has been meeting at the nutrition conference for over ten years.

The model will provide predictions for bacterial protein flows, as in previous versions, based on the fiber (Feed fractions CHO B3 and CHO C; FC) vs non-fiber carbohydrate (Feed fractions CHO A1, A2, A3, A4, B1, and B2; NFC) characteristics, with many of the existing metabolic coefficients, including maintenance and growth potentials, remaining intact. Ruminal protozoal relationships have been studied, quantified, and published, including the uptake of free peptides and amino acids (AA), predation and engulfment of bacteria, and lysis/excretion of nutrients back into their environment. The CNCPS v.7 can capture these relationships, where predictions for protozoal growth and flow will be quantified as a source of microbial nitrogen, carbohydrates, and fatty acids (Table 3 and Table 5). Recreation of previously fed diets and formulation of prospective studies have elucidated a supply of protozoal MP that ranges between 10 and 20% of the total metabolizable microbial supply in most Northeastern US diets. In the study by Dineen et al. (2020) cattle were fed high quality Irish pasture grass, resulting in protozoal contributions representing 23% of microbial supply. It is plausible that cattle fed these highly degradable grasses, with high sugar content, maximize microbial growth and thereby represent the upper limit of protozoal contributions between 22-25% of total microbial yield. The addition of protozoal metabolism also provides insights on the microbial yield response when varying the supply of other carbohydrate fractions to a diet, particularly regarding protozoal growth, and subsequent microbial MP supply, when sugar is increased in a diet. Previous versions of the CNCPS were not sensitive enough to capture the full microbial yield response when sugar was added, only modestly improving NFC degrading bacteria growth. Further efforts to quantify microbial metabolism in the rumen will refine the effect other carbohydrates have on the proliferation of varying microbial communities.

In this version of the model, rumen ammonia levels are estimated based on a sub-model which predicts ammonia production, subsequent hepatic urea production and full urea recycling back to the gastrointestinal tract. This updated approach has at least two benefits. First, it will provide a more stochastic approach to estimating rumen ammonia as the flux generally displays a large amplitude throughout the day but recycling of nitrogen into the rumen is generally constant (Reynolds and Kristensen, 2008). It is important to note that behavioral patterns, including meal frequency and cow time budgets, in conjunction with dietary composition, including carbohydrate digestibility and nitrogen solubility, can interact to cause large swings in rumen ammonia, which can be problematic throughout periods of the day where its concentration could drop below 5.5 mg/dL and causing microbial growth depression. Figure 1 describes the rumen ammonia concentration for a North American based diet that is formulated for 68% forage DM which uses various concentrate feedstuffs to provide other required nutrients. Two of these ingredients, soybean meal and canola meal, are fed at varying levels to provide a different soluble and degradable protein supply in the rumen. As with previous versions of the CNCPS, version 7 can calculate an average ammonia concentration for this diet; however, a static evaluation of this concentration may not provide a meaningful explanation if microbial growth is depressed. For instance, the diet which splits 2.5 kg of DM into equal parts of soybean meal and canola meal has an average ammonia concentration of 6.5 mg/dL which can raise some concerns but does not flag microbial growth depression within the model. Conversely, if a user was to describe the feeding behavior of the target animal, in this case an 8 meal/day behavior was designated, the model would provide a more dynamic form of rumen ammonia concentration that would indicate periods throughout the day where this concentration would be fall below 6.0 md/dL and microbial growth would be marginally depressed. Users will also be provided with a summarized table (Table 4) indicating both average and range of rumen ammonia concentration and microbial growth depression. Depression of microbial growth will become more pronounced with the associated decrease in carbohydrate digestion, specifically regarding potentially digestible aNDFom (pdaNDFom) as we expect the fiber degradation to be disproportionately decreased under N limiting conditions.

Another quantitative addition to the updated version of CNCPS is the inclusion of endogenous transactions which occur ubiquitously throughout the gastro-intestinal tract (Ouellet et al., 2007, Ouellet et al., 2010). The inclusions of these flows do not add an appreciable increase in the supply of metabolizable protein, as the majority of endogenous secretions that are quantified in the model are offset by the maintenance requirement calculated for the loss of these endogenous fractions. This, however, does not mean that these fractions should be left unquantified, given that the remains of salivary proteins, ruminal secretions, and sloughed cells can all be utilized by microbial populations within the rumen to proliferate and further alter the supply of amino acids flowing out of the rumen. Contributions of endogenous proteins within the CNCPS v.7 include salivary proteins (Yisehak et al., 2012), sloughed ruminal, omasal, and abomasal cells (Larsen et al., 2000), omasal and abomasal secretions (Ørskov et al., 1986), pancreatic secretions (Hamza, 1976, Larsen et al., 2000), bile secretions (Larsen et al., 2000), and small and large intestinal sloughed cells and secretions(Larsen et al., 2000, Jansman et al., 2002).

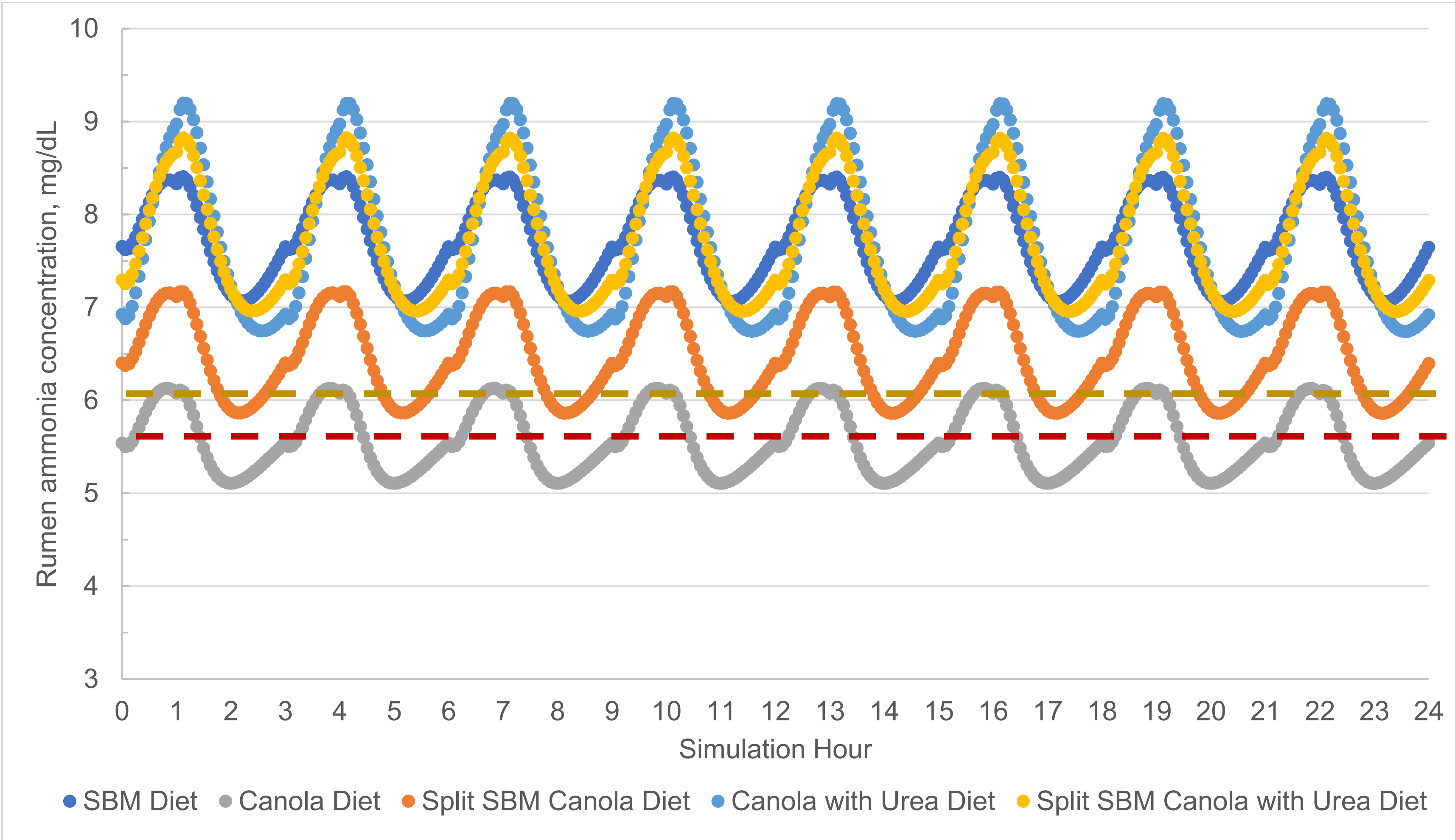

Figure 1. Rumen ammonia concentration, according to CNCPS v.7 after feeding a high forage diet (68% DM) with either A. 2.5 kg of soybean meal (SBM) included; B. 2.5 kg of canola meal included; C. 1.25 kg of SBM and 1.25 kg of canola meal included; D. 2.5 kg of canola meal with 125 grams of urea included; and E. 1.25 kg of SBM and 1.25 kg of canola meal with 125 grams of urea included. Within CNCPS v.7, microbial growth depression begins when ammonia concentration falls below 6.0 mg/dL and is significantly impactful when falling bellowing 5.5 mg/dL. Feed library values from the CNCPS were used to describe all feeds within this ration

Table 2. Output from CNCPS v.7 describing the flux and pool size of fiber fractions within the rumen. Outcomes aid in the determination of dry matter intake according to pdNDF or uNDF fill limits.

Fiber Fraction	Flux, $g \cdot d^{-1}$	Flux, kg $BW^{-1} \cdot d^{-1}$	Rumen pool size, g	Rumen pool Size, kg BW^{-1}
CHO B3; Fast	5187	0.69%	2070	0.28%
CHO B3; Slow	1405	0.19%	1421	0.19%
CHO B3; Total	6593	0.88%	3318	0.47%
NDF Recommendations[1]	-	1.27-1.47%	-	-
CHO C	1987	0.26%	4596	0.61%
uNDF Recommendations[1]	-	0.39-0.48%	-	0.48-0.62%

[1] Recommendations according to Cotanch et al. (2014)

Table 3. Metabolizable protein predictions from feed, bacteria, and protozoa under CNCPS v.7 predictions.

Metabolizable protein flows	Quantity
Feed MP, g	1349
Bacterial MP, g	1343
Protozoal MP, g	325
Feed MP, %	45.0%
Microbial MP, %	55.0%
Protozoal MP, % microbial supply	19.5%

Table 4. Rumen ammonia concentrations and associated microbial growth depression, both with provided minimum and maximums predicted over a day according to CNCPS v.7 predictions.

Rumen N concentrations	Mean	Max	Min
Rumen ammonia, mg/dL	9.3	11.1	8.1
Microbial growth depression			**% Depression**
Mean depression			0.0%
Minimum depression			0.0%
Maximum depression			0.1%

Table 5. Nitrogen supply transactions throughout the gastro-intestinal according to CNCPS v.7 predictions.

Parameter	Quantity	Parameter	Quantity
Ruminal transactions, g		**Duodenal flows, g**	
Feed		Non-ammonia nitrogen	777
Intake	664	Non-ammonia, non-microbial nitrogen	358
Degradation	359	Microbial nitrogen	506
Passage	224	**Small intestinal transactions, g**	
Free peptide and amino acids (PAA)		**Digested and absorbed**	
Degradation to ammonia	278	Feed	216
Uptake by NFC degrading bacteria	160	FC degrading bacteria	132
Uptake by protozoa	27	NFC degrading bacteria	194
Passage	38	Protozoa	79
Urea and Ammonia		Endogenous	38
Intake	81	Ammonia	29
Recycled	208	**Passage**	
Absorption	207	Feed	36
Passage	29	FC degrading bacteria	38
Uptake by FC degrading bacteria	191	NFC degrading bacteria	56
Uptake by NFC degrading bacteria	145	Protozoa	9
Excretion by protozoa	5	Endogenous	48
Microbial		Urea	96
FC degrading bacteria passage	170	**Large intestinal transactions, g**	
NFC degrading bacteria passage	250	Free PAA degraded to ammonia	13
Protozoal passage	87	Free PAA uptake by NFC degrading bacteria	13
Protozoal lysis and excretion	11	Ammonia absorption	163
Endogenous		FC degrading bacteria growth	20
Secretions	146	NFC degrading bacteria growth	27
Degradation	134	Feed excreted	36
Passage	12	Ruminal FC degrading bacteria excreted	37
		Ruminal NFC degrading bacteria excreted	56
		Ruminal protozoa excreted	9
		Endogenous excreted	33

Excretion and Productive Use

There is undoubtedly more pressure on dairy producers to evaluate and decrease nitrogen excretion, while maintaining productivity. As with the current version of the model, there will be excretion predictions for N and because of the model architecture, the user will be provided more information about the sources of N excretion and what typical values are and what can be modified (Table 5). This group aims to have users reference the breakout of nitrogen recycling along the gastro-intestinal tract, as partitioning of urea will be quantified in the rumen, small intestine, and large intestine. In doing so, users are encouraged to feed lower protein diets that will capture the native ability of a ruminant to recycle nitrogen, while minimizing excessive nitrogen loss in manure and maintain productive responses. A comprehensive outline of nitrogen excretion, including the sourcing of excreted nitrogen back to its origin, as well as quantifying metabolic urinary and urea urinary N, will provide the means to explicitly quantify and report excretion numbers for stakeholders and affiliated industries looking to inventory emissions and excretions on dairy farms. Our intent is to provide upper and lower boundaries for these excretion values and incorporate them into the current calculations based on grams of urinary urea N per unit of productivity N.

Efficiency of use has also become a means to measure productive efficiency of cattle, maximizes the productive output of cattle using more targeted nutrient supplies relative to predicted requirements. Amino acid efficiency of use, particularly describing with essential amino acids, has been made a priority within the CNCPS v.7. In addition to calculating the metabolizable gram amount of each essential amino acid, this supply is related to the metabolizable energy supply of the diet (Higgs and Van Amburgh, 2016). Efficiencies of use for each amino acid that are considered energetically optimum have been calculated and used to provide recommendations for the grams of metabolizable amino acid relative to metabolizable energy needed to achieve this efficiency. Users of the new version will be provided with these targets to formulate towards; however, the regressions used to calculate the optimum supply of amino acid relative to metabolizable energy will also provide the efficiency of use for varying supplies of amino acids which might not meet the recommended targets. This is to ensure that in the event nutritional or financial constraints or limitations in feed inventory are preventing the desired amino acid supply, the model will appropriately calculate an efficiency of use for these amino acids and allow the user with a better indication of productive expectations. Conversely, this system will produce marginal improvements in productive outputs if amino acids are supplied in excess, resulting in increased excretion of nitrogen relative to its intake.

Short- and Long-Term Goals

Not surprisingly, our contentment with this model is never satisfied and had it been, it would have reached the commercial space long before now. Currently, the CNCPS v.7 is being programed and packaged so that license holders may begin integrating this system into their existing software platforms. The development of the CNCPS, up until version 7, has existed in a spreadsheet environment that provides a ‘good-enough’ methodology for biologists to evaluate, modify, and update existing equations, while also building new equations in parallel. Version 7 of the model was built in a more spatial environment, allowing for the construction of a system that was more comprehensive and could function dynamically as it integrated biological relationships over a simulated day and as programmed over 10 days. This environment also placates to those who are more visually adept at understanding these concepts; however, it has become computationally burdensome to host a version on this platform. As such, our short-term goal of programming version 7 into a packaged system that retains all of its functional capabilities while be computationally efficient is of utmost importance.

Beyond the computational goals of this system, we continually aim to improve the nutrient supply and predicted requirements for cattle at all stages of life. Given the rate in which fatty acids research is expanding in dairy cattle, it is apparent that the expansion of the fatty acid sub-model is warranted. The further disaggregation of feed fractions to provide better resolution of their supply, particularly regarding five and six carbon sugars, soluble fibers and proteins, and perhaps a fractionation of starch to better define its degradability. Lastly, and perhaps of greatest importance, is the quantification of behavior and its changes over time on nutrient supply. Figure 1 provides a dynamic concentration of rumen ammonia over the course of a day; however, the CNCPS v.7 predicts this concentration cycle as redundantly symmetrical, implying that cattle eat the same amount of dry matter at all meals. This obvious departure from cattle behavior is one that would provide a more robust insight into the way nutrient flows, and by extension the deficiencies of those flow relative to requirements, change throughout a day if they were corrected. Future updates of the model will look to include a behavioral sub-model which will utilize current and new animal inputs provided by the user to provide a more accurate prediction of nutrients flows and productive outputs. Overall, the intent of the updated model is to provide better information about functions that should help nutritionists improve their understanding of what might be limiting milk yield through improved mechanistic solutions.

Now, if only we could get this model out quicker…thank for your continued patience, especially you, Dr. Sniffen.

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