

Protein Nutrition of Dairy Cattle – An Overview

Fred Owens¹
DuPont Pioneer

Abstract

Based on performance trials with lactating and feedlot cattle, the maximum milk yield and rate of gain were achieved only when the dietary protein concentration reached 20.6 and 15.2%, respectively. Because these concentrations are considerably greater than those in commercially fed rations, altering the protein source to supply a larger quantity of specific amino acids or supplying post-ruminal amino acids has been proposed to improve productivity. But which specific amino acids are inadequate for maximum production and to what degree has proven difficult to assess and production responses to amino acid supplementation have proven variable and inconsistent (Robinson, 2010). Considering the wide diversity in composition and in processing of both energy and protein sources being fed to ruminants, variability in production responses should not be surprising. Presumably, this variability can be because 1) amino acid requirements for ruminants are not defined adequately and 2) the supply and availability of amino acids from both microbes and dietary protein that escapes ruminal fermentation are not predicted precisely. Comparison of measured values with those predicted by NRC equations for the intestinal supply of microbial protein and ruminal escape of dietary protein revealed lack of both precision and accuracy. In addition to increasing the supply of amino acids for ruminants, an elevated protein concentration has also consistently increased feed intake and diet digestibility. Whether intake is increased due to effects of an increased supply of limiting amino acids or some indirect response associated with altered digestion or physiology is not clear. Through increasing water consumption and ruminal turnover, additional dietary protein could indirectly increase the efficiency of microbial protein production and ruminal escape of dietary protein sources. Although field tests sometimes detect performance responses to supplementation with specific sources of amino acids, extrapolation of results to other dietary or production conditions must await further refinement in models that predict metabolizable protein as well as specific amino acid requirements for both production and maintenance.

Introduction

Systems for evaluating the requirements for dietary protein for growth and lactation of ruminants have evolved during the last 50 years from simply measuring performance responses to various dietary crude protein concentrations to quantitative estimates of the small intestinal supply of protein (metabolizable amino acids) and estimates of amino acid requirements for production and maintenance. This evolution

¹ Contact at: DuPont Pioneer, Johnston, IA 50131; Phone: (515) 535-6416; Email: Fred.owens@pioneer.com

reflects a deepening understanding of microbial protein synthesis in the rumen and the amino acid composition of ruminant products. In contrast, estimates of amino acid requirements for maintenance have remained elusive.

Our comprehension of amino acid (and protein) metabolism and requirements for animals and humans is based on knowledge gained from thousands of studies conducted with non-ruminants as discussed in detail by the World Health Organization (2007). Among 26 amino acids, 8 to 12 are considered “essential” to include in the diet for various non-ruminant species. The non-essential amino acids can be synthesized by body tissues at a rate sufficient to meet the need for production, but to achieve maximum rates of production, additional amounts of the essential amino acids must be supplied in the diet. Thanks to ruminal bacteria, ruminants have an internal supply of essential amino acids, which are manufactured by microbes within the rumen if and when these microbes have an adequate supply of energy, ammonia and/or peptides, and sulfur. Although the supply of essential amino acids from ruminal microbes is sufficient for survival and low rates of production, dietary supplementation with essential amino acids is required to achieve the high rates of gain by young growing animals or of milk production achieved commercially.

Briefly, when an essential amino acid is limiting, adding it stepwise to the diet for a non-ruminant will increase growth rate, protein retention, other indicators of protein status (even immune responsiveness) until some response plateau is reached (Figure 1). The break between the upslope and the plateau represents the point when the amount of this essential amino acid first fully meets the requirement for that amino acid for the specific response being measured and thereby is considered to be the dietary requirement for the amino acid being studied. (In fact, this break-point simply represents the point where some other amino acid, nutrient, or energy places a ceiling on the response by the animal or bird.) Intake of an individual amino acid beyond this plateau may increase performance slightly due to hormonal (e.g., growth hormone) or antibacterial effects. However, intake of a large excess of single essential amino acids relative to other amino acids typically depresses performance due to antagonisms among amino acids, an imbalance, or toxicity, each of which can depress energy intake and performance. Note that a diet devoid of the essential amino acid may result in a negative response (e.g., weight loss). This indicates that essential amino acids are used both for maintenance and production. Only after maintenance needs are met can an amino acid be used for production.

When supply of an amino acid exceeds the amount required, the excess must be degraded. Surplus amounts of an amino acid will elevate its concentration in blood plasma and increase its rate of oxidation by liver, kidney, or muscle tissue. Consequently, plasma concentrations and rates of amino acid oxidation can and are used as indicators of the adequacy of individual essential amino acids. Conversely, when one amino acid is deficient, the supply of all other amino acid exceeds the amount needed and those excesses must be oxidized. Consequently, the rate of oxidation of a check amino acid will decrease as a limiting amino acid is added to the diet until the requirement for the limiting amino acid is met. Within a group of animals or birds given

free choice access to feed, the break point will differ among individuals due to differences in genetics, in amino acid metabolism or oxidation, or in feed intake. Therefore, when measured within a group of animals, the break point is less abrupt than illustrated in Figure 1 but instead is curved so requirements usually are assessed through curvilinear regression analysis.

Dietary protein requirements for maximum production can be assessed in a similar fashion as for individual amino acids. Again, the break point will vary with various factors (level of production, differences in animal or bird size or feed intake that can influence maintenance requirements, or with differences in the concentration of the second limiting nutrient in the diet), so estimates of required amounts of either amino acids or protein calculated across studies become less precise.

Protein Requirement Models and Systems

The Classical Protein Requirement Model

Traditionally, protein requirements for maximum production of ruminants were assessed and developed by the dose-response measurements discussed above. Performance or production was measured for groups of animals fed a single diet supplemented with various concentrations of protein. When milk production or rate of gain increased when additional protein was provided, the lower protein concentration was considered to be inadequate. Conversely, when removal of protein from a diet failed to reduce animal productivity, the supply of protein provided by the diet was considered to be above the protein requirement already. Various mathematical and statistical models (e.g., curvilinear or broken line regression procedures) have been employed to determine the break point or the requirement. Such an approach can be used in the field by livestock producers for assessing whether or not the protein requirement is being met for a group of animals with a given genetic merit when being fed a specific diet. Unfortunately, small changes in production may not be easily or rapidly detected, particularly with growing or non-lactating ruminants.

If the cost of supplemental sources of dietary protein is high, maximum productivity may not be the most economical level for production. In contrast, when low-cost feeds rich in protein (e.g., distillers' grains) are fed, least cost diets may contain much more protein than required and lowering the protein concentration of the diet may increase cost of the diet (Stewart et al., 2012).

To estimate crude protein requirements of lactating dairy cows, data from multiple experiments must be compiled and analyzed. Consequently, data from 25 lactation trials involving 75 different diets fed to a total of 1151 cows were assembled in the current study. Most of these trials were published after the 2001 NRC Nutrient Requirements for Dairy Cattle publication had been compiled. These trials included both longer-term feeding studies and studies where diets were rotated among cows over time in cross-over or Latin square experiments. Results were plotted and the significance of relationships was assessed by determining the significance of linear or

linear plus quadratic regressions weighted by the number of animals fed each diet and adjusted for the mean effect of trial by including trial as a covariate. Although DM intake and milk yield were reported for cows in all the trials included in this data set, other measurements (apparent digestibility, urinary and fecal excretion of nitrogen (**N**), N retention, milk components, milk urea, and blood urea) were reported in only some of the trials. 'Days in milk' (**DIM**) when these trials began ranged from 1 to 238 days with a mean of 85 days. The fat-corrected milk yield for each individual diet is shown in Figure 2. The points connected by a line are from the same trial, and the best fitting regression line is plotted.

Milk yield increased at a decreasing rate as the dietary concentration of protein was increased both in this summary and in a summary of earlier studies compiled by NRC (2001). Considering the wide diversity in milk yield and days in milk among these trials, it seems surprising that 20.6% dietary crude protein was required to achieve the maximum milk yield. This concentration is considerably higher than fed to most commercial herds. However, this level is lower than the NRC (2001) estimate that 23% dietary crude protein is needed for maximum milk yield! Within individual basal diets (separate lines within Figure 2), yield responses usually were greater (steeper slope) when milk production was greater. Based on averages from these 2 equations, a decrease in dietary protein from 18 to 17, 16, and 15% of diet DM (sequentially reducing the daily dietary protein supply by about 0.5 kg per step) should be expected to decrease daily fat-corrected milk yield by an average of 1.4, 3.0, and 5.0 kg/d below milk yield with an 18% CP diet. Small changes in production may prove difficult to detect (and may be statistically nonsignificant) in single studies or in on-farm trials, but these decreases should be of concern when evaluating recommendations that protein concentrations should be reduced merely to decrease N excretion and improve the efficiency of converting dietary protein to milk protein. A deficiency of protein should have less impact on production in later lactation than early in lactation. Therefore, adjusting dietary protein concentration based on milk production and DIM should help to conserve protein while minimizing adverse effects of a protein deficiency on milk yields.

Concentrations of dietary protein in commercial diets typically are greater for cows early than late in lactation, when the source of forage is alfalfa rather than corn silage, and when supplemental protein sources have a low cost. In contrast, concerns about waste management and disposal often leads producers to lower the protein content of their diets, to switch to protein sources with a high content of essential amino acids or that resist ruminal degradation (e.g., fish meal; bypass soy products) and to attempt to substitute commercial sources of rumen escape amino acids for some of their supplemental dietary protein.

Although dietary concentrations of energy and other nutrients were maintained within each of these trials, intake of dry matter was not limited. In all cases, cows had free-choice access to feed. Generally, dry matter intake increased in a curvilinear fashion similar to milk yield (Figure 3). Similar intake responses were apparent in trials summarized for finishing feedlot cattle with intake of dry matter by feedlot cattle increasing linearly ($P = 0.08$) as dietary crude protein concentration was increased

(Owens et al., 2014). Precisely how and why dietary protein concentration should impact dry matter intake is uncertain. Certainly, with low protein intakes, a deficiency of ruminal ammonia will decrease rate of NDF digestion in the rumen and increases in rumen NDF fill will depress feed intake of cattle fed high NDF diets. In contrast, additional dietary protein, through increasing water intake and rumen passage rate of both solids and liquid, would be expected to increase flow of protein to the small intestine both through increasing efficiency of microbial growth in the rumen and by increasing ruminal escape of dietary protein. Similarly, increases in rumination and chewing time should increase flow of liquids and solids from the rumen. Because dietary protein and NDF concentrations typically are negatively related, maintaining a consistent flow of protein to the small intestine across diets, through retarding ruminal outflow of less digestible forage, should have given ruminants an evolutionary advantage that remains evident in commercial cattle today (Owens et al., 2014).

Concentration of milk protein, often used as an index of protein adequacy, often increases in response to supplementation with ruminally protected amino acids. On that basis, one would expect milk protein concentration to increase when supplemental dietary protein is provided and milk production increases. No such response was detected (Figure 4) in these trials. Instead, milk protein concentration often decreased when very high-protein diets were fed. In a trial by Leonardi et al. (2003), concentration of milk protein decreased when dietary protein was increased even though supplementation with rumen-escape methionine increased the concentration of protein in milk within both their high-and their lower-protein diet groups. Precisely why milk protein concentration may respond to supplemental rumen escape methionine but not to supplemental protein that will increase milk yield is uncertain.

Other changes detected with higher dietary crude protein concentrations included linear increases in milk efficiency (yield/DM intake; $P < 0.03$), in plasma and milk urea concentrations, in milk fat concentration ($P < 0.03$ but peaking at 19.4% crude protein), in crude protein digestibility that increased linearly and quadratically, in dry matter digestibility that peaked at 17.4% protein, in NDF digestibility with both linear and quadratic responses and a peak at 16.9% CP, and in daily intake of digestible DM that peaked at 18.4% CP.

Reducing the environmental footprint of milk production is of increasing public concern. Feeding less dietary protein will improve the efficiency with which dietary N is converted to milk protein (Figure 5). Within each of these trials, adding protein to the diet decreased extent to which dietary N was converted to milk N. However, milk N efficiency continued to increase even when diets contained such a low protein level that milk yield was depressed (Figure 2). This reduction in milk N efficiency is due largely to an increased excretion of urinary N by cows fed higher protein diets although excretion of N in both urine and feces linearly increased ($P < 0.03$) as dietary protein concentration increased. However, the magnitude of the increase in excretion was greater for urine (115%) than for feces (15%) when dietary protein was increased from 14 to 20% of DM.

Protein expenditures by lactating dairy cows at various stages of lactation are compiled and illustrated in Figure 6. Early in lactation, secreted milk protein accounts for about 60% of the total N output by the cow whereas late in lactation, milk will account for less than 40% of total protein expended. Other protein expenses by the cow that involve body maintenance include N lost as metabolic fecal N and endogenous (inevitable) urinary N, as well as scurf (skin, hair, hoof tissue). Very little protein is deposited daily within the developing fetus until very late in pregnancy.

Early in lactation, cows lose weight as energy reserves are raided to meet the energy demand for lactation. The extent to which tissue protein reserves are mobilized during this period has been debated. In trials where N retention was monitored at various stages of lactation, a negative N balance (body N loss) was apparent early in lactation even when very high amounts of protein were fed (circled values in Figure 7). This would imply that, as with energy, providing an excess of dietary protein early in lactation does not prevent the increase in mobilization of tissue protein reserves driven by hormonal changes early in lactation. Indeed, mobilization of protein reserves early in lactation should supply amino acids for synthesis of milk protein and reduce the need for dietary protein.

Because milk protein yield decreases later in lactation, the need for dietary protein decreases. In 2000, Wu and Satter, based on milk production responses with their diets and the levels of milk production their cows achieved, concluded that 17% dietary protein was adequate for maximum milk production during the first 7 weeks of lactation, possibly due to protein sparing by mobilization of tissue protein reserves. A higher concentration of protein (19%) was required from 7 to 16 weeks of lactation (Figure 7), but thereafter 17% protein was adequate to 30 weeks and 16% CP was adequate after 30 wk of lactation. Note that except for the first period, protein requirements decreased in parallel with milk protein yields. However, even late in lactation when production was reasonably low, Kalscheur et al. (1999) concluded that milk yield often increased when more supplemental CP was provided. However, when dietary crude protein concentration dropped below 16% of DM, NDF digestibility declined and this may have caused a reduction in energy intake. Nevertheless, altering dietary protein concentration in an attempt to match the need for N with specific segments of lactation rather than targeting a single CP for an entire lactation is a logical and effective approach both to avoid waste of N and to maximize productivity.

Metabolizable Protein Models

Since initially proposed by Burroughs et al. for growing cattle (1974) and lactating dairy cows (1975), the metabolizable protein concept has stimulated development of sophisticated models of protein metabolism that often are used to explain production responses and to formulate diets. These models all divide the N needs for ruminants into two fractions, one for growth of and fermentation by ruminal microorganisms, and a second to meet the animal's need for essential amino acids for both maintenance and production as illustrated in Figure 6. The general scheme behind these models and the interchange among these compartments is diagrammed in Figure 8. Central to all

models is an estimate of the supply of protein to the small intestine. Small intestinal protein supply (metabolizable protein) equals the sum of 1) microbial crude protein synthesized in the rumen that is flushed or sluiced to the small intestine and 2) dietary protein that escapes ruminal digestion. Numerous interchanges among pools are apparent, but transfer coefficients and the magnitude that external factors may alter these coefficients are not well understood. If amino acid supply has an impact on energy intake, as implicated in Figure 3, simulating the effect of protein supplementation on production becomes quite involved. Efficacy of any model must be compared with other models that predict productivity, but for any model that has intermediate points that can be measured, values at those intermediate points must be accurate if the model is working properly. To evaluate efficacy of the metabolizable protein model described by NRC (2000) that employs most of the same coefficients employed in other models, the precision with which this model predicted microbial protein supply to the small intestine as well as the amounts of dietary escape protein and of total protein reaching the small intestine was examined.

For this evaluation, a data set was compiled consisting of published data from 21 trials with 37 diets supplemented with various levels or sources of protein for a total of 117 different diet-protein combinations. Small intestinal supply of microbial protein, total protein, and by difference, ruminal escape dietary protein had been measured with growing-finishing steers in each of these trials. Based on the reported feed intake and feed composition, the NRC (2000) model was used to predict microbial protein flow and the amount of undegraded dietary protein that should reach the small intestine. Accuracy with which this model predicted the microbial protein supply and the amount of dietary protein that escaped ruminal digestion were plotted and regression coefficients were calculated.

Microbial Protein Supply

The quantity of microbial protein produced in the rumen that reaches the small intestine typically is limited by the amount of energy available from fermentation of organic matter within the rumen. Because the amount of organic matter fermented in the rumen from various feeds is not readily measured, some proxy for ruminally digested organic matter is used. Typically the proxy for ruminal organic matter digestion is feed digestibility (e.g., total digestible nutrients, **TDN**). This in turn is multiplied by dry matter intake to give an estimate of the total amount of energy available for synthesis of microbial protein. This in turn results in linear estimates of predicted yield of microbial protein from equations as illustrated from equations advanced by NRC (2000) for beef cattle, by NRC (2001) for dairy cattle, by Burroughs et al. (1975), and by Valadares Filho et al. (2010) as shown in Figure 9. Although estimates from NRC (1985) for beef cattle and values from Clark et al. (1992) are based on concentrate and roughage intake and therefore are tied as closely to TDN intake, regression estimates also are provided from those sources. Measured microbial protein flows to the small intestine measured in individual metabolism trials also shown in Figure 9 can be compared with the values predicted from these models. Measured microbial N flow to the small intestine was considerably less than predicted by any of the published equations even

though microbial protein supply increased linearly as intake of digestible energy increased. Imprecision in prediction of published models causes one to question whether the published models provide valid and realistic predictions of the supply of microbial protein to the small intestine.

Most metabolizable protein models use TDN as an estimate of the quantity of energy available for ruminal microbes to grow. But the extent to which TDN or dietary organic matter is fermented within the rumen varies drastically with grain and forage processing procedures and with the ruminal residence time that ruminal microbes have to digest feeds. As an example, Firkins et al. (2001) reported that the extent to which lactating cows digest dietary starch in the rumen ranges from only 53% for dry rolled corn to 88% for high-moisture ground corn grain. That a constant proportion of TDN from various feeds will be fermented within the rumen is an erroneous assumption. Furthermore, the primary source of energy for microbial growth is fermented carbohydrate. Consequently, ruminally fermented carbohydrate would seem preferable even to organic matter for predicting yield of microbial protein. Because it seems unlikely that tabular values can accurately predict the extent of ruminal digestion of carbohydrate from a totally mixed ration or an individual feedstuff processed in a specific fashion, other screening methods to appraise the availability of energy for ruminal microbes (e.g., gas production measurements; Fermentrics) may prove useful to refine estimates for specific feeds and feed processing methods.

The extent to which dietary organic matter had been digested within the rumen was measured in these trials. This was compared with the TDN content of each diet that had been calculated from diet composition and tabular TDN values for feeds from NRC (2000). The plot relating ruminal digestion of organic matter to TDN content of the diet is shown in Figure 10. Obviously, within this data set, extent of digestion of organic matter within the rumen, presumably the primary factor that limits yield of microbial mass in current metabolizable protein models, was not reliably predicted by TDN content of the diet. Considering that microbial yield increased with intake of TDN in these studies (Figure 8) but that TDN was not related to extent of organic matter fermented in the rumen, one could conclude that this relationship is driven by intake of ruminally fermented organic matter (Figure 11), not intake of TDN (Figure 11). Whether the remaining variability within this regression is due to analytical errors in analysis or reflects the fact that additional factors (e.g., rate of passage) are altering efficiency of conversion of digested organic matter into microbial protein remains uncertain.

That level of intake is a major factor driving the supply of microbial protein should not come as a surprise. Higher energy intakes permit a higher percentage of the available energy to be used for growth (with less expended for maintenance) for ruminal microbes just like for growing or lactating cattle. Consequently, ruminal residence time or dilution rate as well as the extent to which dietary organic matter is fermented within the rumen would seem preferable to TDN intake as a predictor of microbial N flow to the small intestine.

Rumen Escape Protein

The amount of dietary protein that escapes ruminal fermentation was calculated from the amount of each individual ingredient supplied to the cattle, the protein concentration of each feed component, and the fraction that is proposed to escape ruminal fermentation based on tabular values of undegraded intake protein (**UIP** or 100-Degraded intake protein, **DIP**) specified in tables from NRC (2000). Such rumen escape values presumably were estimated largely from estimates of protein solubility or the extent of enzymatic or microbial degradation of the protein from various feeds. The relationship between the measured amounts of dietary protein reaching the small intestine versus these predicted values are shown in Figure 12. Results force one to question the validity of UIP values for individual feeds. For refining such estimates, those feeds contributing the highest proportion of protein to the diet should be of primary concern. Effects of processing of grains and forages on their ruminal degradation rate and ruminal residence time also need to be included.

Metabolizable Protein Supply

Separation of microbial protein from total protein flow to the small intestine relies on some marker of microbial protein. For the animal, total flow of protein to the intestine from microbes plus feed is the factor of primary importance. Metabolizable protein flow to the duodenum according to most metabolizable protein models is calculated as 64% of microbial protein (based on the assumption that 80% of microbial protein consists of amino acids and true digestion in the small intestine is 80%) plus 80% of dietary protein that escapes ruminal fermentation (small intestinal true digestibility). Such estimates are compared with measured duodenal flow of microbial plus feed protein to the small intestine with cattle fed these 117 diets in Figure 13. Microbial protein synthesis from TDN intake was imprecisely predicted ($R^2 = 0.48$) estimating that the amount of microbial protein reaching the small intestine was $130 \pm 27\%$ of observed values (ranging from 74 to 224%) and ruminal escape of dietary protein was imprecisely predicted ($R^2 = 0.41$) estimating that the amount of rumen escape protein reaching the small intestine (Figure 12) was $113 \pm 84\%$ of observed values (ranging from 0 to 549%). Nevertheless, the predicted metabolizable protein supply still tended to increase as measured metabolizable protein supply increased. Predicted metabolizable protein on the average was $113 \pm 24\%$ of observed metabolizable energy (ranging from 60 to 203%) as shown in Figure 13. This would indicate that total protein flow to the small intestine was predicted more precisely than flow of its components, microbial and rumen-escape protein. Yet, all metabolizable protein models are based on the concept that microbial and rumen escape protein shall be predicted separately and combined in order to estimate the total metabolizable protein supply for producing ruminants. Based on that premise, efforts to improve precision of estimating these two components are needed if performance is to be predicted reliably so that diets can be formulated correctly based on such estimates.

Conclusions

Based on its imprecision in reliably predicting either microbial protein or rumen escape protein flow to the small intestine, the utility of the metabolizable protein model that was tested must be questioned. Because other metabolizable protein models are based on similar inputs and equations, their validity also seems questionable. High variability forces one to question whether current models are simulating ruminal metabolism correctly and properly. If duodenal supply of protein, a measurement that can be readily checked, is not predicted reliably by current prediction models, it seems useless to compare this supply with some additional estimate of the post-ruminal need for protein or individual amino acids for production plus maintenance of producing ruminants because these measurements cannot be readily quantified. The fact that a model may predict whether milk yield will decrease or increase with a given dietary change when other factors (e.g., energy intake or digestibility) change does not prove that a model is either accurate or precise. Current models may lack important components, transfer coefficients may be inaccurate, or modulation of coefficients by recognized or unrecognized factors may be underestimated. Improvements might be achieved by substituting ruminally fermented carbohydrate for TDN intake and by altering estimates of both microbial protein yield and ruminal escape of dietary protein based on ruminal residence time. Yet, even if duodenal flows can be predicted reliably, deficiencies still cannot be predicted reliably from metabolizable protein supply alone because the amounts of individual essential amino acids required for both maintenance and production of ruminants still must be quantified with a high degree of precision.

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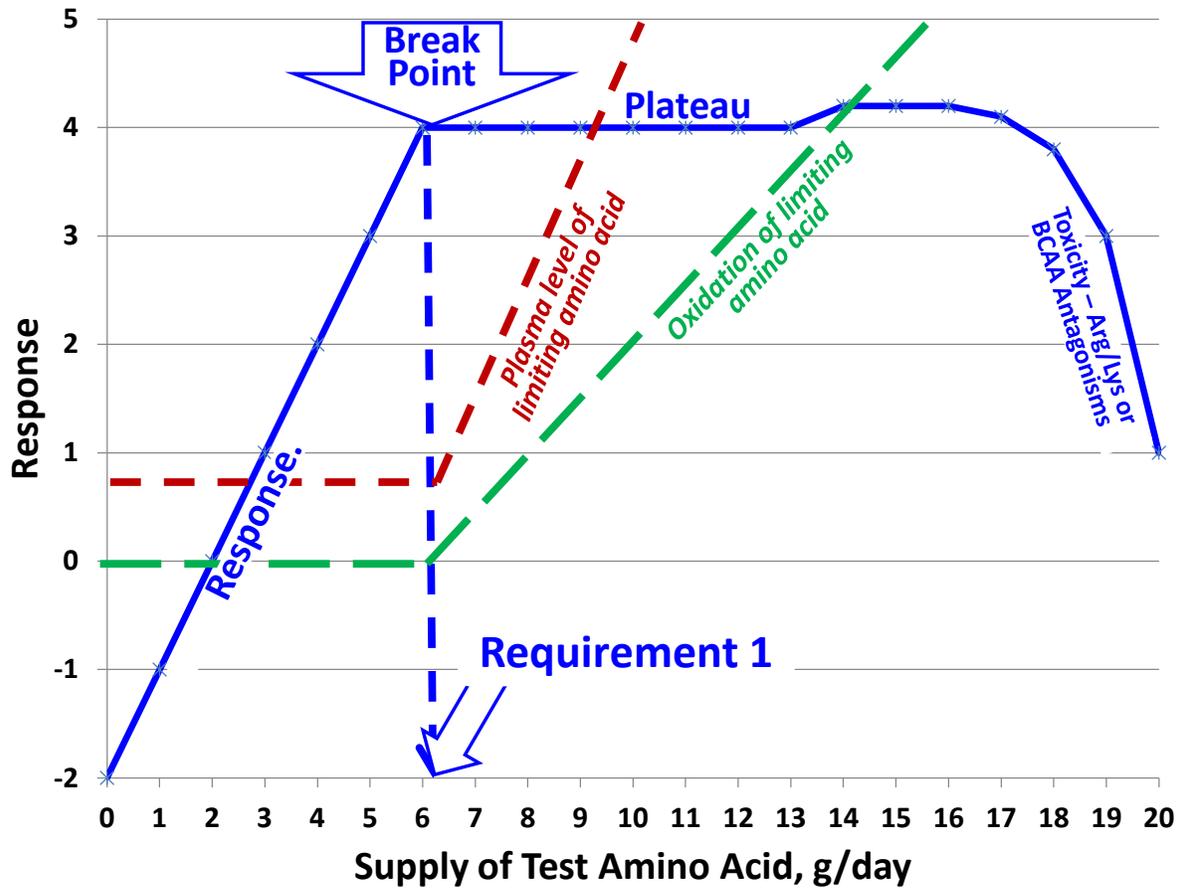


Figure 1. Classical physiological responses (e.g., growth rate) to supplementation with a limiting essential amino acid. BCAA = Branched chain amino acids; Arg = arginine; Lys = Lysine.

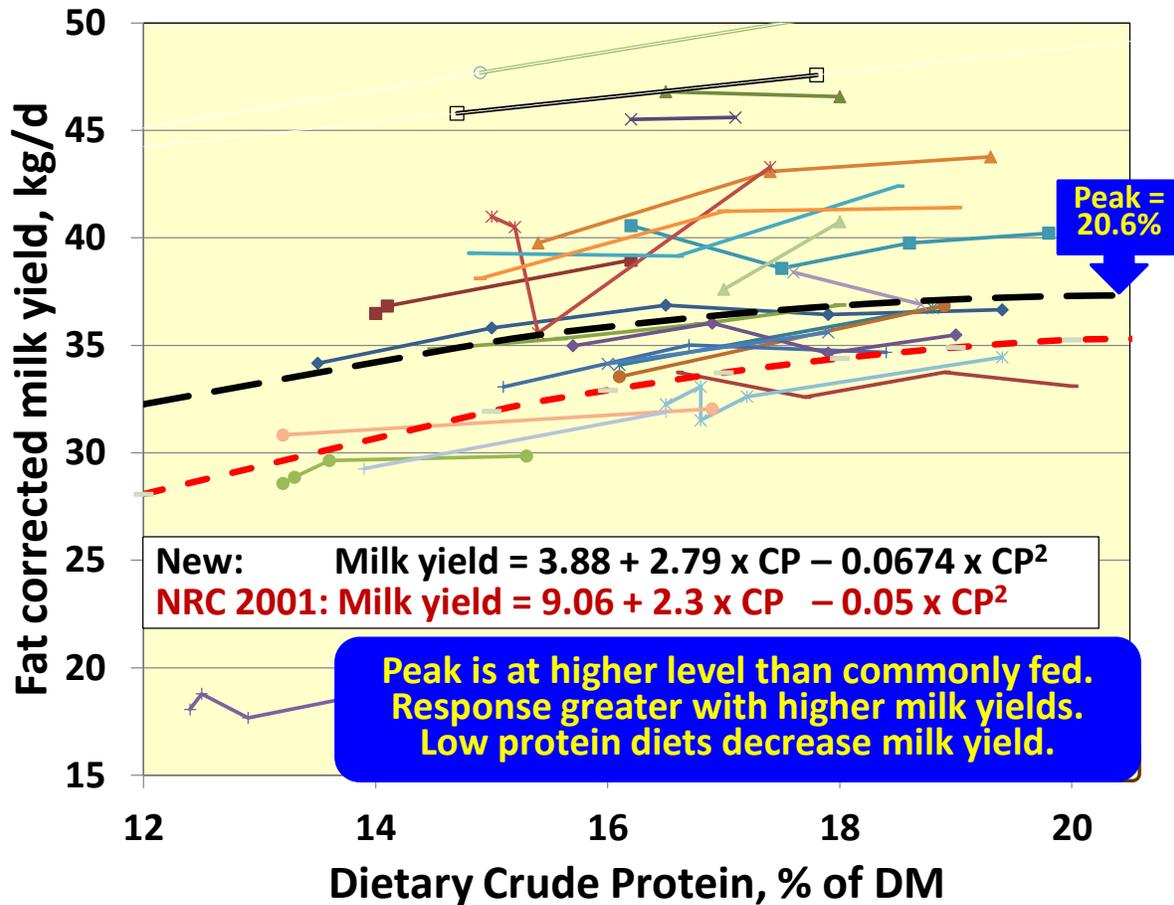


Figure 2. Fat-corrected milk yield by lactating cows fed diets with different crude protein concentrations. Lines connect milk yields from individual studies. The upper dashed dark line is the best fitting regression among these trials whereas the lower dashed curve is the NRC (2001) relationship.

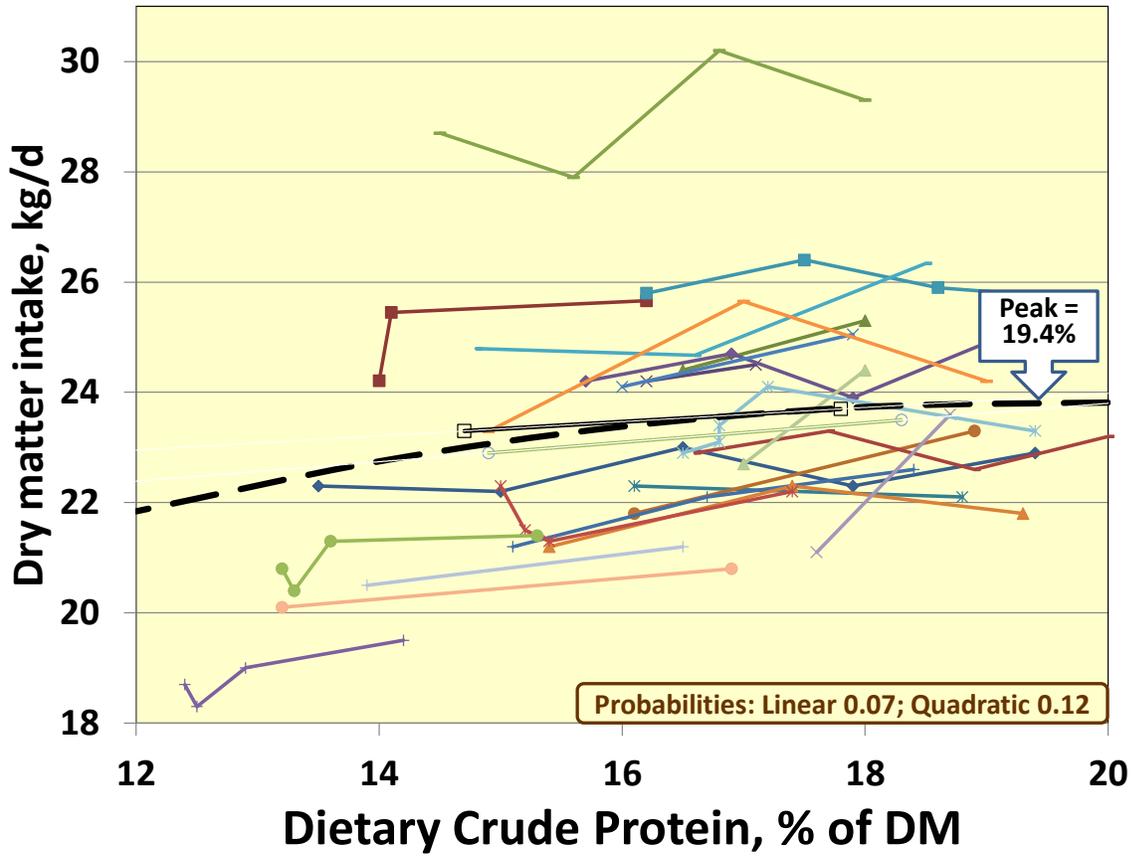


Figure 3. Dry matter intakes by lactating cows fed diets that differed in crude protein concentration.

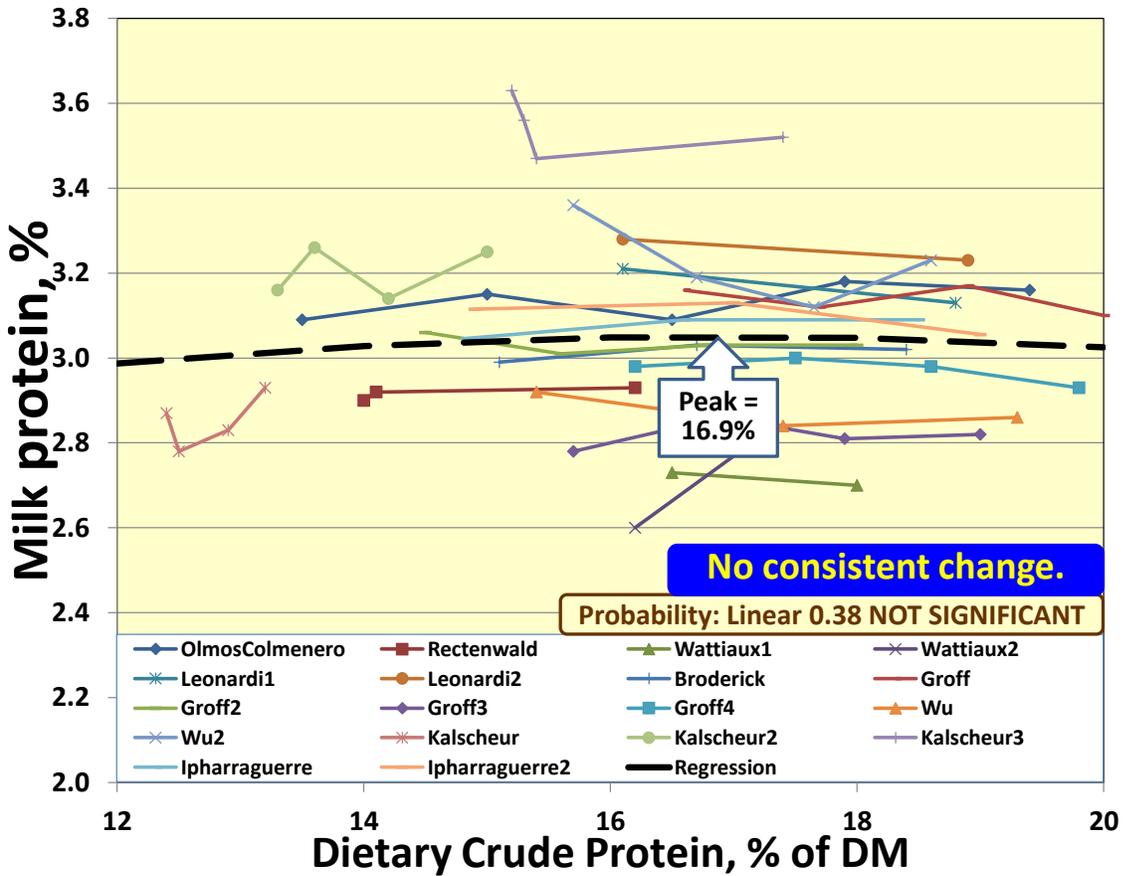
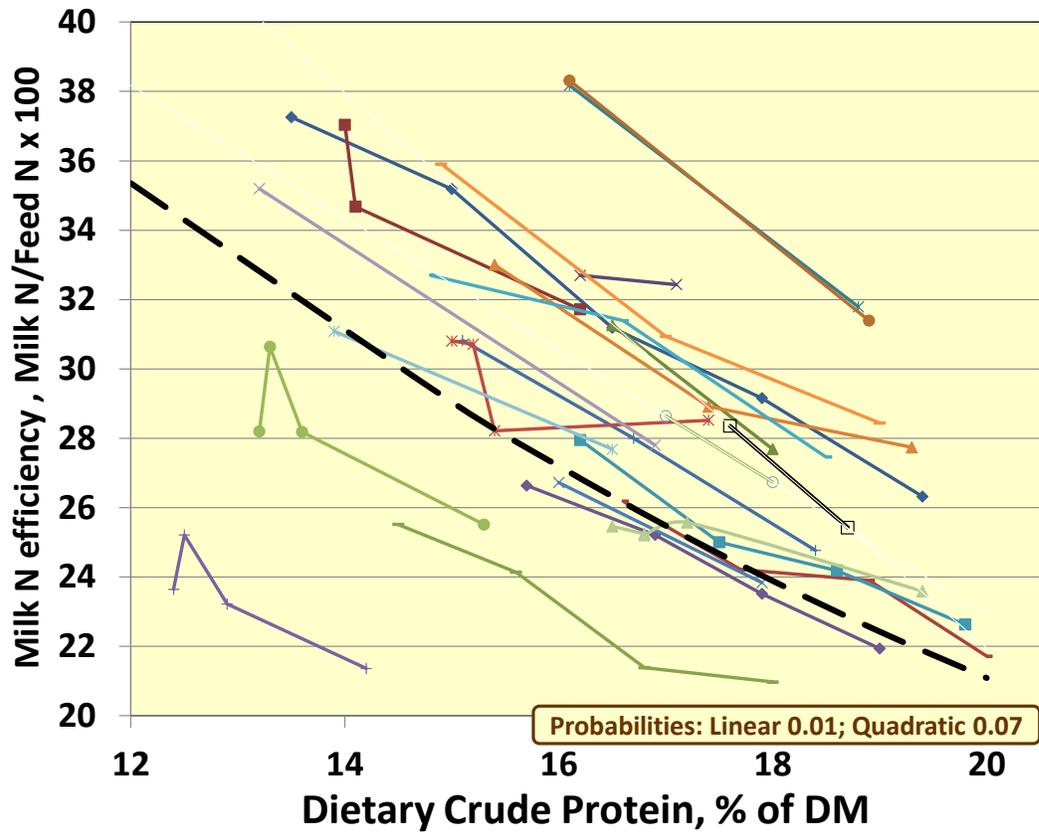


Figure 4. Milk protein concentration responses to varying dietary crude protein concentrations.



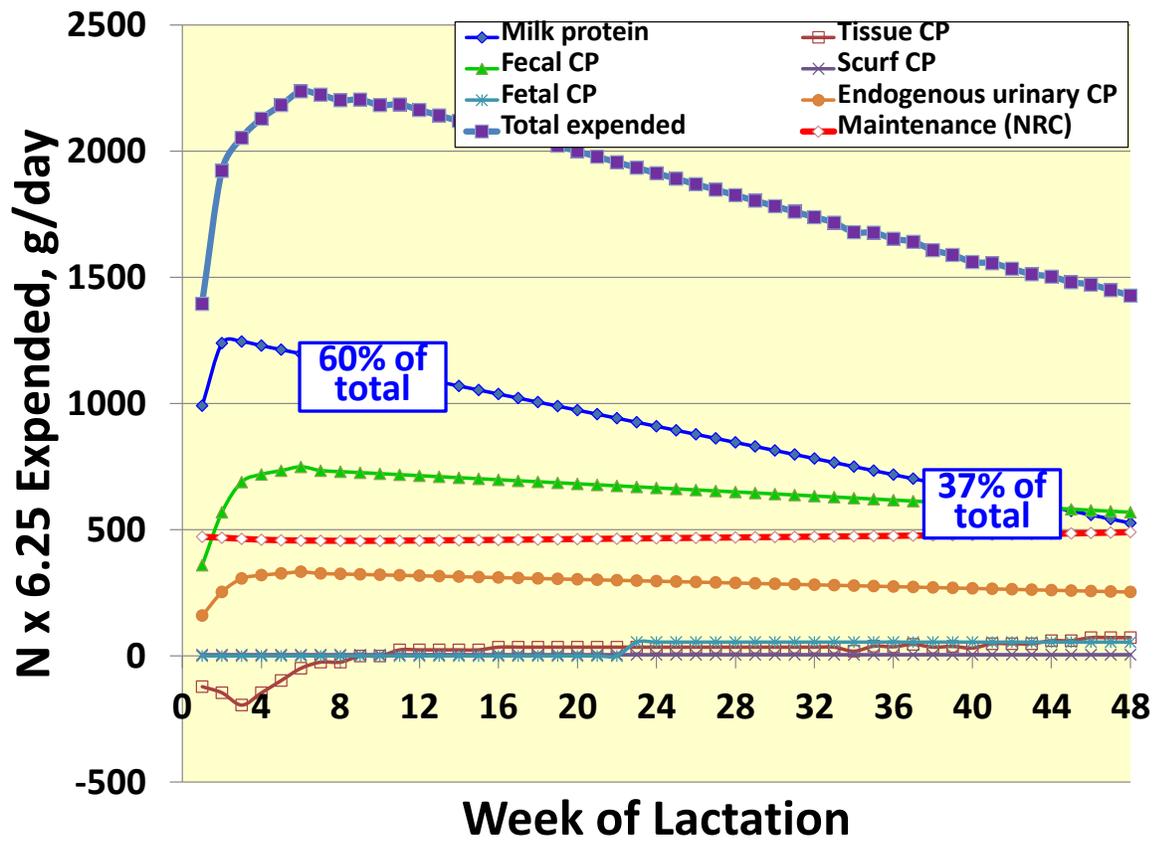


Figure 6. Daily protein expenses by lactating dairy cows at various weeks of lactation.

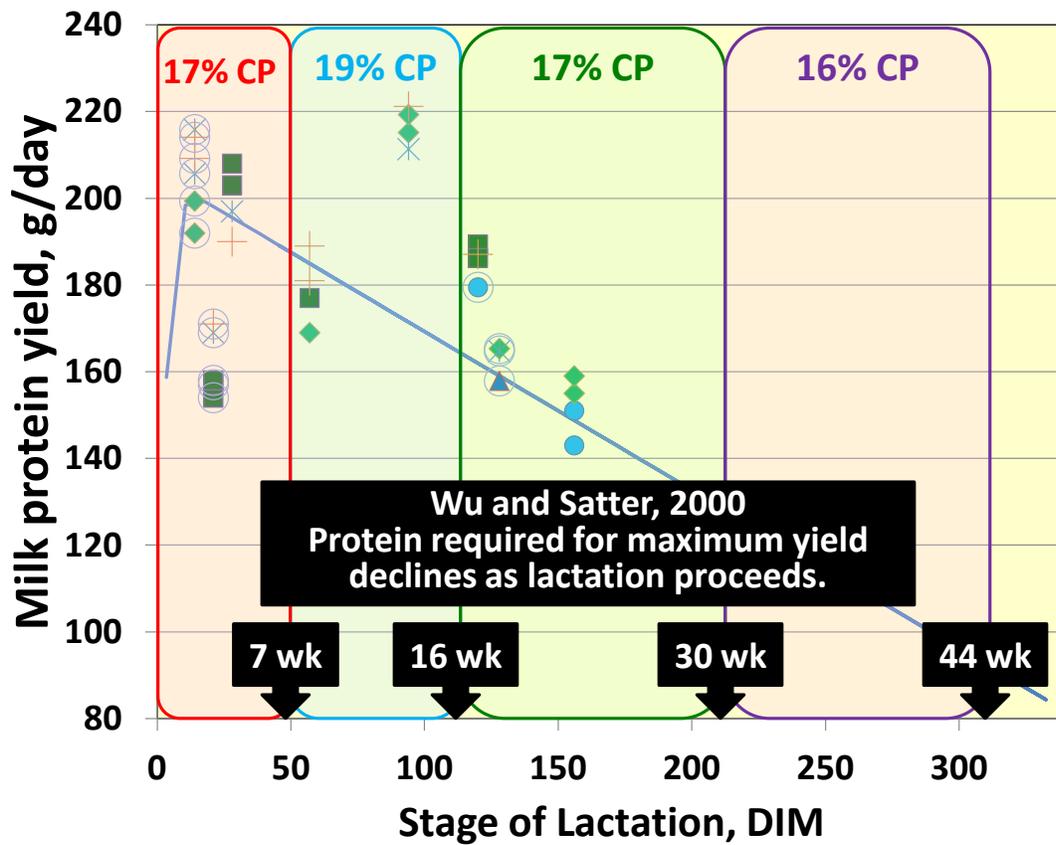


Figure 7. Milk protein yields, responses to protein supplementation (with negative nitrogen balance values being circled) and estimates of dietary protein requirements at various stages of lactation of dairy cows from Wu and Satter (2000).

Models of Ruminant Protein Metabolism

Metabolizable protein:

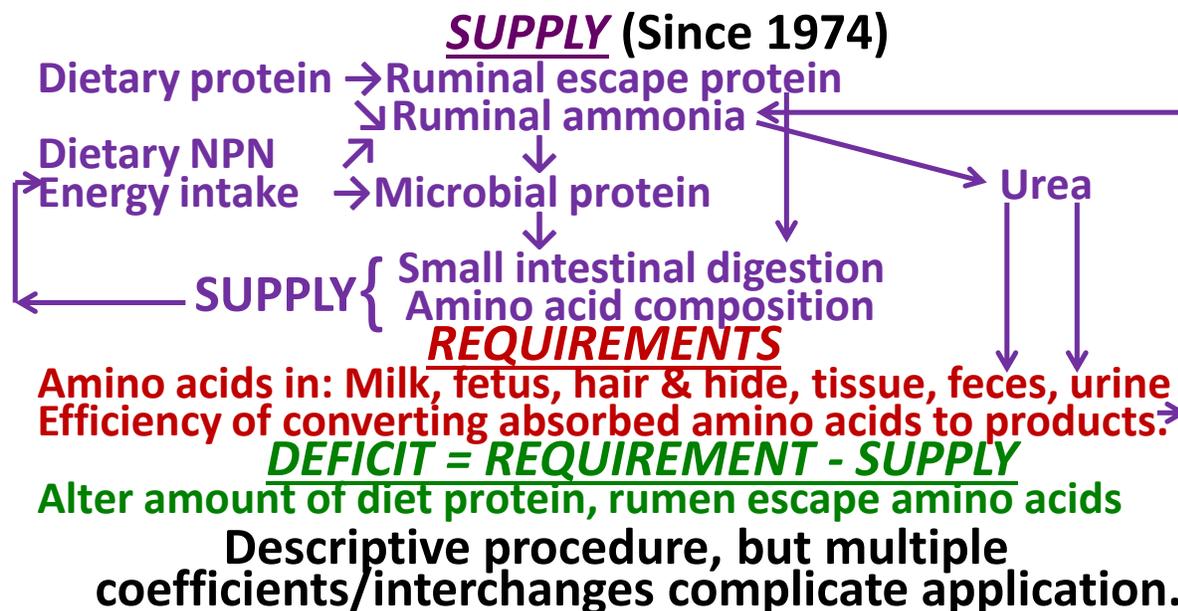


Figure 8. Schematic of typical modeling approaches to estimate protein requirements of ruminants.

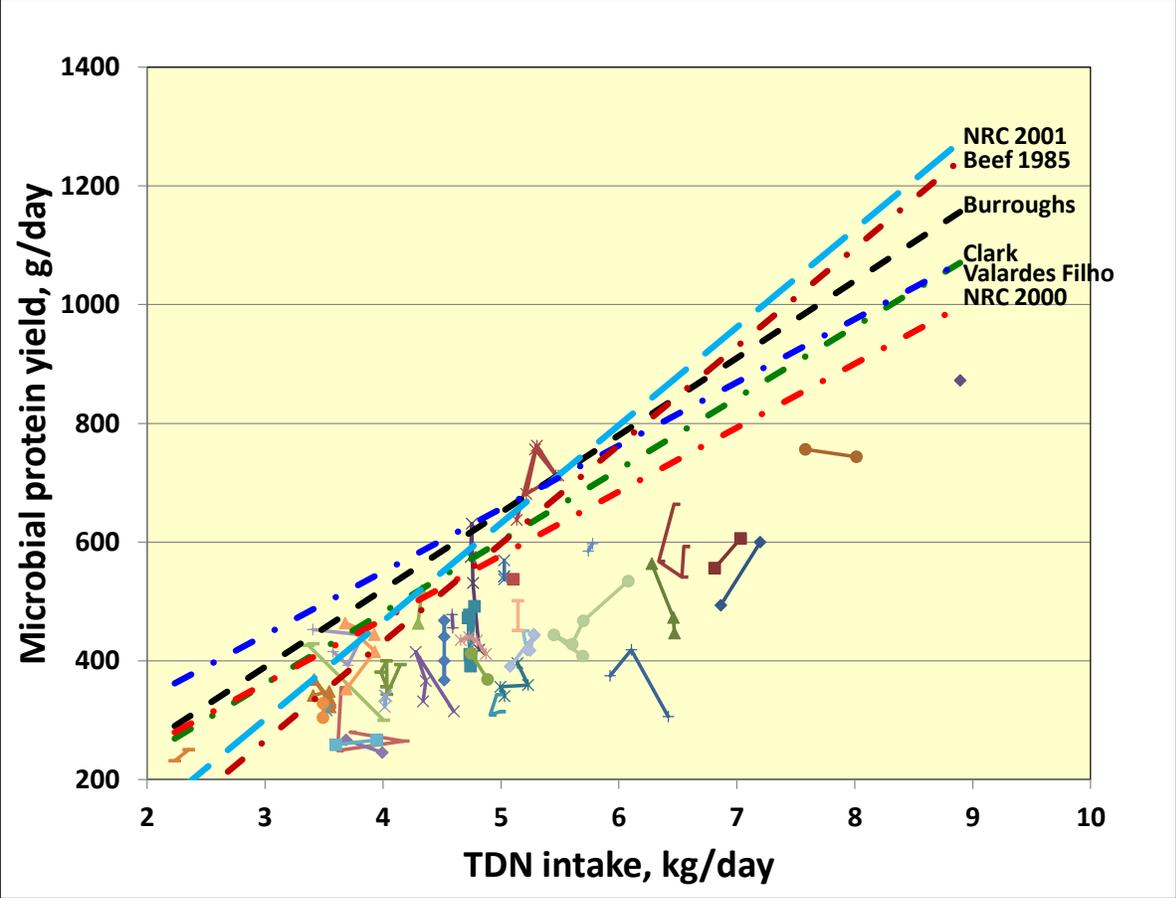


Figure 9. Microbial N yield from published equations compared with measured values from 117 diets fed in metabolism trials for cattle consuming various amounts of total digestible nutrients.

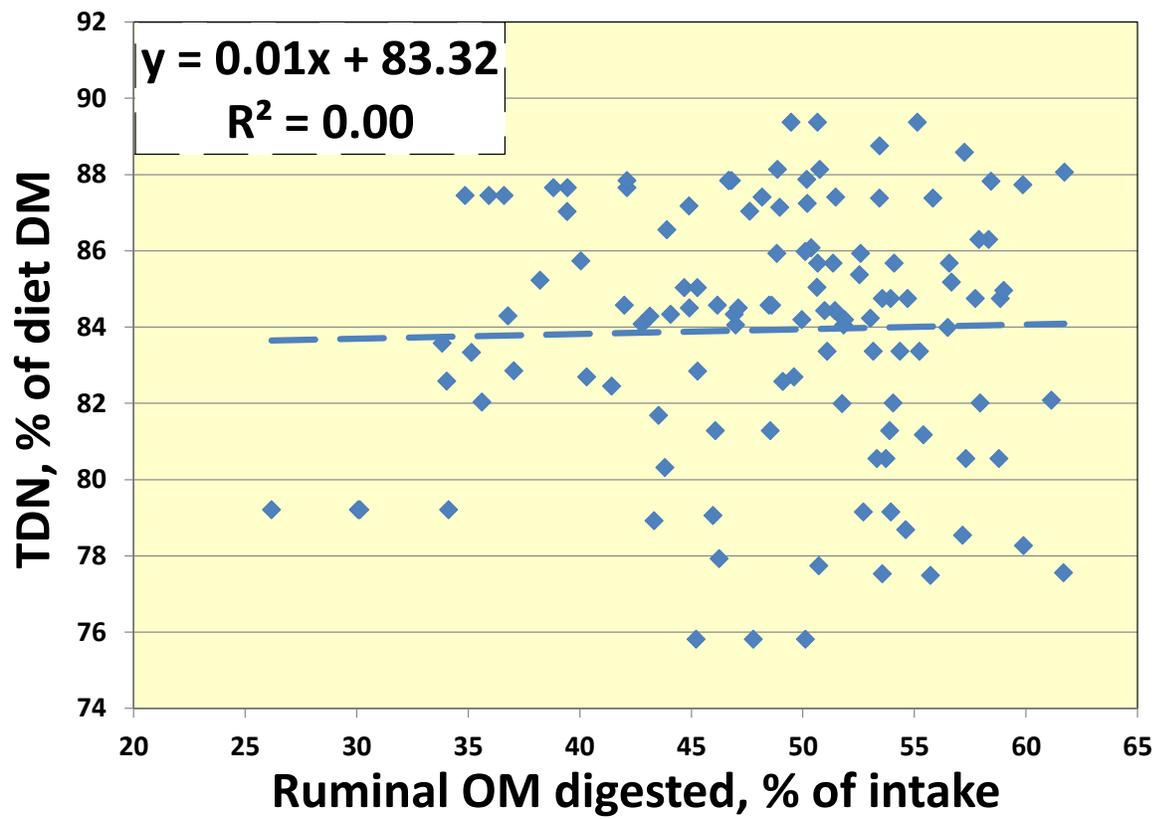


Figure 10. Extent of ruminal digestion of dietary organic matter for diets that differed in total digestible nutrient content among 117 diets from metabolism studies.

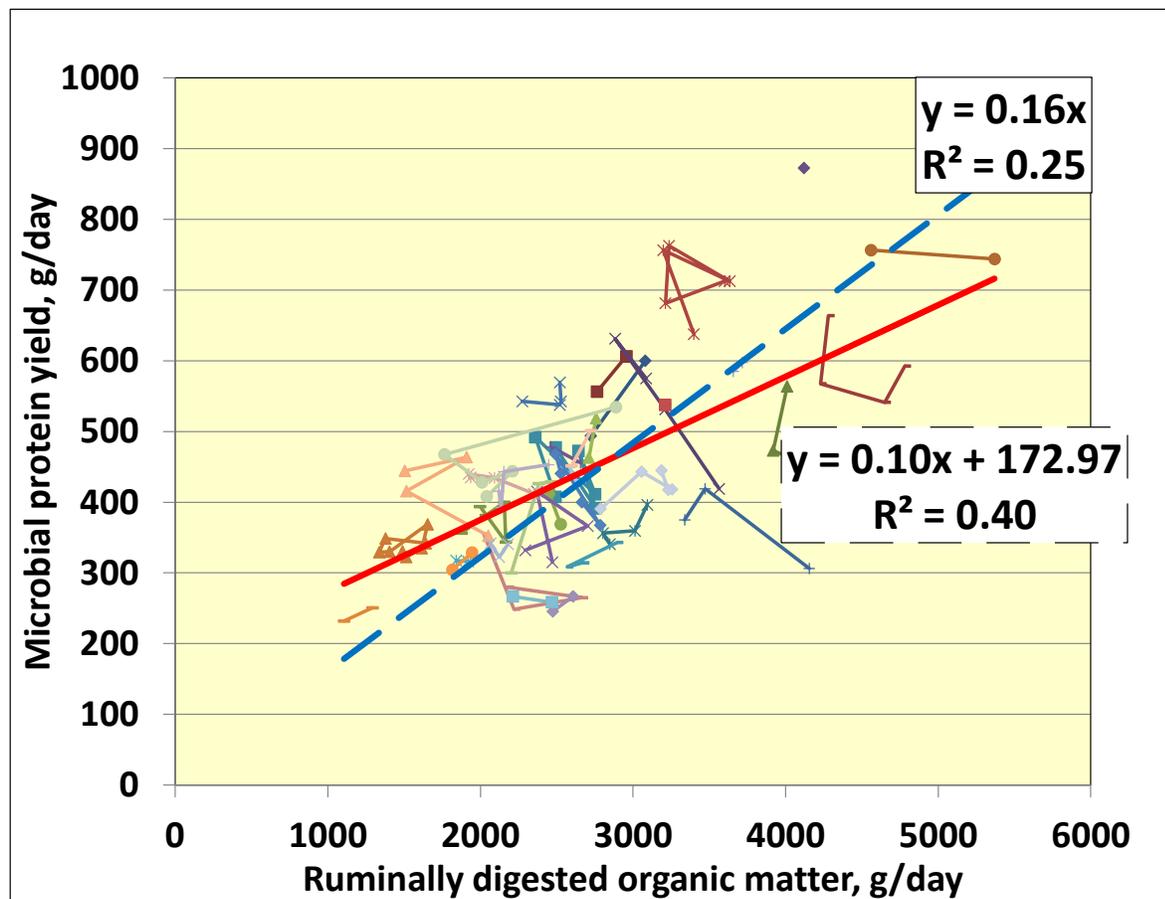


Figure 11. Relationship of microbial N yield to the amount of organic matter digested within the rumen.

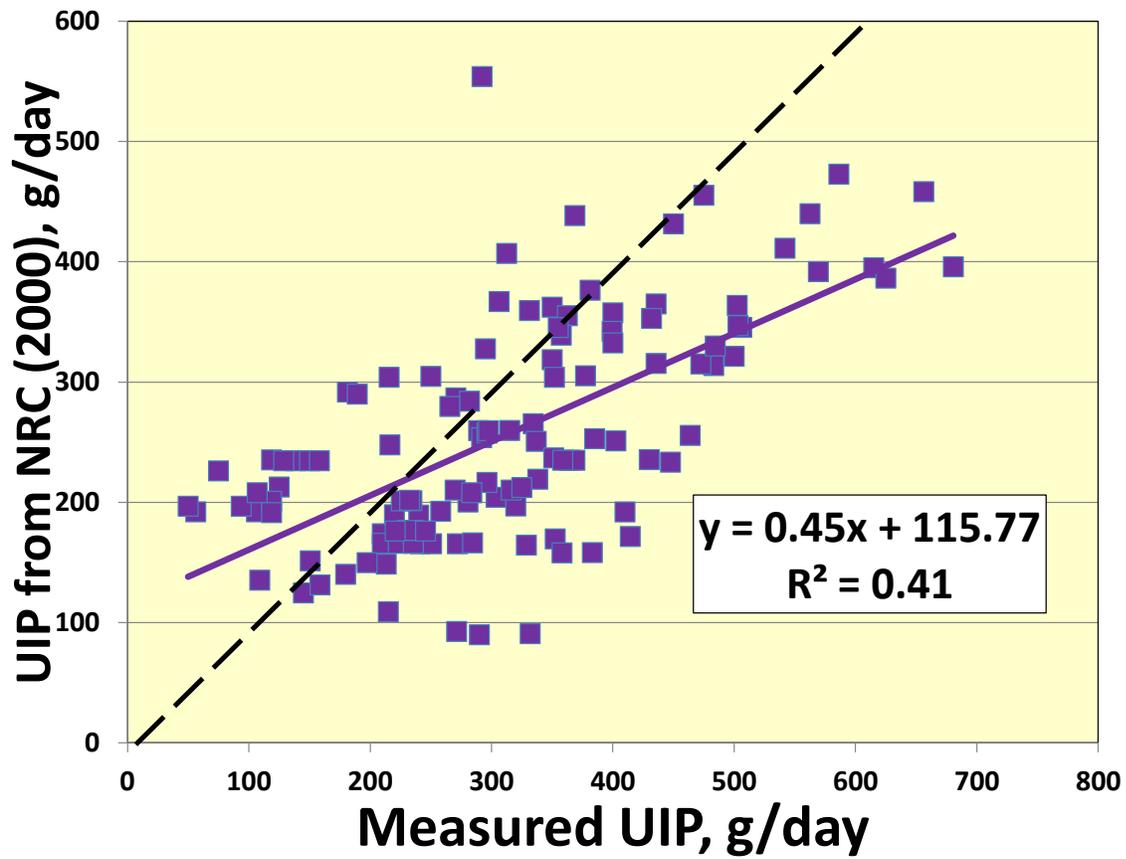


Figure 12. Relationship between undegraded dietary protein intake (UIP) predicted from NRC (2000) equations and flow of undegraded dietary protein to the small intestine.

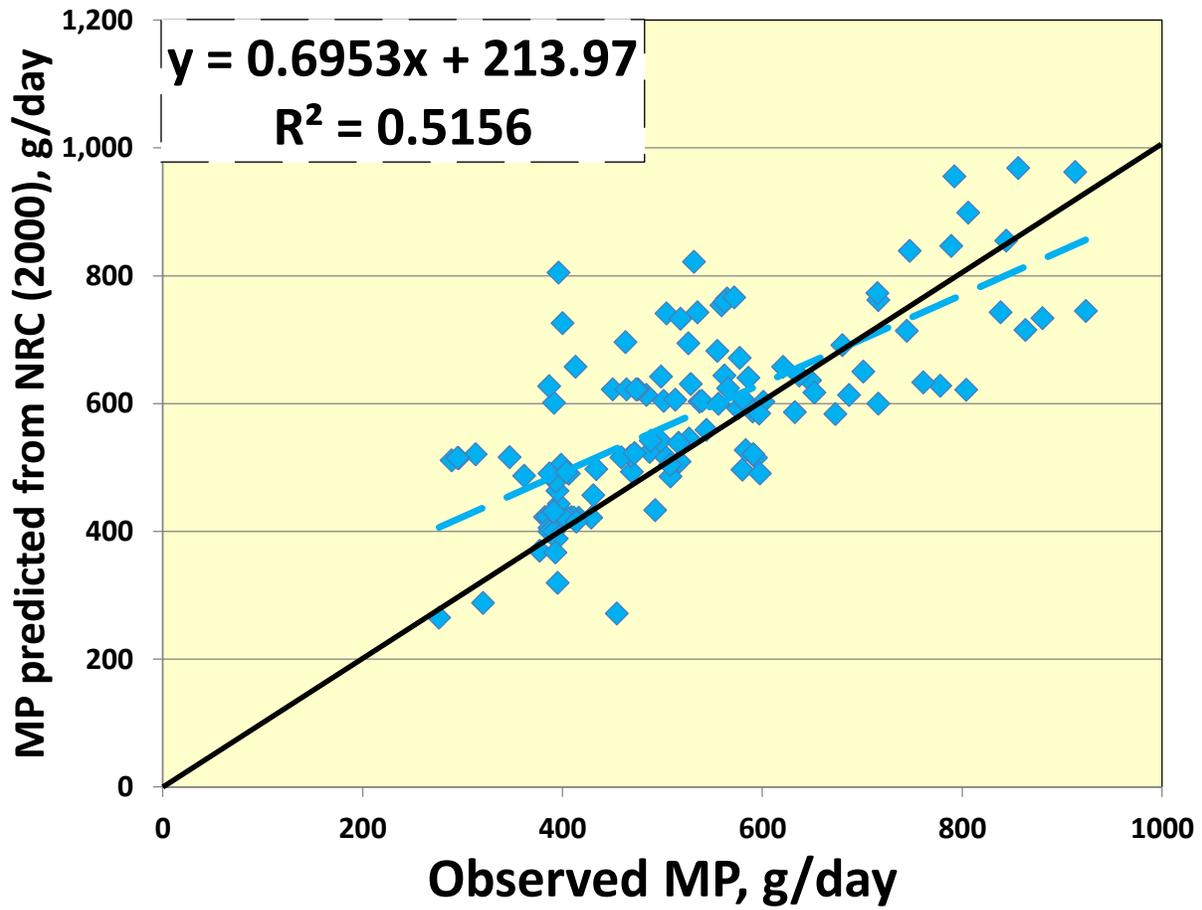


Figure 13. Relationship between metabolizable protein (MP) flow to the small intestine predicted from NRC (2000) equations and measured flow of metabolizable protein to the small intestine of cattle.

SESSION NOTES