Economic Factors Affecting Nutrient Balance on Dairy Farms

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■ Take Home Message

Numerous practices can reduce excretion and improve nitrogen utilization on dairy farms. The contribution of nutrition and management to reduction in nitrogen excretion while maintaining the total national supply of milk can be funneled through one or more of the five following routes:

- From a better definition and targeting of optimum allocation of inputs (i.e., operate at optimum),
- From increased animal productivity (reduction of 8% in national N excretion from a 25% increase in cow milk production),
- From an improved knowledge of the biology included (reduction of 8% in N excretion),
- From feeding larger herds with larger and more numerous pens (reduction of 8% in N excretion from feeding 6 groups vs. a one-group TMR), and
- From technical shifts (e.g., protected amino acids).

■ Introduction

Over the last two or three decades, point sources of pollution have been aggressively regulated. Reducing pollution for nonpoint sources appears to be the direction taken recently. Many believe that agriculture is the leading source of impairment to the nations rivers and lakes. In agriculture, the increased concentration of animal production units, a consequence of large economies of scale observed in animal production, has been a main focus of legislators because primarily of its visibility (Pelley, 1996). At this point, the debate is widely open on the costs and benifits of environmental regulations for the animal production industries (Boyd, 1997; Nowlin, 1997; Van Vuuren et al., 1997).

Extensive models of nutrient flows through farming systems have been developed (Dou et al., 1996; Grusenmeyer and Cramer, 1997; Kohn et al., 1997; Van Horn et al., 1994). All models have used a budget approach to nutrient balance in which animal productivity is an input to the model. The effects of management or nutritional changes on N and P excretion are being assessed assuming a constant level of productivity by animals (Ferguson et al, 1992; Kohn et al., 1996). This is incorrect for two reasons. First, current excretion models are based on nutrient requirements of individual animals. However, in modern feeding practice, animals of various genetic and physiological status are fed in groups. Second, requirement models, once inverted into response models, imply constant return to inputs. This linear response is not typical of empirical relationships between nutrient inputs and level of productivity (Coulon and Rémond, 1991; Roffler et al., 1986) . In essence, the assumptions of efficiency of dietary protein utilization used for the calculation of requirements cannot be used as predictors of nutrient partitioning. Wilkerson et al. (1997) proposed a set of empirical polynomial equations to predict manure production and N excretion by Holstein dairy cattle. The problem with this approach is that the large number of independent variables and their interactions, all of which are random with some unknown distribution and correlated in the context of forecasting, lead to unstable predictors. The inference range can be very limited. None of the models reviewed included the effect of animal grouping on nutrient excretion. The objectives of this paper are (1) to explain the relationship between nutrient requirements of individual animals and the milk response of groups of animals, (2) to demonstrate how uncertainty in level of nutrient composition of feeds and nutrient requirements by individual cows affect the optimum level of feeding to a group of animals, and (3) to calculate the cost to the dairy industry from enforcing maximum nutrient efficiency vs. optimum economic allocation of nutrient inputs.

▪ Because We are Milking More Than One Cow

Concepts of Nutrient Requirements and Production Response

It is critically important to understand the clear distinction between nutrient requirements and production response systems. Models such as those developed by the NRC (1989) or the Cornell Net Carbohydrate and Protein System (Fox et al, 1992) are examples of nutrient requirement-based systems. In a requirement system (Figure 1), the physiological status of an animal, including its production level, serve as inputs. Animal and sometimes environmental characteristics are used to calculate levels of nutrients required to sustain the given level of production. Least-cost formulation of diets optimizes the combination of feed ingredients that supplies the required levels of nutrients at least cost. In a production response system (Figure 2), feed ingredients still supply nutrients, but from the flow of nutrients through an animal, a projection on animal status and productivity level are derived. The animal responds to levels of nutrients. Physiological status and production level are outputs of the system.

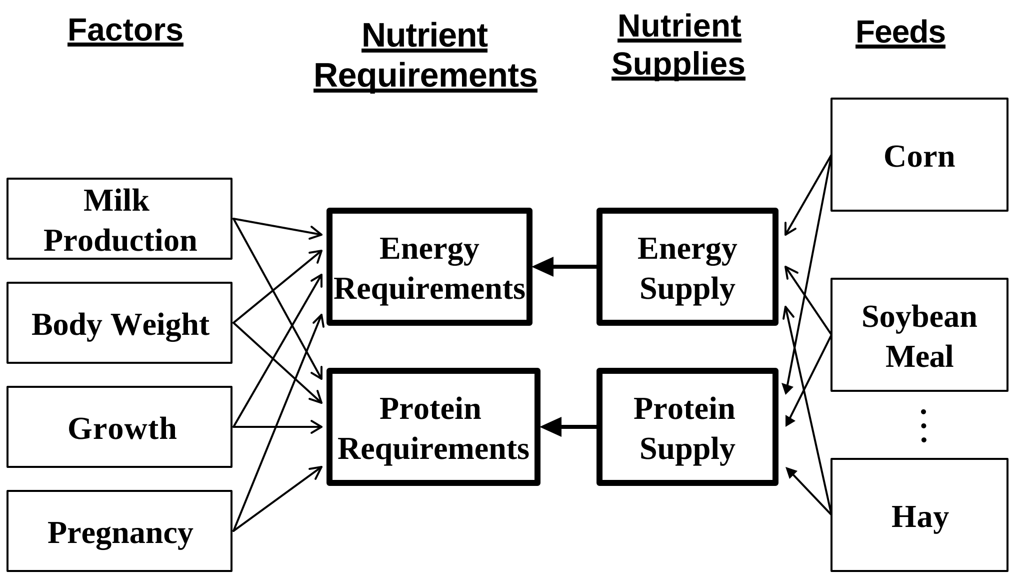


Figure 1 . Schematic representation of a requirement based system.

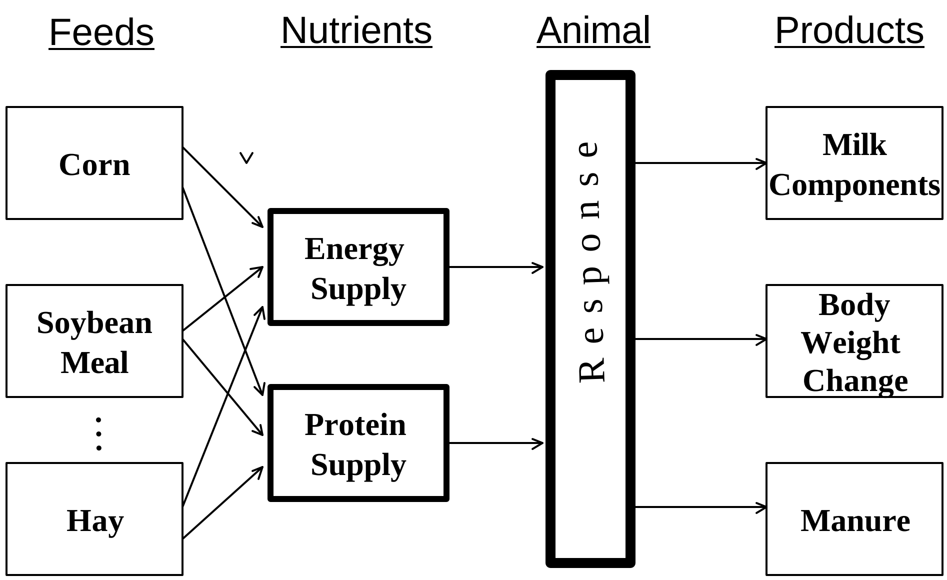
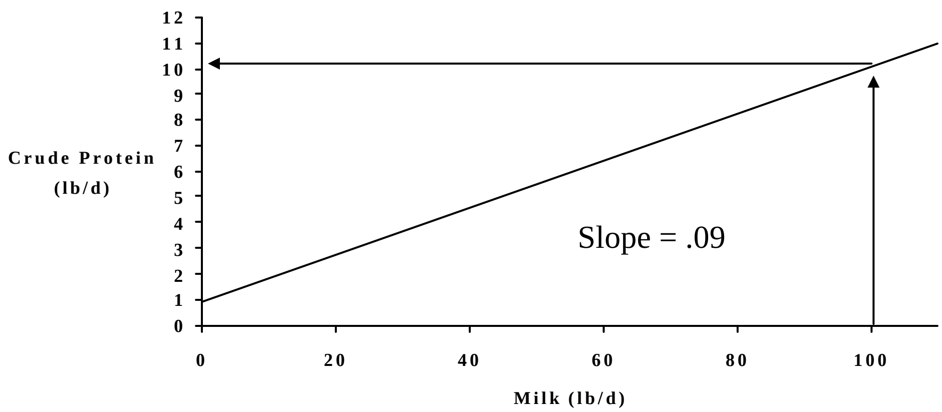


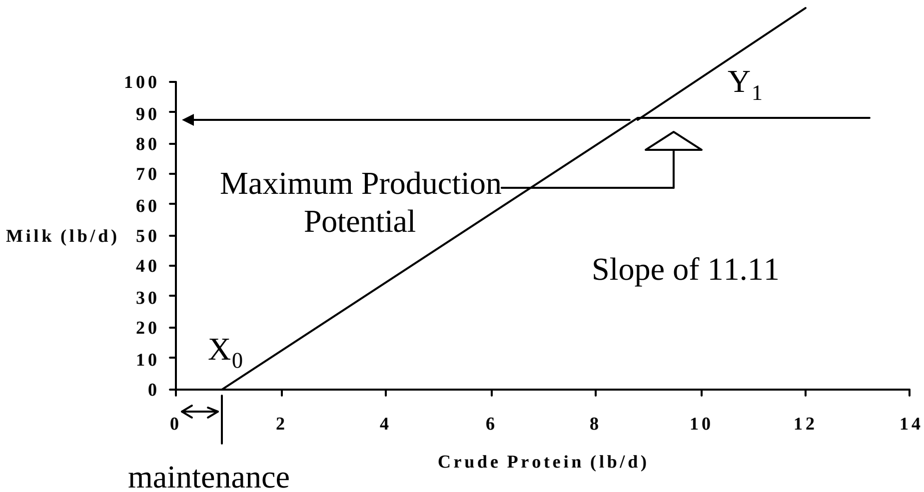
Figure 2. Schematic representation of a production response system.

The crude protein requirement function for a 625 kg cow according to NRC (1989) is a good and simple example of a requirement function (Figure 3a). Approximately 417 g of CP are required for maintenance, and 90 g of CP are needed for each kilogram of FCM produced. Therefore, 40 kg of milk production requires an intake of 4.225 kg of CP. Milk production is the independent variable, and CP is the dependent variable. It is tempting to rotate the two axes (Figure 3b) so that CP becomes the independent variable, and milk production the dependent. This rotation leads to major conceptual flaws. First, the response to nutrient intake is linear. This does not match empirical evidence in which response function are clearly nonlinear (Coulon and Rémond, 1991; Roffler et al., 1986; Vérité and Peyraud, 1988). Second, the linear response has no limits and does not account for variability among cows, environments, and their interactions. The feeding of 20 kg of CP would result in 215 kg of FCM production, regardless of the animal to which it is fed. To correct these flaws, we must introduce the concept of maximum production potential (MPP). Each individual cow, at a given time and under a given set of environmental conditions, has an implicit maximum production level that cannot be exceeded through the feeding of additional nutrients. Cows differ in their maximum production potential and CP maintenance requirements. Therefore, each cow has its own response curve made of two straight segments. However, the production response of a population of cows (pens) has a shape that is makedly different from that of individual cows. The response function of a population of cows (Figure 3c) is curvilinear and is found by deriving the expected production level (average milk production) given a certain level of nutrient intake. The algebraic derivation of this response function is very messy and of little interest to most people. The important point is to understand the concept that a group of animals doesn't have requirements, but instead respond in a classic curvilinear fashion to nutritional inputs. Producers tend to understand this concept easily. Most producers have tried to change a nutritional input in the past while using milk production to see if the cows 'responded' to the change.

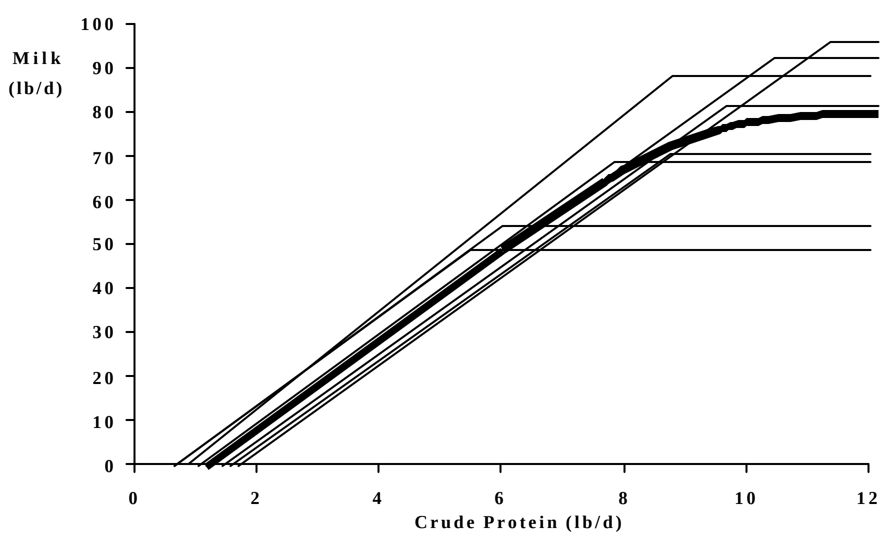
Figure 3. From individuals to population:



3(a) Crude protein requirement function for a 625 kg cow



3(b) Crude protein response function for an individual 625 kg cow



3(c) A crude protein response function for a population of cows.

The model expansion from one nutrient to multiple nutrients is straightforward algebraically but it makes for messy graphics. With two nutrients, the response function of one individual is a three-dimensional, truncated pyramid. With three nutrients, we would need to graph in four dimensions. We will leave this exercise to fans of Star Trek.

In our study, we examined the milk response of cows as a function of crude protein (CP) and Net Energy for lactation (NE_L) intake. Other, more 'fashionable' nutrients could be used (e.g., rumen undegradable protein). Because the conclusions would not change, we thought that using the simplest set of nutrients would be appreciated by most readers.

Estimating Nitrogen Excretion

Over a long enough period of time, nutrient inputs to a cow must be balanced by the sum of all outputs because of the law of mass conservation. When only animals of producing age are considered, retained N is negligible and N excreted in the manure (feces plus urine) is equal to N intake minus milk N (which is easily calculated by dividing milk protein by 6.38). Amazingly, this very simple mass balance has been ignored by the builders of some nutrient management models. The amount of N retained within the body of mature animals (> 2 years) is insignificant over a lactation. Therefore, the following equation can be used to estimate the amount of N excreted in the manure:

$$Nex = NI - MN$$

where Nex = N excreted (g/d)
NI = Nitrogen Intake (g/d)
MN = Milk Nitrogen (g/d)

Nutrient Costs Estimates

Our analysis required a good estimate of nutrient costs. Cost estimates for NE_L and CP were calculated using the maximum likelihood method of St-Pierre and Glamocic (2000). A total of 23 different feed ingredient prices were taken for each of four quarters (January, April, July, and October), at two different markets (Chicago and Los Angeles), for a period of 15 years (1982 to 1997). The estimates averaged \$0.07/Mcal NE_L and \$0.40/kg of CP (Table1). During this period, markets showed large variation in their valuation of each of the two nutrients, with maximum implied costs exceeding minimum costs by more than two folds.

Table 1. Market cost estimates per unit of NE_L and CP.[1]

Label[2]	Year	NE_L ($/Mcal)	CP ($/kg)
A	Average	0.070	0.40
H-H	1997	0.092	0.61
H-A	1984	0.095	0.37
A-H	1988	0.074	0.58
L-L	1986	0.043	0.31

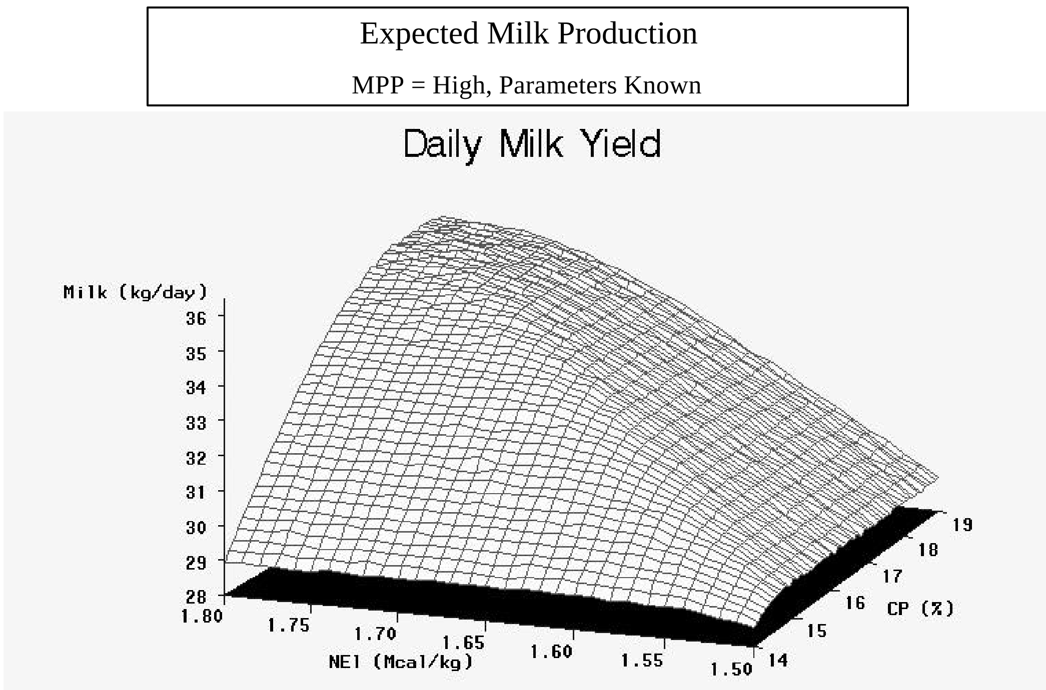
[1]Costs were estimated by regression using 23 feed ingredient prices, at two markets, four times per year during the 15 year period from 1982 to 1997.

[2]A = average from 1982-1997 at two markets from 23 feed ingredients. H = high, A = average, and L = low for NE_L and CP, respectively.

Cow Response to Nutrients: High Genetic Potential in a Known World

We can now examine what happens when nutrient levels (CP and NE_L) are changed in a large group of cows. First, let us look at the situation where we assume that we know perfectly the nutritional composition of all feeds and the exact nutritional requirements of individual cows for a large group of cows with high genetic potential (11,340 kg of milk/cow per year). The response in milk yield to NE_L and CP concentration in the diet ([NE] and [CP] respectively) is shown in Figure 4(a). A maximum milk production of 33.95 kg/d is achieved at a level of [NE] = 1.80 Mcal/kg and [CP] = 18.5%. The efficiency of N utilization can be expressed as kilograms of milk produced per kilogram of N excreted (MNRATIO). As shown in Figure 5, MNRATIO varies between 60.0 and 86.9, with the maximum efficiency achieved at [NE] = 1.75 and [CP] = 17.0. Therefore, it is already apparent that the optimum diet for maximizing milk production is quite different than the optimum diet for maximizing N efficiency (minimizing N excretion per unit of milk produced). But we also know from economics 101 that the optimum diet from an economics standpoint is not the one that maximizes milk production. Using the data reported in Table 1 for input prices and a blend price of $30/hl for milk, we calculated the expected income over feed costs (IOFC) for our 'herd' (Figure 6). If costs other than feeds are considered fixed (not a bad assumption in the short and medium term), then the point of maximum IOFC is also the point of economic optimum (maximum profitability).

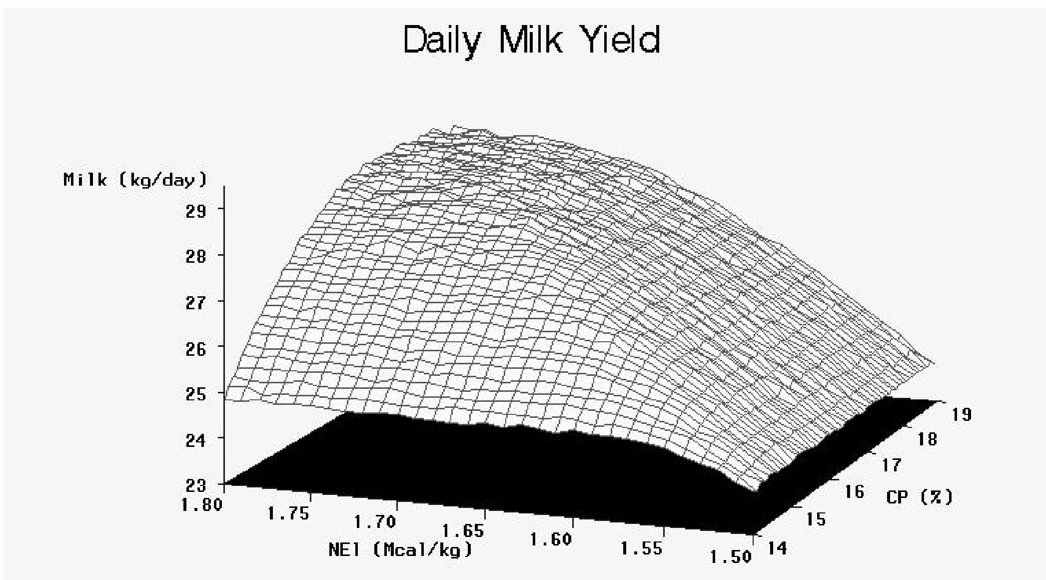
Figure 4. Response in milk yield to NE and CP concentrations in the diet:



4(a) High herd potential (11,340 kg/cow per year) in a known world.

Expected Milk Production

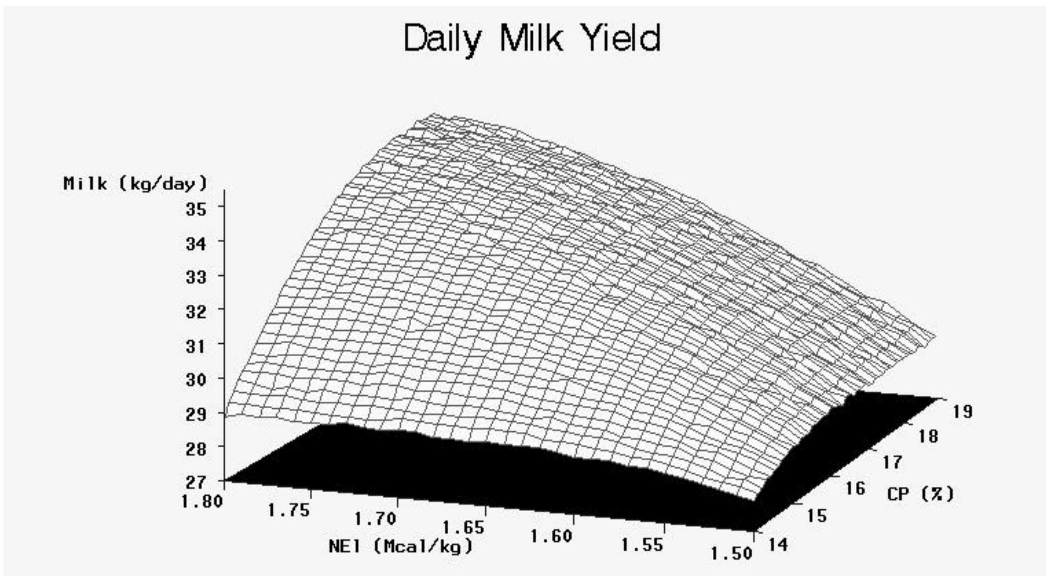
MPP = LOW, Parameters Known



4(b) Low herd potential (9,070 kg/cow per year) in a known world.

Expected Milk Production

MPP = High, Parameters = RANDOM



4(c) High herd potential (11,340 kg/cow per year) in an uncertain world.

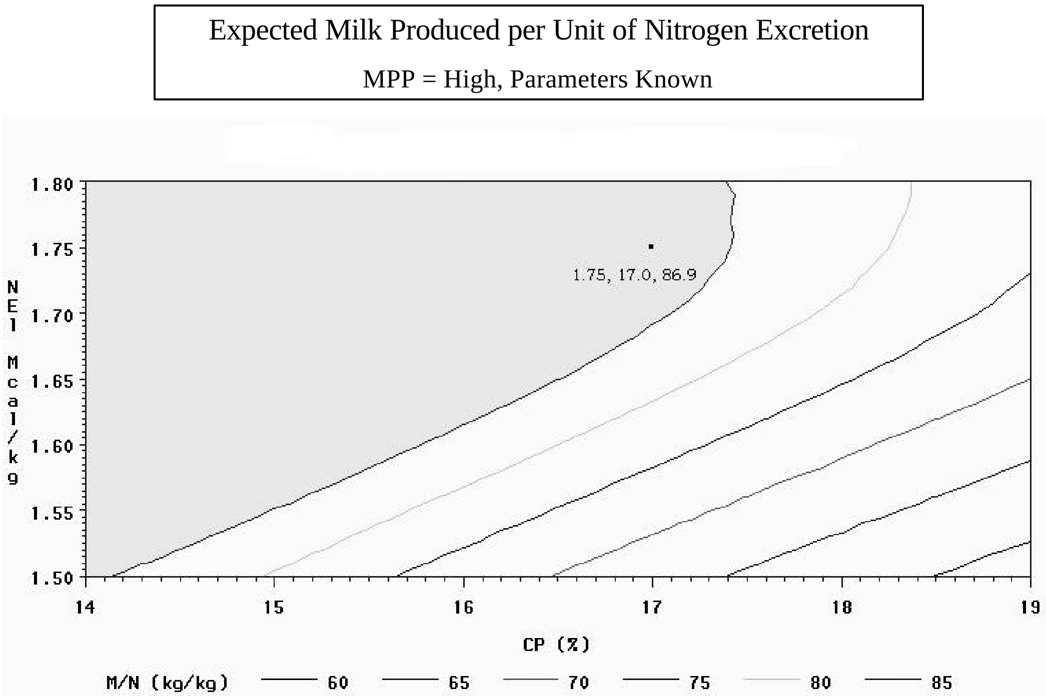


Figure 5. Expected milk produced per unit of N excreted (MNRATIO) as a function of NE_L and CP concentrations for high herd potential (11,340 kg/cow per year) in a known world.

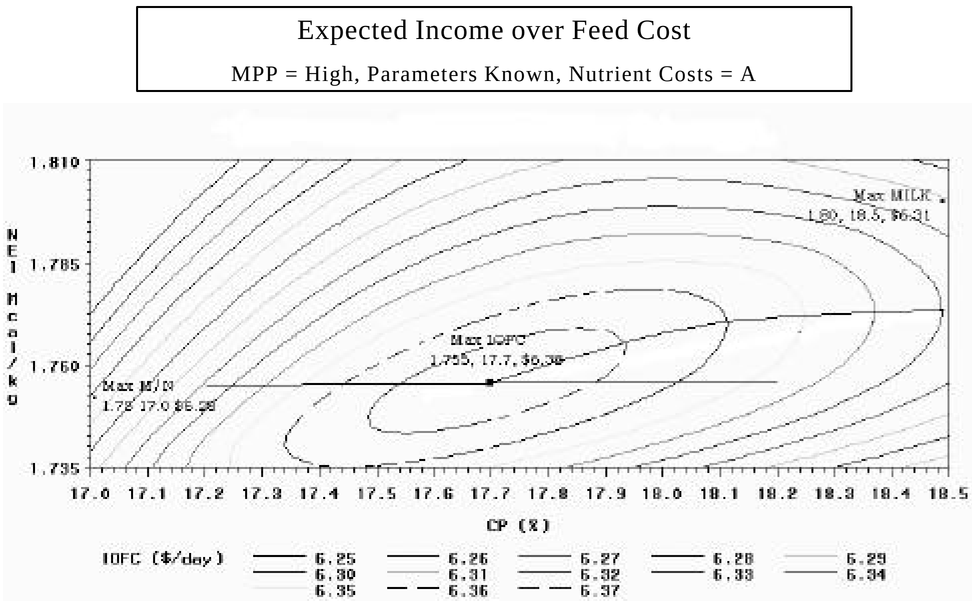


Figure 6. Response in income over feed costs (IOFC) as a function of NE_L and CP concentrations for high herd potential (11,340 kg/cow per year) in a known world.

The point of maximum economic efficiency at average nutrient costs ([NE] = 1.755, [CP] = 17.7) differs from both the point of maximum production ([NE] = 1.80, [CP] =18.5) and the point of maximum N efficiency ([NE] = 1.75, [CP] = 17.0). Under conditions of uncertainty of level of inputs, the optimal strategy would be to increase the average level of both inputs because the curve is much steeper going from O to A than from O to A' (Figure 5). The optimum allocation of inputs will shift along the line of least descent (O - B) when uncertainty regarding level of inputs is considered.

The effect of nutrient costs on the optimum economic allocation of [NE] and [CP], expected milk production, N efficiency, and the resulting IOFC are reported in Table 2. Although nutrient cost scenarios are based on extreme observations over a 15-year period, the optimum allocation of inputs changes very little. In economic terms, this is known as a very low input price elasticity. Optimal adjustments made to inputs, expected output level, N excretion and MNRATIO all follow a pattern in line with classic mathematical economic theories.

Table 2. Effect of nutrient costs on optimum allocation of NE_L, and CP, expected milk production (milk), N excretion (Nex), N efficiency (M/N), and income over feed costs (IOFC).

Nutrient Costs[1]	NE_L (Mcal/kg)	CP (%)	Milk (kg/d)	Nex (g/d)	M/N[2] (kg/kg)	IOFC ($/d)
A	1.755	17.7	35.7	425	84.0	6.38
H-H	1.730	17.4	35.2	417	84.4	4.77
H-A	1.740	17.6	35.4	423	83.7	5.55
A-H	1.750	17.4	35.4	420	84.3	5.55
L-L	1.77	17.9	35.8	432	82.9	7.70

[1]A = average from 1982-1997 at two markets from 23 feed ingredients. H = high, L = low for NE_L and CP costs, respectively.

[2]Milk production per unit of N excreted.

Cow Response to Nutrients: Effect of Milk Production Potential

What is the effect of milk production potential (combination of genetics and environment) on the optimal diet? In Figure 4(b), we show the response surface of milk to [NE] and [CP] when cows have a maximum milk production potential of 9,070 kg/cow per year. The comparison of this surface to that of a high potential herd (Figure 4(a) shows the smoothing and compressing effect that a reduction in herd potential has on the response function. Milk production is maximized at [NE] = 1.78 and [CP] = 18.2. N efficiency (MNRATIO) is maximized at [NE] = 1.69 and [CP] =14.4. IOFC is maximized at [NE] = 1.70 and [CP] = 16.7. Table 3 reports some of the differences resulting from high vs. low herd potential. Clearly, the milk production difference was expected. Although cows excrete less N at low herd potential, they do excrete more N per unit of milk produced. In fact, raising herd productivity from an average of 8,960 to 11,935 kg/cow per year improves N efficiency by 8.7%.

Table 3. Effect of herd production potential on optimal allocation of NE_L and CP, expected milk production, N excretion, gross N efficiency and milk produced per kg of N excreted (MNRATIO).

	Herd Production Potential[1]		
	High	**Low**	**Diff (%)**
Optimal NE_L (Mcal/kg)	1.75	1.70	+2.9
Optical CP (%)	17.7	16.7	+6.0
Expected milk production (kg/d)	35.7	28.2	+26.6
N Excretion (g/d)	425	365	+16.4
Gross N efficiency (Milk N ¸ Intake N)	0.296	0.279	+6.1
MNRATIO (kg/kg)	83.9	77.2	+8.7

[1]High = 11,340 kg/cow per year, Low = 9,070 kg/cow per yr.

Because We Live in an Uncertain World

To this point, our analysis has assumed that we live in a pretty nice world where we know exactly the nutrient requirements of individual cows, the exact dry matter intake of each cow and the exact composition of all the feeds used in the diets. In the real world, all of these assumptions cannot stand. Nutrient requirements are derived from experimental data. This implies that requirements are estimates and therefore subject to errors (uncertainty). The variation in dry matter intake is obvious to anyone who ever attempted to predict dry matter intake (e.g., Roseler et al., 1998). As for the composition of feeds, even an aggressive feed analysis program leaves some uncertainty regarding their true composition. After all, only samples are analyzed. The methods used in the laboratories are not perfectly replicable. Laboratories vary. We recognized these sources of uncertainty and examined their effects on production efficiency and economics using what is called a stochastic model.

The resulting milk response surface is shown in Figure 4(c). The surface is noticeably more curvilinear than that obtained with fixed parameters (Figure 4a). Milk production was maximized at [NE] = 1.79 and [CP] = 18.6%. N efficiency was maximized at [NE] = 1.78 Mcal/kg and [CP] = 14.9%. Using average nutrient costs, IOFC was maximized at [NE] = 1.79 Mcal/kg and [CP] = 18.0%. Table 4 compares optimal levels of inputs, milk production, N excretion and efficiency, and IOFC depending on the level of certainty that we have. Uncertainty in model parameters results in higher [NE] and [CP] optima even though expected milk production is reduced by 1.1 kg/d. This same uncertainty is also responsible for an 8.2% increase in N excretion and a 10.7% decrease in MNRATIO. Consequently, uncertainty of parameter estimates reduced IOFC by $0.42/d, or $133 per lactation.

Table 4. Effect of uncertainty in composition of feeds, animal requirement and dry matter intake on optimal NE_L and CP, expected milk production, N excretion, milk produced per kilogram of N excreted (MNRATIO) and income over feed costs (IOFC).

	Uncertain	Certain	Diff (%)
Optimal NE (Mcal/kg)	1.79	1.75	+2.3
Optimal CP (%)	18.0	17.7	+1.7
Expected milk production (kg/d)	34.6	35.7	-3.1
N excretion (kg/d)	460	425	+8.2
MNRATIO	75.0	84.0	-10.7
IOFC ($/d)	5.96	6.38	-6.6

Do We Really Want to Maximize N Efficiency? At What Cost?

In crop production, some have argued for a tax on inputs (fertilizer, irrigation water) as a means to reduce the leaching of nutrients into underground water and aquifers (Larson et al., 1996). In animal production, taxes on N and P excretion have been proposed to force livestock enterprises towards maximum N and P efficiency (Faeth, 1993). The idea that maximum N efficiency can be accomplished without significant economic losses to dairy enterprises is a concept that has infiltrated the literature with neither proof nor challenge. For example, Dinn et al. (1998) used three levels of CP, 18.3, 16.7 and 15.3% in combination with rumen-protected amino acids to show reduction in N excretion resulting from an improvement in N efficiency. Cows fed the 15.3% CP diet excreted 313 g of N/day, which was 109 g less than that from cows fed the 18.3% CP diet, but they produced 32.8 kg of milk per day, which was 1.4 kg/d less than the cows fed the high CP diet. Nevertheless, the low CP diet had the highest MNRATIO, 98.1, compared with 77.7 for the high CP diet. Using average costs for NE_L and CP and $30/100 kg of milk, the lowest CP diet resulted in an IOFC of $5.20/cow/day, a reduction of $0.44/cow/day compared to the highest CP diet, or approximately $139 per lactation. The adoption of the low CP diet as a strategy to reduce N excretion and improve N efficiency would cost $4.40 per kg of reduction in N excretion, or over six times the cost of inorganic N fertilizer.

Table 5. Immediate economic consequences of enforcing maximum N efficiency (MAX M/N) as opposed to optimum economic allocation of nutrient inputs (MAX IOFC) on the national cost of producing 70 billion kg of milk, assuming a national herd with a milk production potential of 25,000 lbs/cow per year.

	MAX IOFC	MAX M/N
Actual milk production (kg/cow/year)	10,955	9,812
N excretion (kg/cow/year)	146	111
Income over feed costs ($/cow/year)	$1,893	$1,639
Net income ($/cow/year)[1]	$622	$368
Number of cows (millions)	6.39	7.13
N excretion (metric tons/year)	932,940	791,430
Net income (million $/year)	3,975	2,624
Reduction in net income per kilogram of reduction of N excretion ($/kg N)	--	9.55

[1]Assume fixed costs of $3.50/cow per day.

Similar results are deduced from our model. Table 5 reports the immediate consequence of a national dairy herd (with a MPP = 11,340/cow per year) moving away from a maximum IOFC feeding strategy to a maximum MNRATIO strategy. Average milk production per cow is reduced by 10.4% or 1143 kg/cow per year, but N excretion is also reduced by 24% or 35 kg/year per animal. The net result is a reduction of $254 per cow in annual net income, assuming fixed costs of $3.50/cow per day. Because of the reduction in productivity, 740,000 more cows would be needed in the US to maintain the current supply of 155 billion pounds of milk per year. The national aggregate excretion of N would be reduced by 141,510 tons, a 15% reduction. This reduction would be achieved at a cost of 1.35 billion dollars nationally, or $9.55 per kg reduction in N excretion. This analysis does not factor in the expected reduction in the national supply of milk resulting from lower operating margins. A reduction in supply would increase the unit price for milk paid to producers and would offset, at least partially, some of the described losses to producers. However, the total societal cost would still be 1.35 billion dollars. This 1.35 billion dollars figure is actually a conservative estimate of the total cost because we assumed that the national herd was made exclusively of herds with production potential of 11,340 kg of milk/cow per year. Remember that as we lower the production potential, the milk response curve becomes flatter and the difference between the optimum combination of NE_L and CP for the economic optimum and the N-efficiency maximum widens. Therefore, the estimated economic cost would be higher had we used 9,070 kg of production potential, a number more in line with the average national milk production (approximately 8,400 kg/cow per year in 2000).

This argumentation does not imply that N excretion cannot be reduced nutritionally. First, it is clear that all herds are not fed at the economic optimum. Much gain could be accomplished from better ration balancing using our current knowledge in dairy nutrition. We used a model based on crude protein, whereas most recent models are based on RDP and RUP. According to NRC (1989), a RDP/RUP system can reduce N intake by 6 to 7% compared to a CP system at identical milk production level. Also, it is likely that improvements in our knowledge of amino acid requirements and supplies in ruminants will allow further improvements in N efficiency. These improvements, however, imply a translocation of the response surface (e.g. Figure 4c) and not a move along the surface. We noted previously that for a herd with a mean MPP of 11,340 kg/cow per year, the economic optimum was at [NE] = 1.79 and [CP] = 18.0%. However, new knowledge and technologies may allow a new economic optimum to be translocated to [NE] = 1.79 and [CP] = 16%. Excretion of N would be reduced not because maximum N efficiency is achieved or sought but because of the technological shift in N utilization. There are large economic differences between creating incentives to improve N utilization versus creating incentives (or penalties) to force maximum N efficiency.

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