

PROTEIN AND CARBOHYDRATE NUTRITION OF DAIRY COWS¹

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Ruminants make efficient use of diets that are poor in protein content or quality because ruminal microbes synthesize good quality protein plus capture recycled urea N that would otherwise be excreted in the urine. Numerous studies show that dairy cows use feed crude protein (CP; N × 6.25) much more efficiently than other ruminant livestock; however, dairy cows still excrete about 2-3 times more N in manure than in milk. Inefficient N utilization necessitates feeding large amounts of supplemental protein, increasing milk production costs and contributing to environmental N pollution. A cow producing about 18,000 lbs of milk per lactation also excretes about 23 tons of wet manure with about 240 lbs of N distributed in those solids (Van Horn et al., 1996). The 15 million dairy cows and replacement heifers in the U.S. produce over 1 million tons of manure N every year (Kellogg et al., 2000). Of this amount, only 30% is actually recovered and applied to cropland (Kellogg et al., 2000). Dairy farms are thought to be significant contributors of nutrients to the hypoxia zone in the Gulf of Mexico, ground water in the Central Valley of California, and the Chesapeake Bay (Burkart and James, 1999; Harter et al., 2002; Ritter et al., 2003). It is estimated that about 25% of dairy manure N is lost as ammonia under current U.S. practices (Pinder et al., 2003; NRC, 2003). Dairy farmers (especially in the West) are increasing herd size, importing more feed, and feeding more protein, further contributing to nutrient accumulation on land in dairy regions and greater impacts on the environment (Bundy and Sturgul, 2001). In the future, promulgation and enforcement of Confined Animal Feeding Operation rules likely will result in dairy farmers being held more accountable for environmental impacts coming from their animals' excreta.

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Are We Overfeeding Crude Protein?

The function of dietary CP is to supply the dairy cow with metabolizable protein (MP)--in the form of absorbed amino acids (AA)--to meet her requirements for maintenance and production. Because extra dietary CP that is not utilized by the cow ends up mainly in the urine, we wanted to test the effects of increasing CP intake on N excretion as well as production using diets formulated from typical Mid-western ingredients. In the first of these trials, energy density was increased by reducing forage from 75, to 62 and 50% of dietary DM, giving diets with 36, 32, and 28% NDF; dietary CP was fed at about 15.1, 16.7, and 18.4% of DM at each NDF level (Broderick, 2003). There was no interaction between energy density and CP—that means that the cows responded to CP the same way at all 3 energy levels. Milk and protein yield both increased with the first CP increment, but there was no difference between production at 16.7 and 18.4% CP (Figure 1). There was a linear increase in N excretion with increased CP in the diet and most of the extra manure N was in the urine. Virtually the entire incremental urinary N was excreted as urea, the form that can be quickly broken down and lost as volatile ammonia. This experiment was followed up by a second study in which step-wise increases of about 1.5 percentage units, from 13.5 to 19.4% CP, were added to a 50% forage ration (Olmos and Broderick, 2003). As expected, milk urea N (MUN), urinary urea, and milk N:N-intake reflected the linear decline in N efficiency with increasing CP (Table 1). We also found that production was highest on the 16.5% CP diet and observed a quadratic response indicating that milk and protein yields were greatest at, respectively, 16.8 and 17.1% CP. Over-feeding protein actually appeared to suppress production. These results were surprising because of the common practice of feeding high producing cows diets with 18% (Shaver and Kaiser, 2004) or more CP (Gunderson et al., 1998; G. R. Oetzel, Personal Communication). This may have happened because CP was increased by adding solvent soybean meal (SBM), at the expense of high moisture corn, which diluted dietary energy (Olmos and Broderick, 2003). Moreover, there is a cost of 7.2 kcal of metabolizable energy per g of excess N excreted as urea (NRC, 1989). Similar findings of no increase (Sannes et al., 2002; Groff and Wu, 2003), or even reduced, milk yield (Wattiaux and Karg, 2004), with more than about 16.5% dietary CP have been reported from a number of trials.

Our experiments were reversal studies (in which diets were switched after 3-4 weeks) conducted largely with mid-lactation cows and, thus, represent only the first iteration for identifying “optimal” CP levels. However, Wu and Satter (2000) found that the dietary CP regime supporting optimum yield of fat-corrected milk (FCM) over the whole lactation involved feeding 17.4% CP for the

first 16-weeks after calving, followed by 16.0% CP for the remaining 28 weeks (Table 2). Increasing dietary CP to as high as 19.3% during the first-phase, or to 17.9% CP in the second phase, did not improve FCM yield. The approach of testing various CP levels in standard diets is now being used in conjunction with substituting different sources of rumen-undegraded protein (RUP); however, our objective should always be to feed the minimal amount of CP needed to maintain production. Reducing dietary CP intake in lactating cows substantially reduced volatile N losses from the stored manure (Külling et al., 2001).

Tracking Diet Composition

Dairy farmers and the consultants advising them often have to deal with considerable variation in, and imprecise information on, feed composition. Uncertainty on protein content is perhaps the major reason for the wide spread over-feeding of CP. It is difficult to hit diet composition targets even when using daily ingredient sampling and TMR adjustment during feeding trials conducted under controlled conditions, including using defined forage sources (e.g., Broderick, 2003). Greater problems are to be expected on commercial dairies due to greater variation and constantly changing feedstuffs. This makes paramount the frequent collection and analysis of representative feed samples. Feed sampling is a logical process that requires care to prevent separation of component fractions of differing densities and particle sizes. Proper sampling methods have been described in detail for forages, our most heterogeneous feeds (Putnam; <http://alfalfa.ucdavis.edu/sampling/hayprobe.html>). Briefly, sampling techniques should account for as much variation as possible (e.g., cutting number, storage shed, and forage lot for a given hay shipment), with random collection of enough samples to represent the whole supply, and using proper coring or other approaches to prevent fractionation, and sending the complete sample (i.e., a blend of all subsamples) to a laboratory certified by the National Feed Testing Association. A current list of certified laboratories is available on-line (www.foragetesting.org). Although there is less variation in composition of concentrate ingredients, a similar sampling and testing philosophy should be reasonably applied to determine composition of all feeds used in the ration.

Clearly, having only a CP content of an unknown feedstuff tells little about its metabolizable protein and AA content. However, knowing the feed's identity and its CP content on a DM basis provides much of the information required to properly utilize that ingredient. Reliable analyses, and accurate tracking of DM, CP, and NDF in ration ingredients are the primary objective of most feed analyses (Mertens, 1997). Within a ration composed of a limited

number of macro-ingredients, CP content is the major factor dictating N utilization and excretion. Monitoring MUN is also a very useful technique in this context. Urea is the primary form of excretory N in mammals and blood urea equilibrates rapidly throughout body fluids, including milk; MUN concentrations reflect blood urea (Rook and Thomas, 1985) and equilibration between blood and milk occurs within 1-2 hours (Gustafsson and Palmquist, 1993). Therefore, MUN serves as a useful index of inefficient N utilization in the lactating dairy cow (Baker et al., 1995; Kohn et al., 2002). We found that dietary CP concentration, expressed on either a DM ($R^2 = 0.84$) or energy ($R^2 = 0.83$) basis, had the strongest relationship to MUN (Broderick and Clayton, 1997). The equation for computing CP from MUN was: dietary CP (% of DM) = $0.269 \text{ MUN (mg/dl)} + 13.7$. Associations were not as strong for two other factors related to CP utilization: excess N intake ($R^2 = 0.77$) and N efficiency ($R^2 = 0.63$); ruminal ammonia was the most poorly associated ($R^2 = 0.57$) of the factors we studied in depth. Urea in body fluids, including milk, results not only from excess protein degradation in the rumen but also from inefficient use of absorbed AA. Nousiainen et al. (2004) recently reported a robust linear regression relating MUN (measured by infrared methods) to dietary CP from Nordic feeding trials. This equation can be rearranged to compute CP from MUN concentration: dietary CP (% of DM) = $0.59 * \text{MUN (mg/dl)} + 8.4$. Kauffman and St-Pierre (2001) and Wattiaux and Karg (2004) both developed predictions for urinary N excretion from MUN that differ only slightly. It is clear that reliable field estimates of MUN will help identify diets that are too low or high in CP, and dietary CP content (% of DM) may be estimated from MUN. Accurate and timely determination is perhaps the key to successful application of MUN for monitoring dietary CP. It is possible that MUN readings will some day be made at cow side in the milking parlor. Indeed, Jenkins et al. (2002) have attempted to analyze MUN during milking. Their system, although not robust enough for practical application, showed considerable promise.

Using Nutritional Models in Ration Formulation

The value of applying nutritional models, such as the NRC (2001) or the Cornell system (e.g., O'Connor et al., 1993), to formulation of dairy cow rations does not need extensive elaboration. Hanigan (2005) recently compared these 2 models with 3 others and concluded that the NRC (2001) model was somewhat more accurate at predicting MP supply. Both the NRC (2001) and Cornell protein models are sound and useful but both require accurate characterization of feedstuffs, not only chemical composition but also ruminal and intestinal degradation and digestion. The tabulated estimates of feed RUP in the NRC

(2001) illustrate this problem. Although based on a simple, single compartment in situ model, many RUP estimates derive from very few in situ measurements. Data on solvent soybean meal came from 14 determinations but only 3 values contributed to the mean for corn gluten meal. Another difficulty relates the time-lag between data production and model development. The equation from NRC (1989), when applied to data published from 1989 to 1999, was less reliable for predicting ruminal microbial protein at the higher feed intakes of these higher producing cows than the revised NRC (2001) equation. However, we found that microbial nonammonia N (NAN) predicted using the revised NRC equation yielded a slope of only 38% when regressed on microbial NAN flows measured at the omasum in six recent experiments. Part of the discrepancy may have derived from an effect of intake level. The mean microbial NAN flow of 440 g/day observed in these six trials was near the extreme of 500 g/day in the data set used to develop the revised NRC (2001) equation for computing microbial protein from intake of discounted TDN. However, the overall NRC (2001) model was much more reliable for predicting RDP, RUP and total protein flows measured in the same trials. This indicates that, while underestimating microbial synthesis, the model probably over-predicted RUP, yielding an overall estimate of protein flow that was more nearly correct. Similar results have been found using the Cornell system (D. G. Fox, personal communication). What is also surprising is that the NRC (2001) protein model does a more effective job at predicting milk and protein production than it does for ruminal outflow of microbial protein, RUP and total protein.

Reducing Degradability of Forage Protein

Silage harvesting methods are better mechanized than those used for making hay and putting up hay-crops as silage reduces weather damage and increases (apparent) preservation of nutrients. The proportion of alfalfa and other forages fed as hay to dairy cattle in the U.S. declines yearly although more hay likely is fed in the West. However, when forages are ensiled, plant cell rupture releases proteases that break down forage proteins to nonprotein N (NPN) (McDonald et al., 1991). This breakdown is extensive and NPN typically accounts for more than 50% of the total CP in alfalfa (Luchini et al., 1997) and other hay-crop silages (McDonald et al., 1991). Charmley and Veira (1990) found that suppressing NPN formation in ensiled alfalfa from 65 to 40% of total N increased NAN flow to the abomasum in sheep from 22 to 27 g/d; about 60% of the increase was from microbial NAN. Although energy availability in alfalfa silage actually exceeded alfalfa hay in three of our lactation trials, cows fed silage were more responsive to fish meal RUP, indicating that the CP in silage was used

more poorly than that in hay (Table 3; Broderick, 1995; Vagnoni and Broderick, 1997). In vitro studies using forages from 2 of these 3 trials indicated that there was similar ruminal protein degradation for both hay and silage, but greater microbial protein yield on hay (Peltekova and Broderick, 1996). Silage NPN, which is largely peptides and free AA (Muck, 1987), may be used with lower efficiency because ruminal microbes degrade these compounds to ammonia more rapidly than they degrade intact hay protein. Degradation of intact forage proteins, although rapid, may be more synchronous with ruminal microbial growth and result in more efficient capture of N from degraded protein than when similar amounts of CP are fed as silage NPN. Greater milk yields in the West may result at least partly from greater feeding of alfalfa forage as hay rather than silage.

Matching Carbohydrates with Rumen-Degraded Protein

Because microbial protein accounts for most of the dairy cow's metabolizable protein, one of the major tenets of the NRC (2001) model is to first meet the requirement for rumen-degraded protein (RDP). Matching ruminal carbohydrate fermentation with RDP will be very effective for improving N efficiency regardless of dietary protein degradability. There are substantial differences among starch sources (Herrera-Saldana et al., 1990), and within grains due to processing, in the rates of energy release in the rumen. Effects of processing on extent of ruminal digestion of corn starch are much greater than on total tract digestibility (Table 4; Owens et al., 1986; 1997). We found a grind size (a hammer mill with 3/8" screen) for high moisture corn that optimized ammonia uptake in ruminal in vitro incubations (Ekinici and Broderick, 1997). Feeding this ground high moisture corn (1.7 mm mean particle size) to lactating cows increased milk yield more than 5 lbs/day and protein yield more than 0.25 lb/day compared to control high moisture corn (4.3 mm mean particle size). Much the same thing happens with dry corn. Processing dry shelled corn to reduce mean particle size from 3.5 to 0.6 mm increased ruminal starch digestibility from 54 to 70% (Remond et al., 2004). This would be expected to increase microbial protein formation and MP supply to the cow.

Ruminal acidosis and associated metabolic problems limit the amount of readily fermented carbohydrate that may be fed to produce MP from microbial growth. There are "optimal" levels of dietary carbohydrate and forage that will support maximal ruminal protein synthesis and milk production. A high forage diet with 80% alfalfa silage and 20% concentrate was diluted stepwise by increasing high moisture corn to (% alfalfa silage DM/% concentrate DM) 65/35,

50/50, and 35/65 in a reversal trial (Valadares et al., 2000). True protein and NPN, as a proportion of total CP, were held constant by adding solvent SBM and urea as the alfalfa silage was decreased. The observed quadratic response curves indicated that DM intake and yield of 3.5% FCM were maximal at 51% concentrate (38% nonfiber carbohydrate; NFC); maximum fat yield was at 43% concentrate (34% NFC). However, milk and protein responses were not quadratic but linear--both were still going up at 35% forage and 65% concentrate. Moreover, purine derivative excretion in the urine, an indirect measure of ruminal protein formation, also showed a linear response, despite low ruminal pH and other signs of NFC over-feeding (Valadares et al., 1999). Clearly, the lactating cow's demand for energy is substantial and optimal dietary concentrate probably is dictated more by long-term rumen and animal health than by maximum milk production.

A number of years ago, considerable research was directed toward synchronizing carbohydrate fermentation with N release in the rumen to improve microbial capture of RDP. Ruminal organisms fermenting NFC, particularly soluble sugars and pectins, appear to make greater contribution to microbial protein synthesis per unit of fermented carbohydrate (Russell et al., 1992). Chamberlain et al. (1993) reported that supplementation of grass silage diets with small amounts of sugars was more effective than starch in stimulating increased urinary excretion of purine derivatives in sheep; the order of carbohydrate effectiveness was sucrose > lactose > fructose > xylose > wheat starch. Later Scottish work indicated that ruminal infusions of sucrose (Kim et al., 1999a) and maltodextrin (partially digested starch; Kim et al., 1999b), in supplement of grass silage diets fed to dairy cattle, stimulated microbial protein synthesis in the rumen. Trevaskis et al. (2001) reported that sucrose infusion into the rumen was more effective for stimulating microbial protein formation (as indicated by urinary excretion of purine derivatives) when it was synchronized with the ammonia peak occurring 1-2 hours after feeding. In the Scottish work, effect of maltodextrin supplementation was greater in one case when synchronized with ruminal ammonia (Kim et al., 1999b), but not in the sucrose trial (Kim et al., 1999a). Korean research (Kim et al., 2000) also showed a positive effect of sucrose infusion into the rumen but no advantage of synchrony with ruminal ammonia. Molasses and a number of other byproduct feeds may serve as economical sugar sources. Harvesting forages in late afternoon, just after maximal photosynthetic activity, can increase sugar and NFC contents of forage (Owens et al., 1999). Trevaskis et al. (2004) reported that managing grazing cows such that they consume most of their forage as late-afternoon foliage was effective for improving milk production. However, most evidence, including that from recent studies (Cabrita et al., 2003; Richardson et al., 2003; Trevaskis et al.,

2004) show little or no production benefit from direct manipulations to synchronize protein degradation and energy fermentation in the rumen. Nevertheless, none of this research attempted to minimize CP intake. We speculate that, when feeding low CP diets, there would likely be more and longer periods of the day when RDP was limiting and microbial protein formation might be improved under these circumstances by synchronizing energy fermentation with N release in the rumen.

Corn silage is commonly used to provide high energy “forage” with which to dilute hay-crop forages and their highly degradable protein. Dhiman and Satter (1997) replaced 1/3 or 2/3 of the dietary alfalfa silage with corn silage. Compared to 100% of the forage from alfalfa, milk yield was 6% higher over the whole lactation when 2/3 of the dietary forage was alfalfa silage and 1/3 was corn silage; there also were comparable improvements in N efficiency. Brito and Broderick (2003) assessed the effects of step-wise replacement of alfalfa silage with corn silage. The greatest improvement in N efficiency, without loss of production of milk, fat and protein, occurred at about 50% of the forage from alfalfa silage and 50% from corn silage (Table 5). Additionally, replacing some of the dietary starch with very rapidly fermenting sugars holds promise for enhancing ruminal capture of degraded N. Corn starch was replaced with sucrose (Broderick et al., 2000), or dried molasses or liquid molasses (Broderick and Radloff, 2004), in 3 separate feeding studies; basal diets were formulated from alfalfa and corn silages plus high moisture corn and solvent SBM and averaged 2.6% total sugars in dietary DM. An overall analysis of the data from the three trials indicated maximums for total sugars (on a DM basis) were 6.8% for DM intake and 4.8% for protein yield. However, the positive production effects of sugar feeding in these trials were primarily driven by increased feed intake.

Feeding Rumen-Undegraded Protein and Protected Amino Acids

The primary advantage of the newer rationing systems is their value in identifying when lactating cows will respond to RUP supplements. Midwestern diets are often based on high CP, high NPN alfalfa silage and there are often substantial responses to higher “bypass” proteins produced by heat-treating soybean proteins (Broderick et al., 1990; Faldet and Satter, 1991) or using special manufacturing processes such as reducing the soluble protein content of fish meal (Broderick, 1992). Table 6 summarizes relative ruminal degradabilities and milk protein yield responses observed in feeding studies with expeller-heated soybean meal (Broderick et al., 1990) and low and high-soluble fish meal (Broderick, 1992). Although there were similar ruminal degradabilities found for expeller

soybean meal and high-solubles fish meal, lactation response was greater for the fish meal. Moreover, the protein response to low-solubles fish meal was out of proportion to its relative ruminal escape. This reflects the higher quality AA pattern of fish meal protein. Compared to an iso-nitrogenous diet containing urea, we also found an interesting pattern of response to three true proteins that differed in RUP and AA content (Brito and Broderick, 2004). Flow of RUP and total protein (NAN x 6.25) from the rumen was greatest on cottonseed meal, intermediate on canola meal and lowest on solvent SBM; however, milk and protein yield were highest on canola, intermediate on SBM, and lowest on cottonseed meal (Table 7). We also tested whether we could reduce dietary CP below 16.6% by feeding a heat-protected SBM (Olmos and Broderick, 2004). Although milk and protein yields were similar on the 2 diets with 16.6% CP (with or without added RUP) to that obtained on 17.6% CP, 2.6 lbs/day of milk was lost by reducing dietary CP to 15.6%, even though that diet was supplemented with a SBM high in RUP (Table 8). Methionine and lysine are the two AA most often cited as limiting for lactating dairy cows (e.g., Schwab, 1996). The enhanced production with RUP supplementation may have derived from the AA patterns of fish meal and canola meal being complementary with microbial protein as AA sources for milk protein formation (Broderick, 1994). These results also indicate that RUP from SBM may not be as effective. Responses to ruminally protected methionine (RP-Met) have been more consistent than to protected lysine (Armentano et al., 1997) and this has reduced commercial interest in supplying protected lysine products. The advantage of post-ruminal supplementation of a specific AA is clear--requirement for the limiting metabolizable AA may be met with relatively little N input. The potential value of exploiting this strategy was shown recently in Germany where supplementing RP-Met at 14.7% CP resulted in milk protein secretion equal to that at 17.5% CP, and with 31 versus 27% conversion of dietary N to milk N (Kröber et al., 2000). We obtained similar protein yield, and even greater milk and FCM yields, when RP-Met was fed with 17.3 and 16.1% CP diets versus an 18.6% CP diet without RP-Met (Broderick et al., 2005).

Future Developments

Recently, there has been renewed interest in supplementing with the liquid form of the hydroxy-analog of methionine (MHA, also abbreviated HMB; Koenig et al., 1999) as a post-ruminal source of methionine. Research conducted about 30 years ago suggested some benefit via rumen action to feeding the calcium salt of this compound (Chandler et al., 1976). Wool growth responses with feeding calcium MHA were small, indicating that very little of this material escaped

ruminal degradation (Cottle, 1988). However, a liquid MHA drench gave rise to about 20% of the wool growth response of the abomasally infused compound (Stephenson et al., 1990). Koenig et al. (1999) reported that 50% of liquid MHA supplied orally contributed to post-ruminal methionine supply. It has been speculated that escape may be enhanced because this form of MHA flows with the liquid phase or may be absorbed at the omasum (McCollum et al., 2000). A 50% ruminal escape would make this an economical form of supplemental methionine containing no N. However, recent research based on plasma AA concentrations suggested that very little liquid MHA served as a post-ruminal methionine source (C. G. Schwab, personal communication). A ruminally-protected form of MHA is not available commercially. Branched-chain VFA were another N-free supplement that received considerable attention about 20 years ago. These compounds can be used by certain ruminal bacteria to synthesize the branched chain essential AA that get incorporated into their protein; there was some evidence that supplements of branched-chain VFA stimulated production of dairy cows fed corn silage (Felix et al., 1980). Interest in branched-chain VFA may have waned because the responses observed in large scale collaborative feeding studies, although usually positive, were much smaller than those reported in early trials. There has been about 30 years of experience using a number of the α -keto acids of the essential AA to replace dietary protein in human patients with kidney disease (e.g., Chow and Walser, 1974; Walser et al., 1987). A possible future stratagem might be to use ruminal protection of several of these α -keto acids as N-free sources of AA with the object of reducing N excretion to the environment from lactating cows.

Implications

Dairy cows utilize feed CP with greater efficiency than other ruminant livestock but still excrete about 2-3 times more N in manure than they secrete in milk. This contributes to increased costs of milk production and environmental N pollution. The function of dietary CP is to supply the cow with MP as absorbed AA but any extra dietary CP that does not contribute absorbed AA that are utilized in production are lost in the urine. Urinary N is the most polluting form excreted because much is lost as atmospheric ammonia or into surface and ground water. In a number of trials testing various CP levels in diets formulated from typical feeds, there were no increases in yields of milk, fat-corrected milk or protein with more than 16.5% dietary CP. In one trial, reducing CP to 15.6%, but adding RUP as heated soybean meal (SBM), did not give production equal to 16.6% CP. However, low solubles fish meal and canola meal were found to be more effective sources of RUP than cottonseed meal or heated soybean products.

Supplementing rumen-protected methionine also was effective for allowing some reduction in dietary CP without losing milk yield. Frequent sampling and analysis of feed ingredients is very important for tracking the CP contents of the actual diet fed. Monitoring milk urea can also be used to assess both dietary CP and urinary N excretion in lactating cows. The NRC (2001) protein feeding model is useful for predicting production responses to alterations in dietary protein and carbohydrates and should be used regularly. Hay-crop silages are the most degradable sources of dietary CP. Where possible, replacing alfalfa silage with alfalfa hay will improve CP efficiency and reduce N excretion. Reducing grain particle size increases ruminal starch digestion and increases microbial protein formation, so long as ruminal pH is not depressed. The NRC (2001) model can also be used to match rumen-degraded protein with carbohydrate fermentation. Future research developments will allow even lower dietary CP levels to be fed, thus reducing N excretion, without loss of animal productivity.

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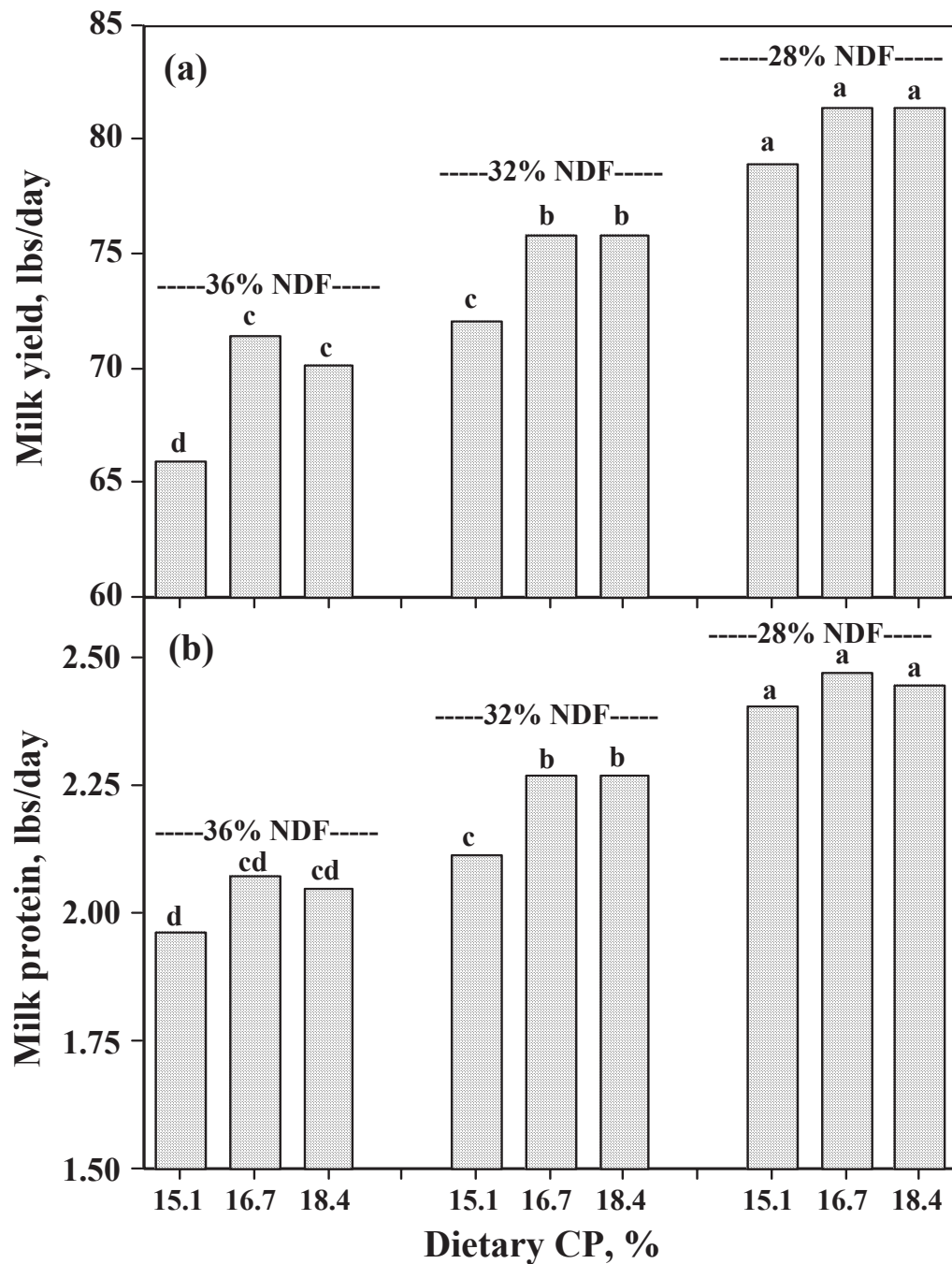


Figure 1. Effect on a) milk and b) protein yield of feeding cows CP at 15.1, 16.7, and 18.4% of DM at each of 3 energy densities (75, 62, and 50% forage DM to give 36, 32, and 28% NDF; Broderick, 2003). Forage was 60% alfalfa silage and 40% corn silage in all diets. Bars with different superscripts differ ($P < 0.05$)

Table 1. Effect of dietary CP on milk production and milk composition, digestibility, and urinary excretion (Olmos and Broderick, 2003)

Variable	Dietary CP, % of DM					Probability	
	13.5	15.0	16.5	17.9	19.4	Linear	Quad
DMI, lbs/d	47.6 ^b	48.1 ^{ab}	49.6 ^a	47.6 ^b	47.8 ^{ab}	0.91	0.12
BW gain, lbs/d	0.49	0.46	0.7	0.57	0.64	0.21	0.72
Milk Production, lbs/d	80.0 ^b	82.0 ^{ab}	84.4 ^a	80.7 ^b	81.6 ^{ab}	0.60	0.11
Milk/DMI	1.71	1.71	1.72	1.7	1.72	0.87	0.99
3.5 % FCM, lbs/d	75.2 ^b	78.5 ^{ab}	80.9 ^a	78.7 ^{ab}	79.6 ^{ab}	0.09	0.17
Fat, %	3.17 ^c	3.26 ^{abc}	3.23 ^{bc}	3.49 ^a	3.45 ^{ab}	0.00	0.99
Fat, lbs/d	2.51	2.65	2.73	2.71	2.73	0.06	0.30
Protein, %	3.09	3.15	3.09	3.18	3.16	0.15	0.92
Protein yield, lbs/d	2.43 ^b	2.54 ^{ab}	2.60 ^a	2.49 ^{ab}	2.54 ^{ab}	0.21	0.10
SNF, %	8.92	8.96	8.93	9.01	9.00	0.09	0.89
SNF, lbs/d	7.08 ^b	7.28 ^{ab}	7.58 ^a	7.14 ^b	7.30 ^{ab}	0.42	0.14
Milk N/N Intake	0.367 ^a	0.344 ^b	0.307 ^c	0.279 ^d	0.255 ^e	<0.01	0.58
DM digestibility, %	71.2 ^c	74.6 ^a	74.0 ^a	72.5 ^b	72.3 ^{bc}	0.79	<0.01
OM digestibility, %	72.1 ^c	75.5 ^a	75.0 ^a	73.6 ^b	73.5 ^b	0.47	<0.01
NDF digestibility, %	45.8 ^c	51.2 ^a	49.5 ^{ab}	48.0 ^b	48.7 ^b	0.18	<0.01
Urea-N excretion, g/d	63.2 ^e	91.0 ^d	128.4 ^c	174.0 ^b	208.1 ^a	<0.01	0.43
Microbial CP flow, g/d	993 ^b	1082 ^{ab}	1144 ^a	1127 ^a	1144 ^a	0.02	0.21

^{a,b,c,d}Means in rows without common superscripts are different ($P < 0.05$).

Table 2. Effect on yield of 3.5% fat-corrected milk (FCM) and excretion of manure N of feeding dairy cows four different CP regimes during the first 16 weeks and last 28 weeks of 44-week lactations. Data from Wu and Satter (2000)

Protein regime	Week of lactation		3.5 % FCM (lbs/lactation)	Manure N
	1-16 (Ration CP, % of DM)	17-44		
Low/Low	15.4	16.0	23,570 ^b	279 ^c
Mid/Low	17.4	16.0	25,640 ^a	309 ^b
Mid/Mid	17.4	17.9	26,020 ^a	358 ^a
High/Mid	19.3	17.9	25,480 ^a	355 ^a

^{a,b,c}Means in columns without common superscripts are different ($P < 0.05$).

Table 3. Effect of diet on DMI, BW gain, and yield of milk and milk components (Vagnoni and Broderick, 1997)¹

Item	AH	AS	AH plus 3% FM	AS plus 3% FM	$P > F^2$		
					Forage	FM	F×FM ³
DM intake, lbs/d	57.8	54.5	56.9	55.1	<0.01	0.96	0.37
Milk, lbs/d	89.7	86.9	90.2	90.6	0.11	<0.01	0.04
Fat, %	3.25	3.48	3.3	3.36	0.01	0.51	0.13
Protein, %	3.14	3.1	3.17	3.17	0.19	<0.01	0.38
Lactose, %	4.83	4.84	4.81	4.84	0.11	0.72	0.63
SNF, %	8.66	8.65	8.69	8.68	0.58	0.2	0.84
Yield, lbs/d							
Fat	2.91	2.95	2.95	3.04	0.25	0.21	0.95
Protein	2.80	2.65	2.84	2.87	0.10	<0.01	0.03
Lactose	4.32	4.14	4.34	4.41	0.32	<0.01	0.04
SNF	7.74	7.39	7.85	7.89	0.15	<0.01	0.04
Efficiency, milk/DMI	1.58	1.60	1.59	1.67	0.01	0.03	0.20

¹AH = Alfalfa hay, AS = alfalfa silage, FM = fish meal, and HMC = high moisture corn.

²Probability of a significant contrast effect.

³Forage × FM interaction.

Table 4. Effect of processing on digestibility of corn & barley starch (Owens et al., 1986)

Processing Method	Proportion of Starch Digestion, %			
	Rumen	Small Intestine	Large Intestine	Total tract
Cracked Corn	69	13	8	89
Ground Corn	78	14	4	94
Steam-Flaked Corn	83	16	1	98
High Moisture Corn	86	6	1	95
Ground Barley	94

Table 5. Effect of replacing alfalfa silage with corn silage (Brito & Broderick, 2003)

Item	Alfalfa Silage/Corn Silage			
	100/0	74/26	47/53	21/79
<u>Composition (% of DM)</u>				
Alfalfa Silage	50.5	37.1	23.6	10.2
Corn Silage	0	13.3	26.7	40.0
Crude Protein	17.3	17.0	16.8	16.6
<u>Production</u>				
DM Intake (lbs/d)	58.4 ^a	57.1 ^a	55.1 ^b	51.1 ^c
Milk Yield (lbs/d)	91.5 ^a	92.6 ^a	91.5 ^a	87.1 ^b
Rumen ammonia (mg/dl)	21.0 ^a	20.0 ^a	17.5 ^b	12.3 ^c

^{a,b,c}Means in rows without common superscripts are different (P < 0.05).

Table 6. Relative ruminal in vitro escape and utilization of supplemental protein from slowly degraded proteins in lactating cows fed alfalfa silage based diets

Test Protein	Relative Response (Solvent soybean meal = 1)	
	Relative in vitro escape	Relative utilization (no. trials)
Expeller soybean meal	1.78	1.48 (3)
Fish meal		
High solubles	1.70	1.56 (1)
Low solubles	1.98	2.07 (2)

Table 7. Effect of supplementing with urea or different sources of true protein on production and omasal protein flows in lactating dairy cows. Diets composed principally of alfalfa and corn silages plus high moisture corn (Brito & Broderick, 2004)¹

Item	Supplemental protein				<i>P</i> > <i>F</i>
	Urea	SSBM	CSM	CM	
CP, % of DM	16.5	16.5	16.6	16.6	
<u>Production (lbs/d)</u>					
DM intake	48.7 ^c	53.4 ^b	54.5 ^{ab}	54.9 ^a	< 0.01
Milk	72.5 ^b	88.2 ^a	89.3 ^a	90.6 ^a	< 0.01
Milk protein	2.03 ^c	2.71 ^{ab}	2.60 ^b	2.80 ^a	< 0.01
Milk fat	2.23 ^c	2.69 ^{ab}	2.60 ^b	2.84 ^a	< 0.01
<u>Omasal protein flows (g/d)</u>					
Microbial protein	2344 ^b	2706 ^a	2706 ^a	2775 ^a	0.04
RUP	538 ^c	987 ^b	1348 ^a	1150 ^{ab}	< 0.01
Total protein	2882 ^c	3693 ^b	4054 ^a	3925 ^{ab}	< 0.01

¹CM = canola meal; CSM = cottonseed meal; SSBM = solvent soybean meal.

^{a,b,c}Means in rows without common superscripts are different (*P* < 0.05).

Table 8. Effect of supplementing RUP from heat-treated SBM or CP from solvent SBM on production and N metabolism in lactating dairy cows. Diets composed principally of alfalfa and corn silages plus high moisture corn (Olmos and Broderick, 2004)¹

CP, % of DM	15.6+RUP	16.6-RUP	16.6+RUP	17.6-RUP	Contrasts		
ESBM, % of DM	4.5	0	5.9	0	A vs. B	B vs. C	B vs. D
<u>Production (lbs/d)</u>							
DM intake	55.6	56.4	56.2	58.2	0.39	0.81	0.09
Milk	85.5	88.2	88.8	88.4	0.08	0.68	0.91
3.5% FCM	90.6	93.0	94.6	94.1	0.21	0.44	0.59
Milk protein	2.67	2.78	2.73	2.80	0.44	0.54	0.76
Milk fat	3.31	3.40	3.46	3.44	0.37	0.43	0.54
<u>Proportion of N-intake (%)</u>							
Milk N	30.1	29.3	28.8	26.8	0.27	0.5	< 0.01
Urinary N	33.3	33.2	35.7	37.6	0.97	0.12	< 0.01
Fecal N	33.9	32.7	32.3	31.4	0.32	0.76	0.30

¹ESBM = expeller solvent soybean meal.