Nutritional Approaches to Maximize N and P Efficiency

M. D. Hanigan and K. F. Knowlton
Virginia Polytechnic Institute and State University, Blacksburg

INTRODUCTION

The competitive nature of the US dairy industry provides significant monetary incentive to increase economic efficiency. Large gains in efficiency have been achieved through intensive genetic selection, which has dramatically increased milk production resulting in a dilution of the cost of maintaining the animal (Hansen, 2000). This strategy works because the partial efficiency to synthesize milk is constant for many nutrients including energy. Therefore the cost to produce each additional unit of milk is the same causing the proportional cost of maintaining the animal to decline as more milk is produced (Vandehaar, 1998).

Environmental concerns and regulations have heightened the awareness and the need to minimize overfeeding of N and P. Phosphorus run-off is one of the leading causes of fresh water eutrophication (Knowlton et al., 2004). One key change in water quality regulations in the past few years is the shift from a primary focus on N to an increasing focus on P contamination of surface water. The 2003 revision of federal Concentrated Animal Feeding Operation regulations calls for site-specific decisions on whether N- or P-based manure application limits are needed to protect water quality (EPA, 2003). Also, some federal cost-share funding is now being linked to the development and implementation of P-based nutrient management plans. Phosphorus-based nutrient management regulations dramatically increase the amount of land required to dispose of manure, and will have a severe, detrimental effect on the agricultural economy in areas of intensive animal agriculture.

Urinary N is rapidly converted to ammonia during manure collection and storage and volatilized into the atmosphere where it contributes to haze and visibility impairment. Ammonia also catalyzes the formation of small particles that penetrate deep into the lungs and thus are a health concern (Erisman and Monteny, 1998). It also is eventually deposited back on the surface in association with rainfall leading to surface water quality impairment (Sutton et al., 1993). The EPA (2004) estimated dairy operations to be responsible for 55 % (4.4 mil tons/yr) of the total annual NH_3 emissions inventory.

Manure application to land is currently regulated for many dairy operations via mandatory nutrient management plans, and the EPA has ruled that dairies of 700 cows or greater must notify Emergency Response officials if 100 lb or more of ammonia is emitted from their operation in a 24-h period (EPA, 2009).

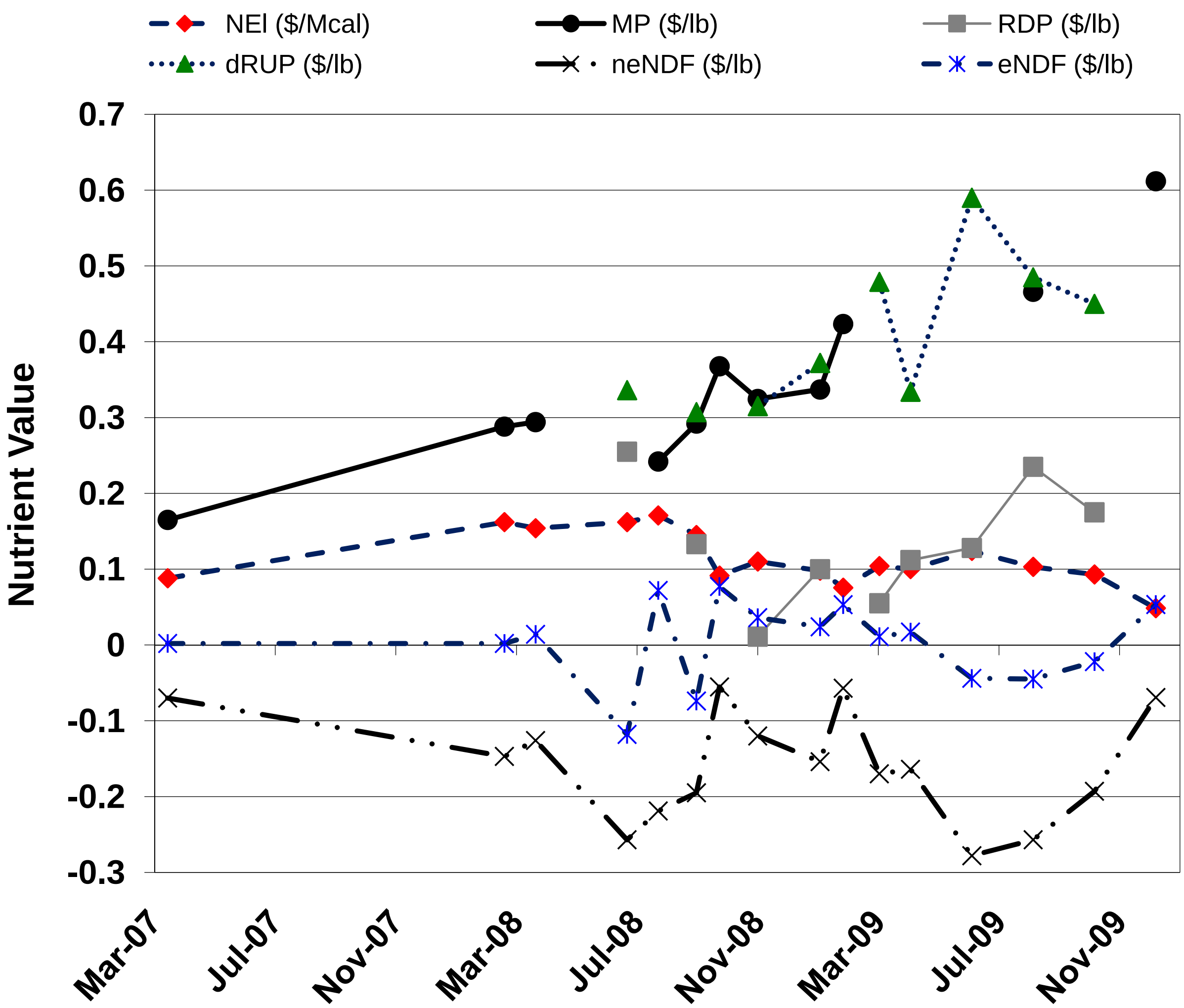
Nutrient Requirements and Efficiency

Nutritional research has focused on determining the amount of each nutrient required to just meet the needs of a given animal at varying levels of production. This approach is logical, although it will not necessarily guarantee maximal efficiency for each nutrient in every individual animal. However if efficiency is measured as excreted waste per unit of product produced, feeding to requirements should generally result in maximal industry efficiency.

If nutrients were readily available in pure form for a reasonable cost, it would be very easy to design feeding programs to meet the needs of a group of animals while minimizing overfeeding. However, such an approach is cost prohibitive. It is much more cost effective to purchase ingredients which contain multiple nutrients. The nutrient profile is, of course, different for each ingredient as is ingredient cost or value. The marketplace rationalizes the cost of the various ingredients depending upon supply and demand. The goal of designing a feeding program is to construct a mix of ingredients that meets all of the nutrient needs at minimum cost. Depending on the mix of ingredients, one or more nutrients may exceed requirements resulting in potential waste of that nutrient.

One can estimate the value of pure nutrients in the ingredient markets through examination of the value of a wide range of ingredients in a range of feeding programs. These nutrient values can be used to determine the cost of providing a dietary nutrient and the value of ingredients in dairy feeding programs relative to other ingredients. St-Pierre and Knapp periodically calculate the value of nutrients in the central Ohio market (Figure 1). For several years, energy has been the most costly nutrient in the ration, typically representing 60 % or more of the total ration cost. However, with the dramatic increase in the price of protein over the past year and the decline in energy costs, a majority of the cost of a lactating

Figure 1. Central Ohio nutrient costs in dairy rations for a 1500 lb cow producing 75 lb of milk/d at 3.1 % protein and 3.8 % fat from July of 2008 through October of 2009[1]. Evaluations generated values for either metabolizable protein or digestible ruminal undegraded protein but not both in the same run.



[1] Aggregated from the Buckeye Dairy News: http://dairy.osu.edu/bdnews/bdnews.html
[2] NE_L = net energy of lactation, RDP = ruminally degradable protein, dRUP = ruminally undegraded protein digestible in the small intestine, neNDF = noneffective NDF, eNDF = effective NDF.

Table 1. Least-cost diet formulations for varying dietary crude protein concentrations[1]. Rations were all designed to meet requirements of a 1300 lb cow consuming 51.8 lb DM and milking 77 lb/d with 3.2 % milk fat and 3.8 % milk protein using the NRC (2001) dairy requirement model. Inclusion rates for wheat straw and corn distillers were restricted to a maximum of 1 and 8 lb as fed/d, respectively. Vitamins and trace minerals were included in all rations to meet NRC requirements.

	Dietary Crude Protein, % of Dietary DM						
Ingredient	**15.0**	**15.5**	**16.0**	**16.5**	**17.0**	**17.5**	**18.0**
	----------------------------- % of Dietary DM ------------------------------						
Wheat Straw	1.66	1.79	1.79	1.79	1.79	1.79	1.79
Grass/legume silage	5.64	17.47	21.96	25.1	28.23	31.31	34
Corn silage	37.7	40.74	36.26	33.12	29.98	26.9	24.21
Corn grain, ground		18.48	15.77	13.05	10.38	7.9	4.18
Soybean meal, solvent	0.76				0.01	0.1	
Corn distillers	4.17		13.92	13.92	13.92	13.92	13.92
Wheat middlings	2.56	1.51	0.04	0.02			0.01
Soybean Hulls		2.04	4.11	6.94	9.72	12.27	15.81
Cottonseed meal	18.61	11.66	4.76	4.79	4.81	4.76	5.02
Tallow	5.71						
Limestone	5.19	1.37	0.37	0.24	0.11		
Dietary Nutrients							
NEL Mcal/lb DM	0.680	0.680	0.695	0.693	0.690	0.687	0.682
NDF % of DM	28.9	36.03	37.7	39.1	40.5	41.7	43.4
ADF % of DM	18.1	22.99	24.0	25.2	26.5	27.6	29.2
NFC % of DM	21.7	38.56	37.0	35.3	33.5	31.9	29.5
CP % of DM	15.0	15.5	16	16.5	17	17.5	18.0
MP g/d	2514	2495	2497	2498	2499	2500	2501
RDP g/d	2039	2260	2325	2424	2523	2620	2716
RUP g/d	1507	1396	1441	1460	1479	1497	1521
EE % of DM	8.0	3.06	3.9	3.9	3.8	3.7	3.6
Ash % of DM	21.0	6.74	6.1	6.2	6.5	6.7	7.0
Ca, % of DM	2	0.86	0.56	0.56	0.56	0.57	0.56
P, % of DM	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N Balance							
N Intake, lb/d	1.24	1.29	1.33	1.37	1.41	1.45	1.49
N in Milk, lb/d	0.39	0.39	0.39	0.39	0.39	0.39	0.39
N in Manure, lb/d	0.86	0.90	0.94	0.98	1.02	1.06	1.11
Efficiency, %	31.0	30.0	29.1	28.2	27.4	26.6	25.9
Cost, $/cow/d	$5.87	$4.22	$3.88	$3.87	$3.86	$3.85	$3.84

[1] Formulated using Formulate2® (Central Valley Nutritional Associates, LLC).

ration is now associated with provision of protein. A cow milking 77 lb/d at 3.2 % protein and 3.8 % fat has an energy requirement of 35.44 Mcal NE_L/d. The cost of meeting that requirement at a December 2009 cost of $0.048/mcal is $1.72 versus a cost of $3.37/d to meet her metabolizable protein (**MP**) requirements of 5.5 lb/d at a cost of $0.61/lb (see NRC, 2001 for requirements). Thus there is considerable economic incentive to maximize protein efficiency in feeding programs.

The cost of P in the ration has also increased over the past few years due to increased costs of mining and transportation and declining reserves of easily obtainable phosphate (Huang, 2009; USGS, 2007). However, it represents a very small proportion of total ration costs, and thus concerns over P revolve around animal performance and environmental impact.

Improving N or P efficiency encompasses efforts to minimize feed waste, minimize overfeeding of N and P relative to current requirements, and refine our requirement systems to better reflect true animal needs so that even lower levels of N and P can be fed.

Feed waste is clearly an economic drain on any dairy, and thus well managed operations actively work to minimize the occurrence. Thus we won't devote further time to this topic, although that should not be taken to indicate that this is a trivial matter.

Minimize Overfeeding of N and P

Feeding to meet N and P requirements has the implicit assumption that requirements are known with great accuracy. Unfortunately that is not true. However, they are known with an acceptable level of precision and accuracy. The 2001 NRC feeding system is likely the best prediction system for determining N and P requirements for the lactating cow (NRC, 2001). Predictions of dietary availability and the relationship between available supply and animal performance have been extensively evaluated for N flows. Less data are available for evaluation of the P digestion model (NRC, 2001). Other models, such as the CNCPS or CPM, have similar components but have not been as extensively tested.

Several methods have been developed and are in use to determine the ruminal and intestinal digestibility of various ingredients used in dairy rations. These methods allow more precise formulation of rations by reflecting variation in the N digestibility and availability for the various ingredients included in the ration. Thus the user can have more confidence that the diet being constructed will provide the nutrients required to support the desired level of production.

The 2001 NRC provides predictions of the absorbable supply of P and most other minerals, which allows some differentiation among the P availability of different ingredients. The P requirement was also reduced based on the work of Wu and coworkers (Wu and Satter, 2000a, b; Wu et al., 2001; Wu et al., 2000) resulting in little need for supplemental P sources under normal feeding conditions.

Both the NRC and the CNCPS/CPM models provide predictions of amino acid (**AA)** flow to the small intestine and information on AA requirements. The NRC AA flow model was derived from a large data set and found to accurately represent AA flows (NRC, 2001). However, the data available for assessing requirements is much more limited and thus it is not clear how well either model works relative to requirements. This limits our ability to construct low protein rations supplemented with limiting AA as is commonly done in the poultry and swine industries.

Despite the limitations in our requirement system, using the current requirement systems should allow formulation of a range of diets to meet needs with less risk of encountering a deficiency than when using older models. To take full advantage of these newer requirement models requires software that allows least cost formulation and uses the newer requirement system. This allows the user to specify limits or maximums for nutrients to achieve greater nutrient efficiency. However, it is important to recognize that forcing down nutrient levels in the ration to achieve greater efficiency will likely result in added ration cost. These costs must be weighed against benefits that might be derived from efficiency gains, such as reduced environmental impact, or costs associated with manure transport.

To have the best chance of devising rations with minimal excess nutrients, it is also advantageous to offer many ingredients for use. This provides more flexibility in mixing ingredients to achieve a ration that meets nutrient requirements but does not overformulate for key nutrients such as N and P.

Using ingredients and ingredient prices from the East Coast and Formulate2® (Central Valley Nutritional Associates, LLC, Visalia, CA) to derive a series of least cost rations, one can see that forcing

Table 2. Least-cost diet formulations for varying dietary phosphorus concentrations[1]. Rations were all designed to meet requirements of a 1300 lb cow consuming 51.8 lb DM and milking 77 lb/d with 3.2 % milk fat and 3.8 % milk protein using the NRC (2001) dairy requirement model. Inclusion rates for wheat straw and corn distillers were restricted to a maximum of 1 and 8 lb as fed/d, respectively. Vitamins and trace minerals were included in all rations to meet NRC requirements.

	Dietary P, % of DM							
Ingredient	**0.31**	**0.33**	**0.35**	**0.37**	**0.39**	**0.41**	**0.43**	**0.45**
	------------------------------ % of Dietary DM ------------------------------							
Wheat, straw	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79
Legume Hay	11.73	0.35						
Grass/legume silage	0.14	12.03	15.17	26.37	28.24	34.57	35.15	32.49
Corn, silage	31.35	33.78	42.62	31.84	29.98	23.64	23.06	25.72
Corn		0.22		0.78	1.64	14.44	17.21	14.3
Soybean meal, Solvent	3.71	3.3	4.61	3.31	0.24	0.08		
Corn Disitillers	12.09	13.92	13.92	13.92	13.92	13.92	13.92	13.92
Wheat, middlings							1.87	4.85
Soybean, hulls	38.07	33.36	20.6	19.52	18.33	5.92	1.24	1
Cotton seed meal				1.41	4.81	4.6	4.64	4.76
Tallow		0.01						
Limestone	0.07	0.18	0.24			0.01	0.07	0.13
Dietary Nutrients								
NEL , mcal/lb DM	0.69	0.69	0.69	0.68	0.68	0.69	0.7	0.7
MP, g/d	2495	2499	2499	2500	2501	2499	2498	2498
CP, % of DM	16.19	16.11	16.35	17.5	17.5	17.5	17.5	17.5
NFC, % of DM	27.68	28.15	29.65	28.86	28.79	35.05	36.78	35.96
NDF, % of DM	48.51	47.6	45.16	44.77	44.83	38.3	36.42	37.2
ADF, % of DM	33.24	32.07	29.79	30	30.04	25.07	23.33	23.42
EE, % of DM	3.55	3.73	3.73	3.64	3.66	3.79	3.86	3.89
Ash, % of DM	5.31	5.56	5.73	6.53	6.65	6.68	6.64	6.54
Ca, % of DM	0.56	0.56	0.56	0.57	0.58	0.56	0.56	0.56
P Balance								
P Intake, g/d	73	78	82	87	92	96	101	106
Milk P, g/d	31	31	31	31	31	31	31	31
Manure P, g/d	38	43	47	52	57	62	66	71
Efficiency, %	48	45	42	40	38	36	35	33
Cost, $/cow/d	4.23	4.13	4.09	4.05	4.01	3.98	3.94	3.90

[1] Formulated using Formulate2® (Central Valley Nutritional Associates, LLC).

dietary CP down from 18 to 16 % can be achieved with minimal cost. However attempting to achieve solutions of 15.5 % CP or less resulted in considerable additional cost and, in the latter case, a ration that would not be suitable for dairy cattle (NRC, 2001) This was achieved by replacing soyhulls and mixed legume forages with corn silage and ground corn grain.

The same can be achieved for dietary P, however, there are costs associated with the reductions starting already at levels well above requirements (NRC, 2001). Low P diets used less legumes, corn grain, cottonseed meal, and more corn silage, soyhulls, and soybean meal. Corn distillers had tremendous value in the ration despite their high P levels, as evidenced by maximal use until dietary P was set at 0.31 % (below requirements). To move the ration from greater than 0.4 % P to the requirement at 0.35 % P costs greater than \$0.14/cow/d, which is significant. However, this cost must be weighed against the cost of transporting manure or limits on facility size. Because all of the excess dietary P ends up in manure, a small change in dietary P intake can result in significant reductions in manure P concentrations (Knowlton and Herbein, 2002)

Can We Do Better?

N Efficiency

The efficiency of use of dietary N is influenced both by losses to microbial action in the rumen and catabolism of AA by body tissues. The former are related to the amount of ruminally degradable protein (**RDP**) being fed, and the latter are related to the amount of MP being fed. An excess of either results in reduced efficiency.

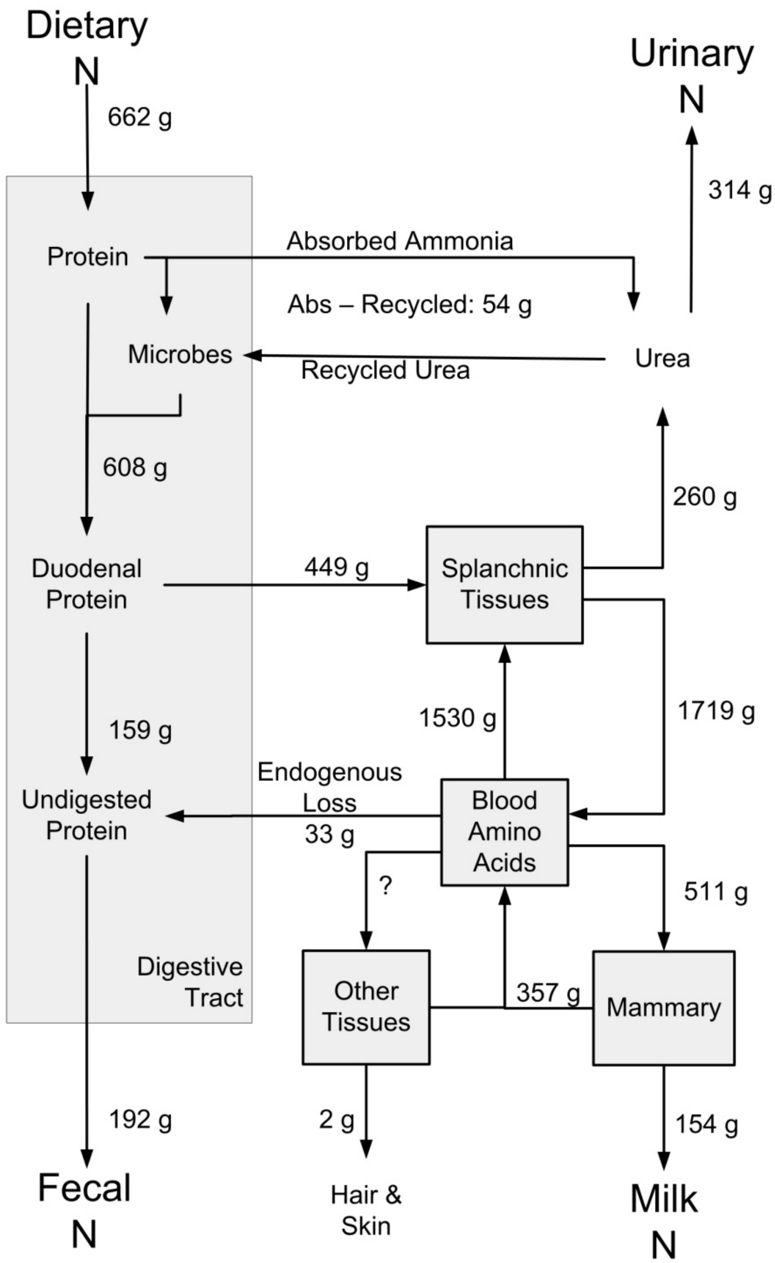
Most of the inefficiencies in N use are related to post-absorptive metabolism (Hanigan et al., 1998a). Of the N absorbed only one third of it is used to produce milk protein. The remaining two-thirds is catabolized and the N largely excreted as urea in urine (Bristow et al., 1992; James et al., 1999) Of the urea synthesized each day, a large proportion of it re-enters the gut where it can be reduced to ammonia (Gozho et al., 2008). This is useful if the released ammonia is captured by the microbes and used to synthesize new microbial protein. Clearly feeding highly fermentable diets can improve the capture of this recycled N in microbial protein (McCarthy et al., 1989), but this does little good if it does not also stimulate AA use for milk protein or dietary protein is not reduced. In the absence of either of those changes, the newly synthesized protein will be digested and absorbed, but since the need for absorbed AA has not increased (milk protein output remains unchanged), the absorbed AA will be catabolized again and the released N returned to the urea pool; around and around we go. So if the increased ruminal fermentability of the diet does not also stimulate milk protein production, dietary RDP should be reduced. While this will make the animal more efficient and reduce N excretion in urine, it will have little impact on dietary costs due to the relatively low cost of RDP in the diet (Figure 1). Conversely, if it is important to reduce N excretion for environmental purposes, achieving such reductions through reduced dietary RDP will also have little cost.

Urea recycling to the rumen is not adequately represented in our current requirement models, which means current RDP requirements may be greater than needed. As noted above, increased fermentable carbohydrate will stimulate microbial growth; which will use more of the recylcled N. Since our RDP requirements don't reflect this variation, there is a lost opportunity to reduce RDP levels when feeding those types of diets and gain efficiency.

There are several studies that have shown that cows can successfully be fed diets with reduced RDP (Huhtanen and Hristov, 2009). However, digestion work has resulted in mixed results. A recent study we conducted clearly demonstrated that microbial growth was compromised when dietary RDP dropped below requirements (Cyriac et al., 2009), but the same diets did not precipitate a loss in production suggesting that MP requirements may be greater than needed (Cyriac et al., 2008).

Another limit in our requirement systems is the approach of balancing for MP first and then looking at AA as a proportion of MP. The tissues of the body require AA; MP is a provider of AA but tells us nothing about the mix of AA being provided. Work in pigs has demonstrated that post-absorptive use of N can be up to 85 % efficient when the supply of AA are well matched to tissue needs (Baker, 1996). Again, this is easy to accomplish with purified diets but certainly not the best economic solution. But if we could reduce dietary MP and supplement with selected AA to address deficiencies, we should be able to improve post-absorptive efficiency of lactating cows from the current 33 % to at least 50 % efficiency or even greater. This should result in substantial cost savings (provided the cost of AA is not too great) and improvements in overall N efficiency (Figure 1). But to achieve this goal requires a much better understanding of the relationship between individual AA supply and milk production.

Figure 2. Schematic of protein metabolism in the lactating ruminant. Arrows indicate fluxes and numbers indicate flux rates (g N/d). Fluxes were calculated from the 17.9 % CP treatment of Ipharraguerre and Clark (2005).



Response curves for methionine and lysine have been established (NRC, 2001). Methionine and lysine responses across diets seem to be fairly repeatable (Pisulewski et al., 1996; Robinson et al., 1995) although the marginal efficiency of conversion of absorbed lysine to milk lysine is relatively low (Armentano et al., 1997; Vyas and Erdman, 2009). Work with other AA has not progressed significantly.

As part of the above effort to better understand AA requirements, we also need to recognize that our current methods for determining nutrient limitations is inappropriate and is likely preventing us from achieving maximal efficiency. Although mammary affinity for AA is relatively high, about 50 % of the AA presented are not utilized (Hanigan et al., 1998b). These unused AA are then returned to general circulation where they are subject to clearance and catabolism by other tissues (Hanigan, 2005). Thus the assumptions underlying our protein and AA requirement systems are not exactly correct. We could increase production on the same supply of AA, if we could stimulate mammary tissue to take up more AA and use it to synthesize milk protein; which would reduce recycling to other tissues and catabolism. There are plenty of AA floating around the system, we simply have to figure out how to feed the cow to maximize the proportion going to milk protein and minimize the proportion going to waste.

A key deficiency in our current protein and AA requirement systems is the assumption that a single nutrient limits performance. Work at the cellular level has identified key regulatory systems that sense hormonal signaling, energy status of the cell, and AA supply within the cell and integrate the signals to set the rate of protein synthesis (Appuhamy et al., 2009; Bell et al., 2009). This is important relative to our requirement systems because multiple AA, cellular energy supply, and at least insulin and IGF-1 concentrations in blood all interact to set the rate of protein synthesis. Based on this, one would expect the cell to be more efficient at extracting AA when energy supply and insulin and IGF-1 concentrations are high, i.e. a high energy diet is being fed. Indeed, this appears to be the case (Rius et al., 2007). Rius fed animals a protein deficient diet, as evidenced by their responsiveness to added dietary protein. However, the animals had even greater production responses when the low protein diet was supplemented with energy, which greatly improved N efficiency. This work demonstrates 2 limitations in our current requirement system:

1. Multiple nutrients limit production simultaneously; and
2. Post-absorptive efficiency is a variable function that is influenced by the mix of nutrients being fed.

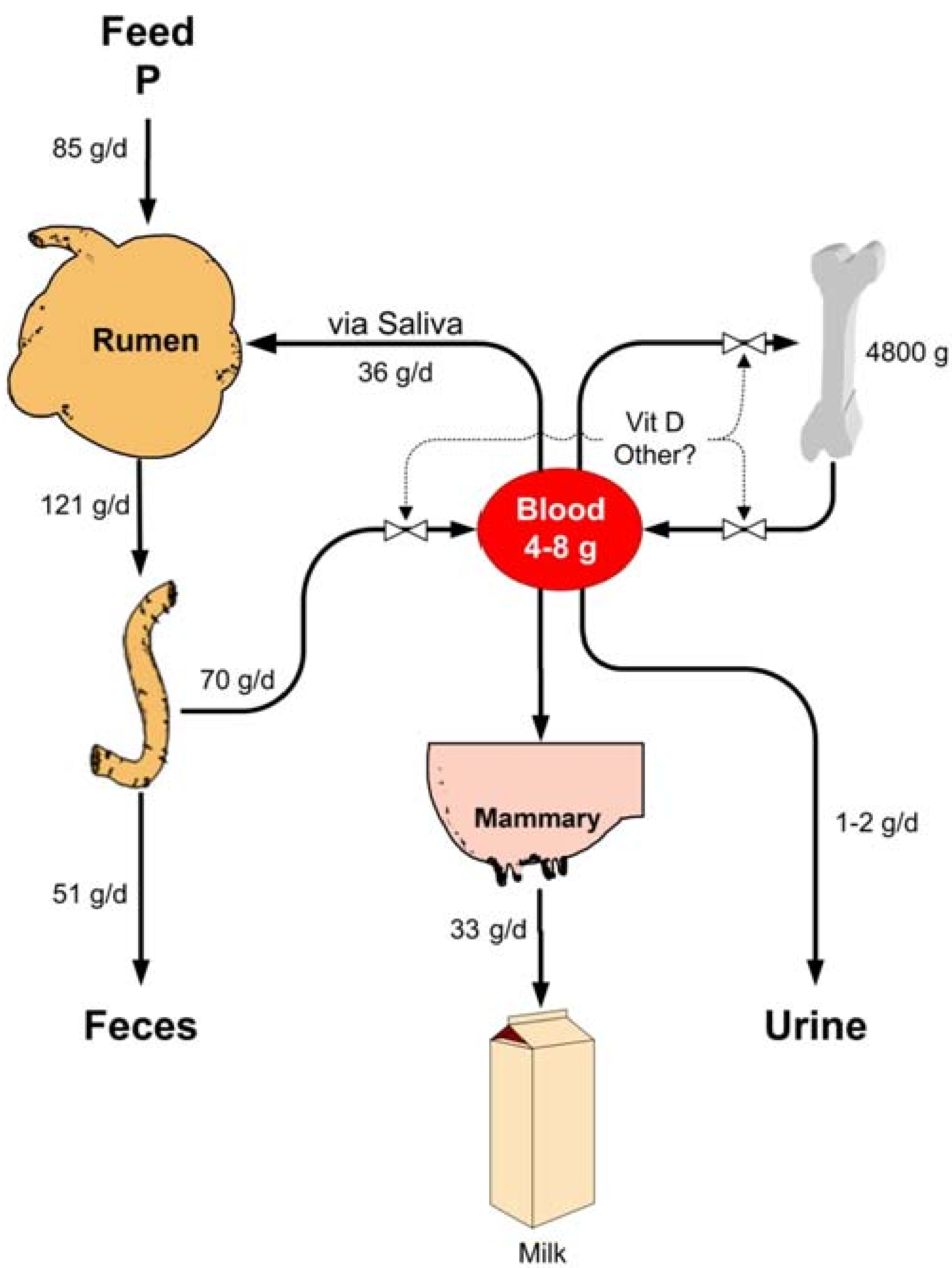
We need to alter our current requirement systems to reflect the fact that efficiency is variable and rederive our AA and MP requirement equations considering the potential interaction and the regulatory roles of each. Hopefully this work will occur and be incorporated into a future NRC model. But in the absence of such a change, it would seem that MP requirements could be undercut when feeding high energy diets. Of course, there is always a risk of losing production when making such calculated wagers; but given current protein prices, it may be worth a trial run with assessment of milk production after a couple of weeks on the diet.

P Efficiency

Phosphorus efficiency in ruminants is considerably better than N efficiency when animals are fed to NRC requirements. The apparent digestibility of P is approximately 45 %. True digestibility is considerably greater, but a large amount of the absorbed P is recycled to the rumen in saliva. Absorption from the gut is regulated to meet demand, and thus the digestion coefficient is variable depending on the dietary supply and post-absorptive use (Hibbs and Conrad, 1983). When dietary supply is high relative to use, the apparent digestibility is reduced, and the reverse when dietary supply is low. This adaptability can buffer large changes in dietary supply.

For years, P was considerably overfed to dairy cattle due to the perception that reproductive performance was responsive to P supply. Given the consistent loss in reproductive performance of the national dairy herd over the past 50 yr, there was considerable pressure to keep dietary P high assuming this would help address the problem. The original evidence for an effect of P on reproduction indicated that reproductive performance declined with dietary concentration were 0.2 % of dietary DM, which is considerably below the 0.45-0.6 % that had become common practice in the industry by the late 1990s. Wu and coworkers (Wu and Satter, 2000a, b; Wu et al., 2001; Wu et al., 2000) clearly demonstrated that reproductive and productive performance were not affected by P concentrations down to at least 0.32 %, and fecal P excretion declined proportional to the dietary P level.

Figure 3. A schematic representation of phosphorus flow in a lactating dairy cow.



Constructing diets with P levels of 0.32 % was generally cost effective, particularly to the extent that inorganic sources of P were removed from feeding programs. However the national craze to convert corn to ethanol has generated a byproduct, distillers grain, that is much higher in P than the parent corn, due to the concentration of the P present in the parent material. The market is flooded with this byproduct; making it very attractive from a price standpoint. Thus achieving diets with low P is not economically advantageous, as it can only occur by displacement of ingredients that are providing other nutrients at a cost advantage.

Basing rations all or mostly on byproducts has another potential risk. Clearly diets with 0.32 % P are much closer to true requirements than diets with 0.5 % P. Phosphorus availability in the various ingredients being fed hardly matters when cows are overfed by 50 %. But when feeding close to requirements, the chance of encountering a deficiency due to inaccurate or incomplete information on P digestibility is greater. The availability of P in feedstuffs are based on relatively few studies (Martz et al., 1999; Young et al., 1966). The NRC model provides the ability to consider varying digestibility by ingredient, but P digestibility data for the myriad of byproducts fed to dairy cattle is limited. Thus confidence that the general digestibility values will apply to each of these ingredients is necessarily less.

One determinant of P digestibility of any ingredient is the form of the P. Phosphorus is absorbed only in an inorganic, soluble form. Organically bound P, including that bound in phytate must be digested to an inorganic form before it can be absorbed. Much of the P present in grain is bound in phytate. The enzyme, phytase, is required to release P from phytate, but is not synthesized by mammals. Thus in monogastrics, exogenous phytase is commonly added to diets to liberate the phytate bound P making it available for absorption. It has been assumed that phytate was well digested in ruminants due to the synthesis of phytase by ruminal microbes. However, quantitative work indicate that as much as 50 % of the phytate bound P is not available for absorption in lactating cows (Duskova et al.; 2001, Hill et al., 2008). Variation in phytate amount and in phytase activity may cause significant variation in P digestibility across and within ingredients (Konishi et al., 1999; Park et al., 1999; Park et al., 2000, Park et al., 2003). The remaining organically bound P is intermediate in digestibility to that of inorganic and phytate, and this value is not well defined.

Knowlton and coworkers have devised a scheme to derive digestibilities for the 3 main forms of P in the diet: inorganic, phytate, and organic excluding phytate. Currently they are working to assess phytate digestibility and to determine the concentrations of each fraction in a wide range of byproduct feeds. Combining this with additional animal work to better define phytate and other organic P digestibilities will allow digestibilities to be assigned to a broad range of feeds, providing greater precision when balancing for P supply to the animal.

Based on current knowledge, it seems that dairy cattle could be managed to have higher P efficiencies by reducing dietary P levels. With current ingredient prices, this would likely have a cost associated with it. Given that only soluble, inorganic forms of P are absorbed, additional dietary P could be made available through the use of supplemental phytase; but this will only improve efficiency if its use is associated with reductions in dietary P. The cost of adding phytase and reducing dietary P must be weighed against the benefits of reducing manure P levels. Given the uncertainty associated with current phytate digestibilities across a range of ingredients, the use of phytase may provide additional insurance that a deficiency is not encountered when fed at current requirements.

REFERENCES

Appuhamy, J. A. D. R. N., A. L. Bell, J. Escobar, and M. D. Hanigan. 2009. Effects of essential amino acid deprivation on protein synthesis signaling in bovine mammary epithelial cells *in-vitro*. Pages 424-425 in XIth International Symposium on Ruminant Physiology. Wageningen Academic Publishers, Clermont-Ferrand, France.

Armentano, L. E., S. J. Bertics, and G. A. Ducharme. 1997. Response of lactating cows to methionine or methionine plus lysine added to high protein diets based on alfalfa and heated soybeans. J. Dairy Sci. 80:1194-1199.

Baker, D. H. 1996. Advances in amino acid nutrition and metabolism of swine and poultry. *In:* Nutrient management of food animals to enhance and protect the environment. E. T. Kornegay, ed. CRC Lewis Publishers, Boca Raton, FL. pp. 11-22.

Bell, A. L., J. A. D. R. N. Appuhamy, J. Escobar, and M. D. Hanigan. 2009. Insulin and essential amino acids have significant but independent effects on protein synthesis signaling in bovine mammary epithelial cells in-vitro. J. Dairy Sci. 92(e-Suppl 1):472.

Bristow, A. W., D. C. Whitehead, and J. E. Cockburn. 1992. Nitrogenous constituents in the urine of cattle, sheep and goats. J. Sci. Food Agric. 59:387-394.

Cyriac, J., A. G. Rius, J. A. D. R. N. Appuhamy, R. E. Pearson, J. H. Herbein, K. F. Knowlton, J. L. Firkins, and M. D. Hanigan. 2009. Varying ruminally degradable protein concentrations in the lactating dairy cow diets maintains rumen fiber digestion and outflow of nutrients. J. Dairy Sci. 92(e-Suppl. 1):1.

Cyriac, J., A. G. Rius, M. L. McGilliard, R. E. Pearson, B. J. Bequette, and M. D. Hanigan. 2008. Lactation performance of mid-lactation dairy cows fed ruminally degradable protein at concentrations lower than National Research Council recommendations. J. Dairy Sci. 91:4704-4713.

Duskova, D., R. Dvorak, V. Rada, J. Doubek, and M. Marounek. 2001. Concentration of phytic acid in faeces of calves fed starter diets. Acta Vet. Brno. 70:381-385.

EPA. 2003. National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations: Final Rule.

EPA. 2004. National Emission Inventory - Ammonia Emissions from Animal Husbandry Operations. USEPA.

EPA. 2009. Emergency Planning and Community Right-to-Know Act (EPCRA) Requirements. Online. Available: http://www.epa.gov/emergencies/content/epcra/index.htm.

Erisman, J. W. and G. J. Monteny. 1998. Consequences of new scientific findings for future abatement of ammonia emissions. Environ. Pol. 102(1, Supplement 1):275-282.

Gozho, G. N., M. R. Hobin, and T. Mutsvangwa. 2008. Interactions between barley grain processing and source of supplemental dietary fat on nitrogen metabolism and urea-nitrogen recycling in dairy cows. J. Dairy Sci. 91:247-259.

Hanigan, M. D. 2005. Quantitative aspects of ruminant splanchnic metabolism as related to predicting animal performance. J. Anim. Sci. 80:23-32.

Hanigan, M. D., J. P. Cant, D. C. Weakley, and J. L. Beckett. 1998a. An evaluation of postabsorptive protein and amino acid metabolism in the lactating dairy cow. J. Dairy Sci. 81:3385-3401.

Hanigan, M. D., J. France, D. Wray-Cahen, D. E. Beever, G. E. Lobley, L. Reutzel, and N. E. Smith. 1998b. Alternative models for analyses of liver and mammary transorgan metabolite extraction data. Br. J. Nutr. 79:63-78.

Hansen, L. B. 2000. Consequences of selection for milk yield from a geneticist's viewpoint. J. Dairy Sci. 83:1145-1150.

Hibbs, J. W., and H. R. Conrad. 1983. The relationship of calcium and phosphorus intake and digestion and the effects of vitamin D feeding on the utilization of calcium and phosphorus by lactating dairy cows. Pages 1-23. The Ohio State University, Ohio Agric. Res. Dev. Center, Wooster, OH.

Hill, S. R., K. F. Knowlton, E. Kebreab, J. France, and M. D. Hanigan. 2008. A model of phosphorus digestion and metabolism in the lactating dairy Cow. J. Dairy Sci. 91:2021-2032.

Huang, W. Y. 2009. Factors contributing to the recent increase in U.S. fertilizer prices, 2002-08. AR-33. Pages 1-21. Economic Research Service/USDA, Washington, DC.

Huhtanen, P., and A. N. Hristov. 2009. A meta-analysis of the effects of dietary protein concentration and degradability on milk protein yield and milk N efficiency in dairy cows. J. Dairy Sci. 92:3222-3232.

Ipharraguerre, I. R., and J. H. Clark. 2005. Impacts of the source and amount of crude protein on the intestinal supply of nitrogen fractions and performance of dairy cows. J. Dairy Sci. 88 (Suppl 1):E22-E37.

James, T., D. Meyer, E. Esparza, E. J. Depeters, and H. PerezMonti. 1999. Effects of dietary nitrogen manipulation on ammonia volatilization from manure from Holstein heifers. J. Dairy Sci. 82:2430-2439.

Knowlton, K. F. and J. H. Herbein. 2002. Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. J. Dairy Sci. 85:1227-1236.

Konishi, C., T. Matsui, W. Park, H. Yano, and F. Yano. 1999. Heat treatment of soybean meal and rapeseed meal suppresses rumen degradation of phytate phosphorus in sheep. Anim. Feed Scie. Tech. 80:115-122.

Martz, F. A., A. T. Belo, M. F. Weiss, and R. L. Belyea. 1999. True absorption of calcium and phosphorus from corn silage fed to nonlactating, pregnant dairy cows. J. Dairy Sci. 82:618-622.

McCarthy, R. D., T. H. Klusmeyer, J. L. Vicini, J. H. Clark, and D. R. Nelson. 1989. Effects of source of protein and carbohydrate on ruminal fermentation and passage of nutrients to the small intestine of lactating cows. J. Dairy Sci. 72:2002-2016.

NRC. 2001. Nutrient Requirements of Dairy Cattle, 7th rev. ed. National Academy Press, Washington, D.C.

Park, W., T. Matsui, C. Konishi, S. Kim, F. Yano, and H. Yano. 1999. Formaldehyde treatment suppresses ruminal degradation of phytate in soyabean meal and rapeseed meal. British Journal of Nutrition 81(6):467-471.

Park, W. Y., T. Matsui, F. Yano, and H. Yano. 2000. Heat treatment of rapeseed meal increases phytate flow into the duodenum of sheep. Anim. Feed Sci. Tech. 88:31-37.

Park, W. Y., T. Matsui, and H. Yano. 2003. Post-ruminal phytate degradation in sheep. Anim. Feed Sci.Tech. 101:55-60.

Pisulewski, P. M., H. Rulquin, J. L. Peyraud, and R. Verite. 1996. Lactational and systemic responses of dairy cows to postruminal infusions of increasing amounts of methionine. J. Dairy Sci. 79:1781-1791.

Rius, A. G., M. L. McGilliard, and M. D. Hanigan. 2007. Effect of dietary energy and metabolizable protein in lactating dairy cows. J. Dairy Sci. 90(Suppl. 1):213.

Robinson, P. H., A. H. Fredeen, W. Chalupa, W. E. Julien, H. Sato, T. Fujieda, and H. Suzuki. 1995. Ruminally protected lysine and methionine for lactating dairy cows fed a diet designed to meet requirements for microbial and postruminal protein. J. Dairy Sci. 78:582-594.

Sutton, M. A., C. E. R. Pitcairn, D. Fowler, M. Begon, and A. H. Fitter. 1993. The exchange of ammonia between the atmosphere and plant communities. *In:* Adv. in Ecol. Res. Vol. 24. Academic Press, pp 301-393

USGS. 2007. 2006 Minerals Yearbook: Phosphate rock. United States Geiological Survey, Washington, DC.

Vandehaar, M. J. 1998. Efficiency of Nutrient Use and Relationship to Profitability on Dairy Farms. J. Dairy Sci. 81:272-282.

Vyas, D., and R. A. Erdman. 2009. Meta-analysis of milk protein yield responses to lysine and methionine supplementation. J. Dairy Sci. 92:5011-5018.

Wu, Z. and L. D. Satter. 2000a. Milk production and reproductive performance of dairy cows fed two concentrations of phosphorus for two years. J. Dairy Sci. 83:1052-1063.

Wu, Z.**,** and L. D. Satter. 2000b. Milk production during the complete lactation of dairy cows fed diets containing different amounts of protein. J**.** Dairy Sci**.** 83:1042-1051.

Wu, Z., L. D. Satter, A. J. Blohowiak, R. H. Stauffacher, and J. H. Wilson. 2001. Milk production, estimated phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. J. Dairy Sci. 84:1738-1748

Wu, Z., L. D. Satter, and R. Sojo. 2000. Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. J. Dairy Sci. 83:1028-1041.

Young, V. R., G. P. Lofgreen, and J. R. Luick. 1966. The effects of phosphorus depletion, and of calcium and phosphorus intake, on the endogenous excretion of these elements by sheep. Brit**.** J**.** Nutr**.** 20**:**795-805.