

Feeding Dairy Cows to Minimize Nitrogen Excretion¹

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Abstract

Dairy cows utilize feed crude protein (**CP**; N x 6.25) with much greater efficiency than other ruminant livestock but still excrete about 2 to 3 times more N in manure than in milk. This contributes to increased costs of milk production and to environmental N pollution. The function of dietary CP is to supply the cow with metabolizable protein (**MP**) as absorbed amino acids (**AA**), but any extra dietary CP that does not contribute to absorbed AA that are used in production will be largely lost in the urine. Urinary N is the most polluting form of excretory N because much of it is lost as atmospheric ammonia or into surface and ground water. We conducted a number of trials testing various levels of CP in diets formulated from typical Midwest feeds. Generally, 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 rumen undegraded protein (**RUP**) as heated soybean meal (**SBM**), did not support production equal to 16.6% CP. However, fish meal, especially low soluble fish meal, and canola meal were found to be more effective sources of RUP than SBM or cottonseed meal. Supplementing rumen-protected methionine has also been shown to be 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 should be used regularly. Hay-crop silages are the most degradable source 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.

Introduction

Ruminants make efficient use of diets that are poor in protein content or quality because ruminal microbes synthesize high quality protein plus capture recycled urea N that would otherwise be excreted in the urine. Numerous studies show that dairy cows utilize feed CP (N x 6.25) much more efficiently than other ruminant livestock; however, dairy cows still excrete about 2 to 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. An average cow producing about 18,000 lb of milk per lactation and

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also excretes about 23 tons of wet manure with about 240 lb 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). Farm animals contribute about 50% (1.5 million tons of N annually) of the U.S. emission of ammonia and 25% (0.1 million tons N per year) of the total emissions of nitrogen oxides (NRC, 2003). It is estimated that about 25% of dairy manure N is lost as ammonia under current U.S. practices (Pinder et al., 2003), contributing to annual ammonia redeposition of manure N of 20 to 36 lb/acre in the Upper Midwest (Burkart and James, 1999). This unaccounted-for N input may add to nitrate-N losses in tile drainage water and eutrophication of surface waters via runoff. Moreover, dairy farmers are increasing herd size, importing more feed, and feeding more protein, further contributing to nutrient accumulation on land in dairy regions and greater nutrient impacts on the environment (Bundy and Sturgul, 2001). In the future, promulgation and enforcement of Concentrated Animal Feeding Operation rules likely will result in dairy farmers being held more accountable for environmental impacts coming from their animals' excreta.

How Much Are We Overfeeding CP?

The actual function of dietary CP is of course to supply the dairy cow with 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 in mainly 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 found 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 1.5 percentage units, from 13.5 to 19.4% CP, were added to a 50% forage ration (Olmos Colmenero 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 that indicated that milk and protein yields were greatest at 16.8 and 17.1% CP, respectively. 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 even more CP (Gunderson et al., 1998; G.R. Oetzel, University of Wisconsin-Madison, Personal Communication). This effect may be explained by the fact that CP was increased by adding solvent SBM at the expense of high moisture corn, which diluted dietary energy (Olmos Colmenero, and Broderick, 2003). Moreover, there is a cost of about 7 kcal of net energy per g of N converted to urea (NRC, 2001). 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. These experiments were reversal studies (diets were switched after 3 to 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 RUP; however, our objective should always be to minimize the CP fed 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 and imprecision in feed composition data, especially protein contents. This uncertainty is perhaps the major reason for wide spread over-feeding of CP. It is difficult to hit diet composition targets even when using daily ingredient sampling and total mixed ration (TMR) adjustment during feeding experiments conducted under controlled conditions, including using defined forage sources (e.g., Broderick, 2003). Greater problems are to be expected on commercial dairy farms 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, the most heterogeneous feeds (D. Putnam, University of California, Davis;

<http://alfalfa.ucdavis.edu/sampling/hayprobe.html>). Briefly, these techniques involve accounting for as much variation as possible (e.g., cutting number, storage shed, and forage lot for a given hay shipment), randomly collection of enough samples to be representative of the whole supply, using proper coring or other sampling techniques 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 data on CP content of an unknown feedstuff tells little about its MP and AA contents. 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 to 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 factors clearly 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 N inefficiency caused by excess supply of protein to the tissues. 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: 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 could be used to identify diets that were relatively low or high in CP concentration, and dietary CP content (% of DM) could be estimated from MUN. Accurate and timely determination is perhaps the key to successful application of MUN to monitor dietary CP. It may be speculated 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 in cows 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 two models with three others and concluded that the NRC (2001) model was somewhat more accurate at predicting protein flow from the rumen. 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 have been derived from very few in situ measurements. Although data on solvent SBM came from 14 determinations, only three values contributed to the mean for corn gluten meal. Another difficulty relates the time-lag between data production and model development. The NRC (2001) highlights how the equation from the NRC (1989), when applied to data published from 1989 to 1999, was less reliable at higher intakes for predicting ruminal microbial protein than the revised equation. However, we found that microbial nonammonia N (NAN) predicted using the revised equation yielded a slope of only 38% when regressed on microbial NAN flows measured at the omasum in 6 recent experiments. Part of the discrepancy may have resulted from an effect of level. The mean microbial NAN flow of 440 g/day observed in these trials was near the extreme of 500 g/day of the data set used to develop the revised NRC (2001) equation for microbial protein from intake of discounted total digestible nutrients (TDN). However, the overall NRC (2001) model was much more reliable in predicting rumen degradable protein (RDP), RUP, and total protein flows measured in the same trials (data not shown). This indicates that, while underestimating microbial synthesis, the model probably over-predicted RUP, but yielded an overall estimate of protein flow that was more nearly correct. Similar results have been observed using the Cornell system (D.G. Fox, Cornell University, 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 estimating 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 eastern third of the U.S. declines yearly. 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/day; about 60% of the increase was due to greater microbial NAN flow. Although energy availability from alfalfa silage actually exceeded alfalfa hay in 3 of our lactation trials, and cows fed silage were more responsive to RUP from fish meal, 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 forage 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. The higher milk yields in the Western U.S. may result at least partly from greater feeding of alfalfa forage as hay rather than silage.

Matching Fermentable Energy with RDP

Because microbial protein accounts for most of the dairy cow's MP, one of the major tenets of the NRC (2001) model is to first meet the requirement for RDP. Matching ruminal energy fermentation with RDP will be 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 is much greater than the effects on total tract digestibility (Table 4; Owens et al., 1986; 1997). We identified 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 lb/day and protein yield more than 0.25 lb/day compared to control high moisture corn (4.3 mm mean particle size). 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 likely "optimal" levels of dietary concentrate and forage that will support maximal ruminal protein synthesis and milk production. A high forage diet containing 80% alfalfa silage and 20% concentrate was diluted stepwise with increasing amounts of high moisture corn to (% alfalfa silage DM/% concentrate DM) 65/35, 50/50, and 35/65 in a Latin square (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 alfalfa silage decreased. The observed quadratic response curves were solved and maximums found for DM intake and yield of 3.5% FCM were at 51% concentrate (38% nonfiber carbohydrate; **NFC**); maximum fat yield was found at 43% concentrate (34% NFC). However, responses of milk and protein yields 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 synthesis, also showed the same 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.

Corn silage is commonly used to provide a 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 apparent 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 or liquid molasses (Broderick and Radloff, 2004), in 3 separate feeding studies. The 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 3 trials indicated maximums for total sugars (DM basis) were 6.8% for DM intake and 4.8% for protein yield. However, the effects of sugar feeding in these trials were primarily driven by increased feed intake.

Feeding RUP and Protected AA

The primary advantage of the newer ration formulation systems is their value in identifying when lactating cows will respond to RUP supplements. In the Midwest setting where diets are often based on high CP, and high NPN alfalfa silage, there are usually 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 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-soluble fish meal, lactation response was greater for the fish meal. Moreover, the protein response to low-soluble fish meal was out of proportion to its relative ruminal escape. This reflects the higher quality AA pattern of fish meal protein. Compared to a iso-nitrogenous diet containing urea, we also found an interesting pattern of response to 3 true protein sources that differed in RUP and AA content (Brilo and Broderick, 2004). Flows of RUP and total protein (NAN x 6.25) from the rumen were greatest on cottonseed meal, intermediate on canola meal, and lowest on solvent SBM; however, milk and protein yields 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 protected SBM (Olmos Colmerero and Broderick, 2004). Although milk and protein yields were similar with the 2 diets with 16.6% CP (with or without added RUP) to that obtained by feeding 17.6% CP, 2.6 lb/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 may have resulted 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 with a specific AA is clear—requirements for the limiting metabolizable AA may be met with relatively little N input to the animal. The potential value of exploiting this strategy was shown recently in Germany where supplementing RP-Met to a 14.7% CP diet resulted in milk protein secretion equal to that of a 17.5% CP diet, but at 31 versus 27% conversion of dietary N to milk N (Kröber et al., 2000). We will report comparable results at the annual meeting of the American Dairy Science Association this summer. Similar protein yield, and even greater milk and FCM yields, were observed when RP-Met was fed with 17.3 and 16.1% CP diets versus an 18.6% CP diet without RP-Met.

Future Developments—Supplementation with N-Free “Amino Acids”

Recently, there has been renewed interest in supplementing diets 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 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 the liquid MHA supplied orally contributed post-

ruminal methionine. 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 (McCullum 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, University of New Hampshire, personal communication). A ruminally-protected form of MHA is not available commercially. Branched-chain volatile fatty acids (**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 are incorporated into their protein; there was some evidence that supplements of branched-chain VFA stimulated production of dairy cows fed corn silage diets (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 was 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.

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

	Dietary CP, % of DM					SE	<i>P</i>	
	13.5	15.0	16.5	17.9	19.4		Linear	Quad
DMI, lb/day	47.6 ^b	48.1 ^{ab}	49.6 ^a	47.6 ^b	47.8 ^{ab}	0.9	0.91	0.12
BW gain, lb/day	0.49	0.46	0.7	0.57	0.64	0.16	0.21	0.72
Milk Production, lb/day	80.0 ^b	82.0 ^{ab}	84.4 ^a	80.7 ^b	81.6 ^{ab}	2.0	0.60	0.11
Milk/DMI	1.71	1.71	1.72	1.7	1.72	0.04	0.87	0.99
3.5 % FCM, lb/day	75.2 ^b	78.5 ^{ab}	80.9 ^a	78.7 ^{ab}	79.6 ^{ab}	2.4	0.09	0.17
Fat, %	3.17 ^c	3.26 ^{abc}	3.23 ^{bc}	3.49 ^a	3.45 ^{ab}	0.12	0.00	0.99
Fat, lb/day	2.51	2.65	2.73	2.71	2.73	0.13	0.06	0.30
Protein, %	3.09	3.15	3.09	3.18	3.16	0.04	0.15	0.92
Protein yield, lb/day	2.43 ^b	2.54 ^{ab}	2.60 ^a	2.49 ^{ab}	2.54 ^{ab}	0.09	0.21	0.10
SNF, %	8.92	8.96	8.93	9.01	9.00	0.05	0.09	0.89
SNF, lb/day	7.08 ^b	7.28 ^{ab}	7.58 ^a	7.14 ^b	7.30 ^{ab}	0.20	0.42	0.14
Milk N/N Intake	0.367 ^a	0.344 ^b	0.307 ^c	0.279 ^d	0.255 ^e	0.006	<0.01	0.58
DM digestibility, %	71.2 ^c	74.6 ^a	74.0 ^a	72.5 ^b	72.3 ^{bc}	0.6	0.79	<0.01
OM digestibility, %	72.1 ^c	75.5 ^a	75.0 ^a	73.6 ^b	73.5 ^b	0.6	0.47	<0.01
NDF digestibility, %	45.8 ^c	51.2 ^a	49.5 ^{ab}	48.0 ^b	48.7 ^b	1.0	0.18	<0.01
Urea-N excretion, g/day	63.2 ^e	91.0 ^d	128.4 ^c	174.0 ^b	208.1 ^a	6.6	<0.01	0.43
Microbial CP flow, g/day	993 ^b	1082 ^{ab}	1144 ^a	1127 ^a	1144 ^a	67	0.02	0.21

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

¹CP = Crude protein, DM = dry matter, DMI = dry matter intake, BW = body weight, FCM = fat-corrected milk, SNF = solids not fat, OM = organic matter, NDF = neutral detergent fiber, SE = standard error of the differences of the least square means, and Quad = quadratic.

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	Manure N
	1-16	17-44		
	(Ration CP, % of DM)		(lb/lactation)	
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	SE	<i>P</i> > <i>F</i> ²		
						Forage	FM	Forage x FM
DM intake, lb/day	57.8	54.5	56.9	55.1	0.7	<0.01	0.96	0.37
Milk, lb/day	89.7	86.9	90.2	90.6	0.9	0.11	<0.01	0.04
Fat, %	3.25	3.48	3.30	3.36	0.05	0.01	0.51	0.13
Protein, %	3.14	3.10	3.17	3.17	0.02	0.19	<0.01	0.38
Lactose, %	4.83	4.84	4.81	4.84	0.01	0.11	0.72	0.63
SNF, %	8.66	8.65	8.69	8.68	0.02	0.58	0.20	0.84
Yield, lb/day								
Fat	2.91	2.95	2.95	3.04	0.02	0.25	0.21	0.95
Protein	2.80	2.65	2.84	2.87	0.02	0.1	<0.01	0.03
Lactose	4.32	4.14	4.34	4.41	0.03	0.32	<0.01	0.04
SNF	7.74	7.39	7.85	7.89	0.04	0.15	<0.01	0.04
Efficiency, milk/DMI	1.58	1.60	1.59	1.67	0.02	0.01	0.03	0.20

¹AH = Alfalfa hay, AS = alfalfa silage, FM = fish meal, DMI = dry matter intake, BW = body weight, SNF = solids not fat, and SE = standard error.

²Probability of a significant contrast effect.

Table 4. Effect of processing on digestibility of corn and 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 and Broderick, 2003).

Item	Alfalfa Silage/Corn Silage			
	100/0	74/26	47/53	21/79
Composition (% of DM)				
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
Production				
DM intake (lb/day)	58.4 ^a	57.1 ^a	55.1 ^b	51.1 ^c
Milk yield (lb/day)	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 (based on milk protein yield) from slowly degraded proteins in lactating cows fed alfalfa silage based diets.

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

¹Broderick et al., 1990.

²Broderick, 1992.

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

Item	CP, % of DM	Supplemental protein				SED	P > F
		Urea	SSBM	CSM	CM		
		16.5	16.5	16.6	16.6		
Production (lb/day)							
DM intake		48.7 ^c	53.4 ^b	54.5 ^{ab}	54.9 ^a	0.9	<0.01
Milk		72.5 ^b	88.2 ^a	89.3 ^a	90.6 ^a	2.3	<0.01
Milk protein		2.03 ^c	2.71 ^{ab}	2.60 ^b	2.80 ^a	0.07	<0.01
Milk fat		2.23 ^c	2.69 ^{ab}	2.60 ^b	2.84 ^a	0.11	<0.01
Omasal protein flows (g/day)							
Microbial protein		2344 ^b	2706 ^a	2706 ^a	2775 ^a	120	0.04
RUP		538 ^c	987 ^b	1348 ^a	1150 ^{ab}	106	<0.01
Total protein		2882 ^c	3693 ^b	4054 ^a	3925 ^{ab}	220	<0.01

¹CM = canola meal, CSM = cottonseed meal, SED = standard error of the least square means difference, SSBM = solvent soybean meal, CP = crude protein, DM = dry matter, and RUP = rumen undegraded protein.

^{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 Colmenero and Broderick, 2004).¹

Item	CP, % of DM	A	B	C	D	Contrasts (<i>P</i>)		
						A vs. B	B vs. C	B vs. D
		15.6+RUP	16.6-RUP	16.6+RUP	17.6-RUP			
	SBM, % of DM	4.5	0	5.9	0			
Production (lb/day)								
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
Proportion of N-intake (%)								
Milk N		30.1	29.3	28.8	26.8	0.27	0.50	<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

¹RUP = Rumen undegradable protein, SBM = soybean meal, CP = crude protein, DM = dry matter, FCM = fat-corrected milk, and ESBM = expeller solvent soybean meal.

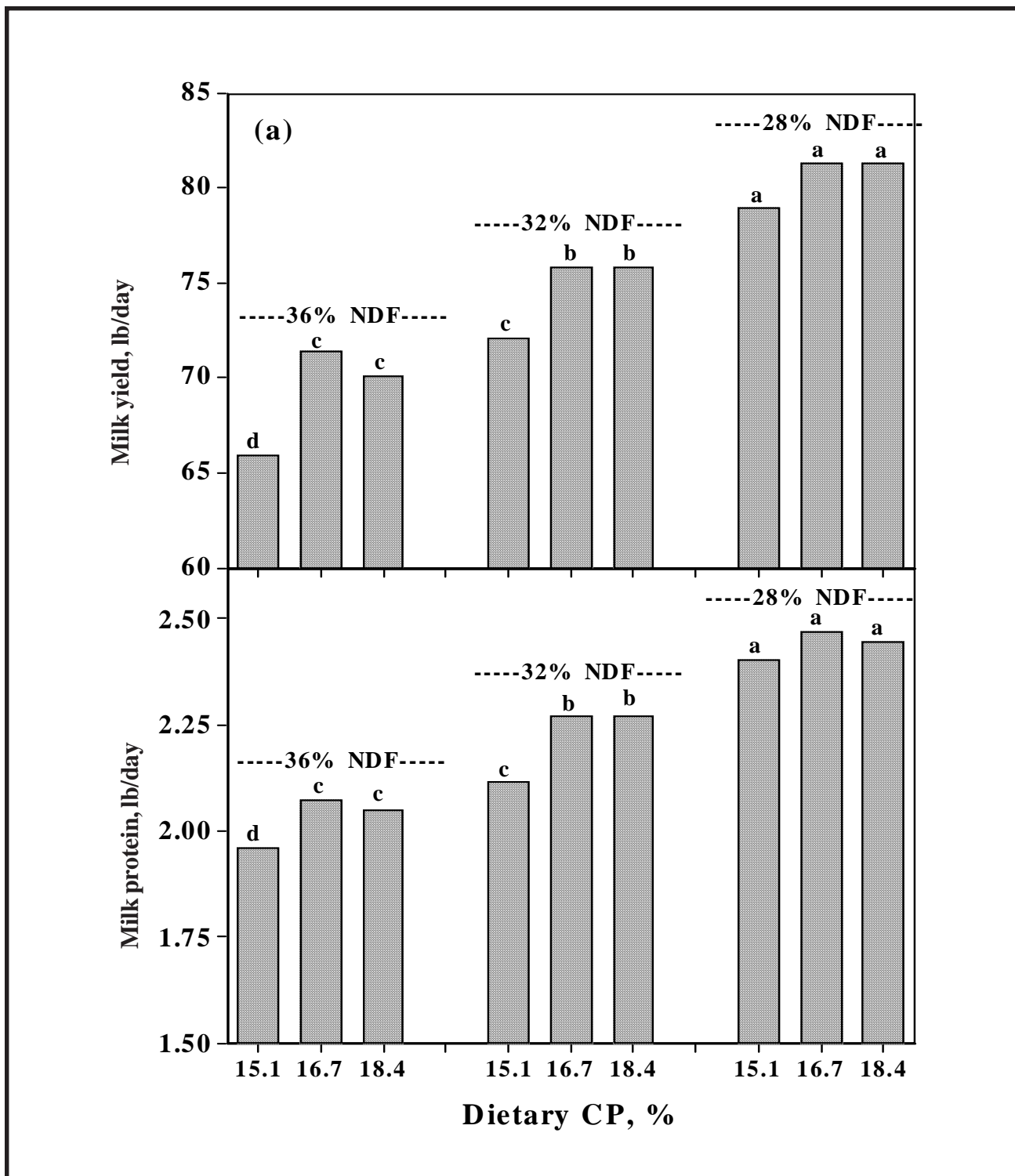


Figure 1. Effect on milk and protein yield of feeding lactating cows crude protein (CP; from solvent soybean meal) at 15.1, 16.7, and 18.4% of DM at each of 3 dietary energy densities (obtained by feeding 75, 62, and 50% of forage DM to give 36, 32, and 28% NDF; Broderick, 2003). Forage was 60% alfalfa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