

Animal Grouping Strategies, Sources of Variation, and Economic Factors Affecting Nutrient Balance on Dairy Farms¹

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ABSTRACT

Increasing environmental concerns are forcing animal industries to reevaluate current feeding practices and their relationships to nutrient excretion. Previous modeling efforts have used simple budgets of nutrient flows through animals, assuming a constant productivity level. This assumption is not valid if animals are not in a steady state. A response model of dairy cow production to levels of net energy for lactation (NE_L) and crude protein (CP) was derived from an abrupt threshold and plateau model of individuals. Monte Carlo techniques were used to simulate populations of cows fed diets of various NE_L and CP concentrations, to derive the optimum allocation of NE_L and CP, and to estimate how the optimum is affected by herd production potential, prices of inputs, and uncertainty of parameters. The simulation showed that a 25% increase in milk production reduced N excretion per kilogram of milk produced by 8%. Improved knowledge of the biology involved and feed composition can reduce N excretion by an additional 8%. Grouping strategies and number of groups used affect optimum allocation of nutrients. An optimum of six milking groups per production unit was derived from the simulation and would reduce N excretion by 8% compared to herds fed in one group.

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(Key words: nitrogen excretion, cow grouping, response function, nutrient requirements)

Abbreviation key: [CP] = diet concentration in crude protein, [NE] = diet concentration in net energy for lactation, FAT% = milk fat percentage, HERD = mean annual milk production potential within herd, IOFC = income over feed costs, ME = metabolizable energy, MIM = month in milk, MN:NEX = kilograms of milk produced per kilogram of N excreted, MP% = milk protein percentage, MPP = milk production potential.

INTRODUCTION

Over the last three decades, point sources of pollution have been aggressively regulated. Reducing pollution from nonpoint sources is perhaps the major remaining challenge for clean water policy in the United States. Agriculture is believed to be the leading source of impairment in the nation's rivers and lakes (58). In agriculture, animal production has been a main focus of environmental concerns because of its visibility and the increased concentration of animal production units (42). In response to public concerns, numerous states have passed legislation regulating manure and nutrient management (17, 23, 24, 44). The debate is still open on the costs and benefits of environmental regulations for the animal production industries (3, 40, 66). It is clear, however, that regulation and enforcement will intensify in years to come as a consequence of mounting evidence of the contribution of agriculture to environmental problems, especially in environmentally sensitive areas (10, 27, 31, 50).

Various farming practices have been proposed to reduce field erosion and N and P losses (59). Those practices, such as no-till, do not generate economic benefits of sufficient magnitude to adequately compensate farmers who adopt and use them (8, 13, 37). Consequently, the rate of adoption is still relatively

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low (38), although large potential environment benefits have been demonstrated (43) and can be accurately modeled (4, 5, 59). Similarly, advances in manure storage structures and designs have contributed to substantial reduction in potential losses of N and P (35, 36). New technologies are under development that will increase the recovery of nutrients from storage systems (51).

Extensive models of nutrient flows through farming systems have been developed (14, 21, 22, 29, 63, 64, 65). 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 with the assumption of a constant level of productivity by animals (18, 28). This presumption 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 statuses 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 (7, 45, 49, 67). In essence, the assumptions of efficiency of dietary protein utilization used for the calculation of requirements cannot be used as predictors of nutrient partitioning (41). Wilkerson et al. (68) 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 (15). The inference range can be very limited. None of the models reviewed included the effect of animal grouping on nutrient excretion. The objectives of our study were (1) to derive a procedure for transforming nutrient requirement functions of individual animals into response functions of groups of animals, (2) to determine how uncertainty in level of inputs, model structure, and parameter estimates influence the optimum allocation of inputs, (3) to quantify how grouping strategies on dairy farms affect nutrient balance and optimum allocation of nutrient inputs, and (4) to evaluate the sensitivity of the economic optimum to nutrient costs and animal productivity potential.

DERIVATION OF A RESPONSE MODEL

Nutrient Requirements

It is critically important to understand the clear distinction between nutrient requirements and

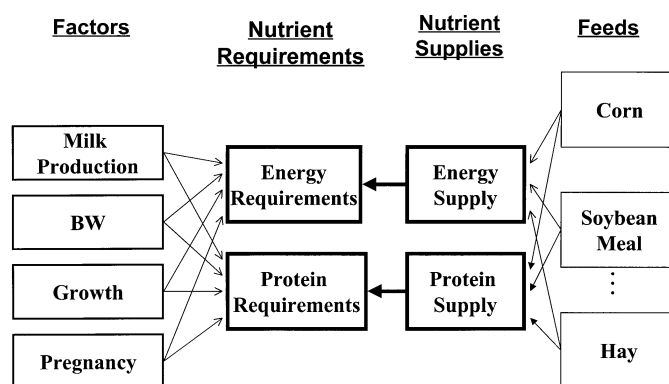


Figure 1. Schematic representation of a requirement-based system.

production response systems. Models such as those developed by the NRC (39) and Institut National de la Recherche Agronomique (25) or the Cornell Net Carbohydrate and Protein System (20, 48, 52) 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. A least-cost formulation of diets optimizes the combination of feed ingredients that supplies the required amount of nutrients at least cost. This balance has been achieved with linear programming techniques (1), although nonlinear models of requirements require nonlinear optimization techniques (55, 56). 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 are derived. The animal responds to levels of nutrients. Physiological status and production are outputs of the system.

The crude protein requirement function for a 625-kg cow according to NRC (39) is a good and simple example of a requirement function. Approximately 400 g of CP is required for maintenance, and 90 g of CP is needed for each kilogram of FCM produced. Therefore, 40 kg of production requires an intake of 4 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 sections of the response approximate linearity but other sections are clearly non-

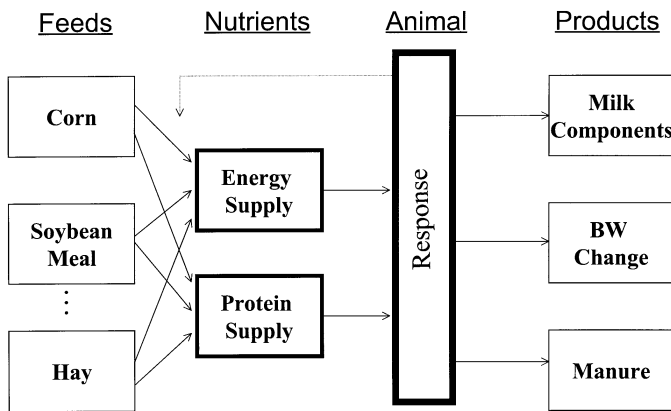


Figure 2. Schematic representation of a production response system.

linear (7, 45, 67). Second, the linear response has no limits and does not account for variability among cows, environments, and their interactions. The feeding of 8.6 kg of CP would result in 100 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 that cannot be exceeded through the feeding of additional nutrients.

From Individuals to Population

Let Y_1 be the maximum production potential of a given cow with CP maintenance requirements of X_0 . Cows differ in Y_1 and X_0 . Therefore, the response function of a population of cows (Figure 3c) is curvilinear and is found by deriving the expected production (mean) given a certain level of nutrient intake, denoted as $E(Y | X)$. Algebraically, this is represented as

$$E(Y | X) = 0 \Pr [X < X_0] + B \Pr [X_0 < X < X_0 + Y_1/B] E[X - X_0 | X_0 < X < X_0 + Y_1/B] + \Pr [X_0 < X_0 + Y_1/B < X] E[Y_1 | X_0 + Y_1/B < X] \quad [1]$$

where:

- Pr = Probability of []
- E = Expectation of []
- B = 1/nutrient requirements per kilogram of FCM
- Y_1 = maximum production potential (random)

- X_0 = maintenance nutrient requirements (random)
- Y = mean production level at a given X
- X = nutrient intake

If we assume that Y_1 and X_0 follow a multivariate normal distribution function $N(X_0, \mu, \sigma^2_{X_0}, \sigma^2_{\mu}, \rho)$, where:

- N = multivariate normal distribution function
- X_0 = mean maintenance nutrient requirements
- μ = mean maximum production potential
- $\sigma^2_{X_0}$ = variance of X_0

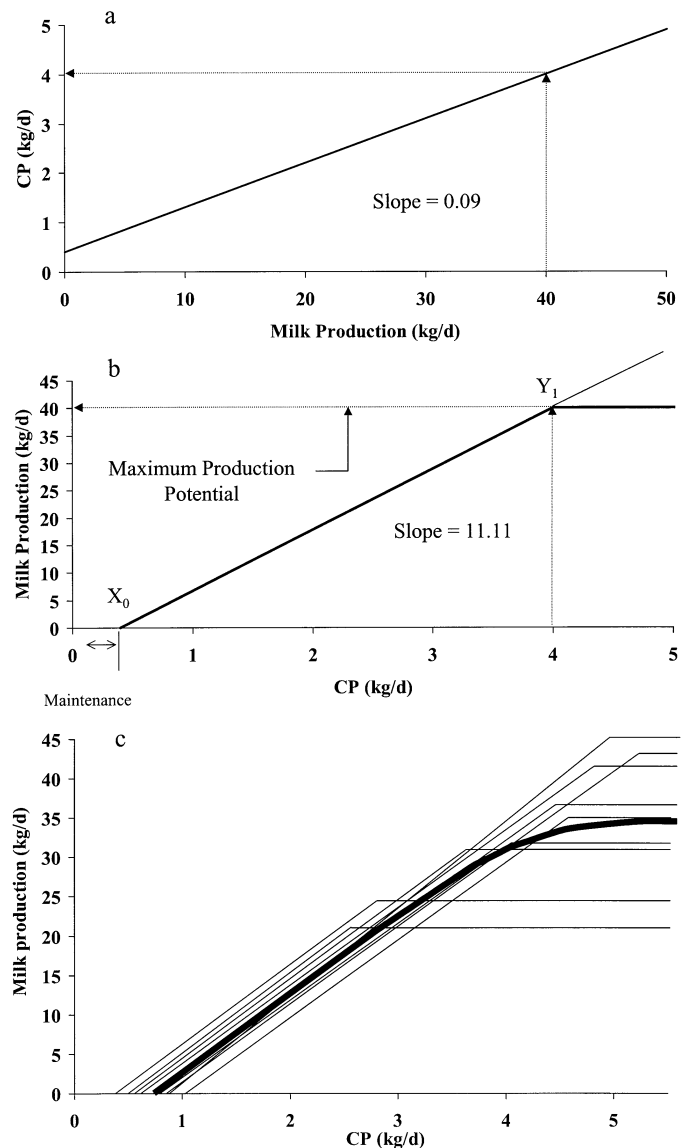


Figure 3. From individuals to population: a) CP requirement function for a 625-kg cow, b) CP response function for an individual 625-kg cow, and c) CP response function for a population of cows.

σ^2_{μ} = variance of maximum production potential
 ρ = correlation between X_0 and Y_1 ,

same argument has been used at the animal level (63). This implies that:

then $E(Y | X)$ is given by the following function (9):

$$NI = MN + FN + UN + RN \quad [4]$$

$$E(Y | X) = \mu N[-X, -\mu; -\rho] - (\mu - BX) N[-X, (BX - \mu)/\theta; -(B + \rho)/\theta] + \phi(\mu) \Phi((X + \rho\mu)/(1 - \rho^2)) - \theta \Phi((BX - \mu)/\theta) \Phi((1 + B\rho)X + (B + \rho)\mu/\theta(1 - \rho^2)) + B \phi(X) \Phi((\rho X + \mu)/(1 - \rho^2)) \quad [2]$$

where

NI = N intake (g/d),
 MN = Milk N (g/d),
 FN = Fecal N (g/d),
 UN = Urinary N (g/d), and
 RN = Retained N (g/d).

where

When only animals of producing age are considered, RN becomes negligible and [4] reduces to

$\phi()$ = univariate normal frequency distribution function,
 $\Phi()$ = univariate normal cumulative distribution function, and
 $\theta = (1 + B^2 + 2B\rho)^{1/2}$

$$NI = MN + FN + UN \quad [5]$$

$N(Z_1, Z_2; \rho)$ is the multivariate normal cumulative distribution function, and Z_i are some normal variates.

Rearranging

$$Nex = NI - MN \quad [6]$$

In a herd or group of cows, the maximum production potential is not normally distributed unless all animals are of the same parity and stage of lactation, and all animals interact identically with their environment. Algebraically, this implies that

where $Nex = N$ excreted (g/d, sum of $FN + UN$).

$$\mu_{Y1} = f(\text{parity, stage of lactation}) \quad [3]$$

MONTE CARLO STUDY

where f stands for "some function of." In most herds, parity and stage of lactation are themselves random variables, each distributed as a multinomial distribution. Under these realistic conditions, the function provided by equation [2] is no longer a valid analytical solution to [1] and the derivation of an analytical solution has eluded all efforts so far. However, $E(Y | X)$ is still numerically tractable using Monte Carlo methods.

Model Specifications

Monte Carlo methods have long been used to study stochastic processes with untractable analytical solutions (19). We used such methods to study the behavior of milk production from changes in the supply of energy and protein. The NE_L concentration (**[NE]**) was varied from 1.5 to 1.8 Mcal/kg by 0.01 increments. Likewise, CP concentration in diets (**[CP]**) was varied from 14 to 19% by 0.1 increments. In essence, this created a 30×50 factorial experiment. At each **[NE]** - **[CP]** locus, the expected milk production was calculated as the mean of the production of 10,000 simulated cows. This large number of replicates was required to estimate the expected milk production with a standard error of less than 0.05 kg/d, the amount of error that was required for estimating net income with an error of less than 1%. For each simulated cow, MPP and BW were modeled using a multivariate normal distribution (19) with the following parameters:

The model expansion from one nutrient to multiple nutrients is straightforward. With two nutrients, the response function of one individual is a three-dimensional, truncated pyramid called a fixed factor response function (12).

$$MPP \approx N(\mu = f(\text{herd, parity, month in milk}), \sigma^2 = 25) \quad [7]$$

$$BW \approx N(\mu = g(\text{parity}), \sigma^2 = 900) \quad [8]$$

Estimating Nitrogen Excretion

Kohn et al. (29) argued that, when considered over a long enough period of time, nutrient inputs to a farm system must be balanced by the sum of all inputs because of the law of mass conservation. The

with a correlation $\rho_{MPP,BW} = 0.1$.

TABLE 1. Mean milk production used for Monte Carlo simulation as affected by herd milk production potential, parity, and stage of lactation.

| Stage of lactation (mo) | Herd milk production potential | | | | | |
|-------------------------|--------------------------------|---------------|--------------------------|--------------|---------------|--------------------------|
| | 9100 kg/yr | | | 11,350 kg/yr | | |
| | First parity | Second parity | Third parity and greater | First parity | Second parity | Third parity and greater |
| 1 | 26.4 | 35.4 | 37.0 | 30.9 | 42.5 | 43.3 |
| 2 | 29.1 | 37.2 | 39.7 | 35.1 | 45.7 | 47.9 |
| 3 | 28.8 | 35.3 | 38.1 | 35.1 | 44.0 | 46.3 |
| 4 | 28.0 | 33.5 | 36.0 | 34.9 | 42.3 | 44.7 |
| 5 | 27.1 | 31.5 | 33.6 | 33.7 | 39.8 | 41.8 |
| 6 | 26.1 | 29.5 | 31.4 | 32.8 | 37.8 | 39.1 |
| 7 | 25.3 | 27.4 | 29.1 | 32.1 | 35.8 | 36.6 |
| 8 | 24.0 | 25.3 | 26.5 | 30.3 | 33.0 | 33.7 |
| 9 | 23.0 | 23.5 | 23.9 | 29.3 | 30.6 | 30.8 |
| 10 | 22.1 | 21.7 | 22.1 | 28.9 | 28.8 | 29.2 |
| 11 | 21.0 | 19.9 | 19.8 | 27.8 | 27.0 | 26.9 |

Two herd potentials (**HERD**) were used: high (H) = 11,350 kg/yr per cow and low (L) = 9100 kg/yr per cow. The function f in [7] was a discrete function with values for HERD, parity and month in milk as reported in Table 1. In [8], the function g was a discrete function with $\mu = 580$ for first parity, $\mu = 630$ for second parity, and $\mu = 650$ for third or greater parity. Parity was modeled as a multinomial (p_1, p_2, p_3) distribution with $p_1 = 0.3$ for parity 1, $p_2 = 0.3$ for parity 2, and $p_3 = 0.4$ for third or greater parity. Month in milk (**MIM**) was modeled as a multinomial distribution with an equal probability for each of the 11 mo of average lactation and 2 mo of dry periods. Requirements of individual cows for NE_L and CP were from NRC (39). DMI of individuals were calculated using the following equation:

$$DMI = (0.078 \times BW^{0.75}) + (0.35 \times FCM) \quad [9]$$

This equation was derived from (39), Table 6-1, without allowances for BW gains. Milk fat (**FAT%**) and milk protein (**MP%**) percentages were modeled using a multivariate normal distribution with the following parameters:

$$FAT\% \approx N(\mu = 3.6, \sigma^2 = 0.09) \quad [10]$$

$$MP\% \approx N(\mu = 3.2, \sigma^2 = 0.04) \quad [11]$$

and a correlation $\rho_{FAT\%, MP\%} = -0.25$.

Nutrient Costs Estimates

Cost estimates for NE_L and CP were calculated using the regression method of St-Pierre and Gla-

moc (54). 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 yr (1982 to 1997). The estimates averaged \$0.07/Mcal of NE_L and \$0.40/kg of CP (Table 2). 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 twofold.

High Herd Potential with Known Parameters

The response in milk yield to [NE] and [CP] is shown in Figure 4a for HERD = H under the assumption of deterministic model parameters. The response surface exhibits the general characteristics of empirical functions: regions of near linearity and regions of distinct curvilinearity. A maximum milk production of 35.95 kg/day is achieved at a level of [NE] = 1.80 Mcal/kg and [CP] = 18.5%.

Using equation [6], we can calculate expected total N excretion for any [NE] - [CP] combination. Likewise, we can use these results to calculate a useful indication of N efficiency, i.e., kilograms of milk produced per kilogram of N excreted (**MN:NEX**) as shown in Figure 5, MN:NEX varied between 60.0 and 86.9, with the maximum efficiency achieved at [NE] = 1.75 and [CP] = 17.0.

The calculation of income over feed costs (**IOFC**) is easily done using the data from Figure 4a, Table 2, and a price of milk of \$30/100 kg (Figure 6). The point of maximum IOFC is also the point of economic optimum under the condition that costs other than

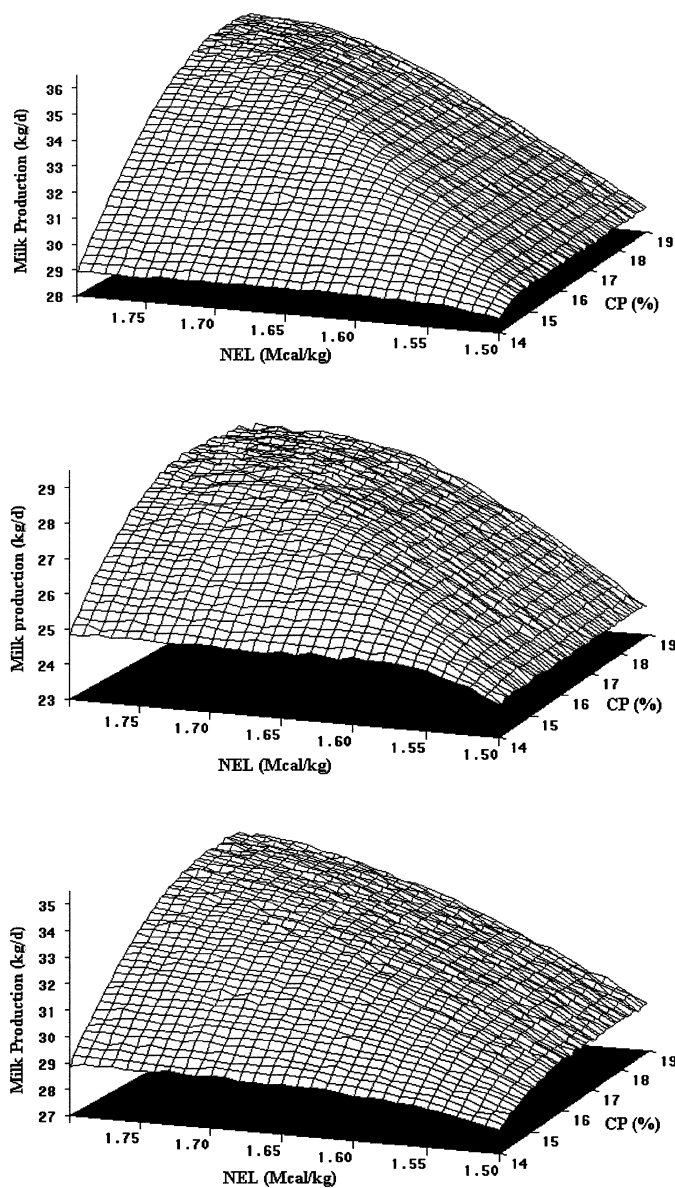


Figure 4. Response in milk yield to NE and CP concentrations in the diet: a) high herd potential (11,350 kg/yr) and known, deterministic model parameters; b) low herd potential (9100 kg/yr) and known, deterministic model parameters; and c) high herd potential (11,350 kg/yr) and uncertain, stochastic model parameters.

feeds are fixed. 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 amount of inputs, the optimal strategy would be to increase the average of both inputs because the curve is much steeper going from O to A than from O to A' (Figure 6). The optimum allocation of inputs will shift along the line

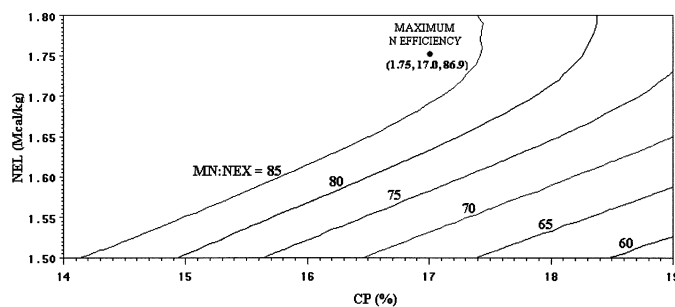


Figure 5. Expected milk produced per kilogram of N excreted (MN:NEX) as a function of NE_L and CP concentrations for high herd potential (11,350 kg/yr) and known, deterministic model parameters.

of least descent (O – B) when uncertainty regarding amount 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 3. Although nutrient cost scenarios are based on extreme observations over a 15-yr 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 MN:NEX all follow a pattern in line with classical mathematical economic theories (6).

Effect of Herd Potential

Figure 4b shows the response surface of milk yield to [NE] and [CP] for HERD = L under the assumption of deterministic parameters. The comparison of this surface to that of a high potential herd (Figure 4a) 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

TABLE 2. Market cost estimates per unit of NE_L and CP.¹

| Label ² | Year | NE_L (\$/Mcal) | CP (\$/kg) |
|--------------------|------|---------------------|---------------|
| Mean | ... | 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 |

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

²Mean is from 1982 to 1997 at two markets from 23 feed ingredients. H = high, A = average, and L = low NE_L and CP costs, respectively.

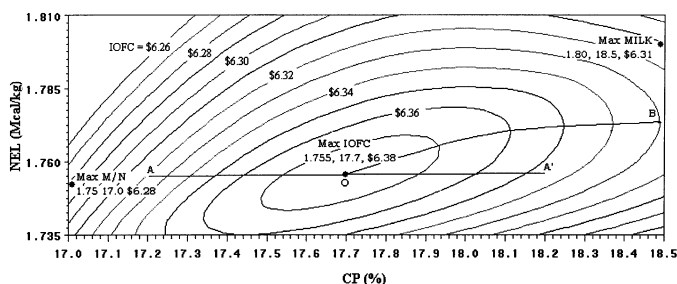


Figure 6. Response in income over feed costs (IOFC) as a function of NE_L and CP concentrations for high herd potential (11,350 kg/yr) and known, deterministic parameters.

[CP] = 18.2. Nitrogen efficiency (MN:NEX) is maximized at [NE] = 1.69 and [CP] = 14.4. IOFC is maximized at [NE] = 1.70 and [CP] = 16.7. Table 4 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 kilogram of milk production. In fact, raising herd productivity from an average of 8955 to 11,336 kg/cow per year improves N efficiency by 8.7%.

Uncertainty of Parameters

To this point, our analysis has assumed perfect certainty of all parameters in the model. There are two fundamental reasons why this assumption cannot stand. First, although the primary reference (39) does not report any measure of variance around nutrient requirements, the fact that these were derived from experimental data implies de facto that requirements are estimates and are therefore subject to errors. Second, it can be argued that the efficiency of nutrient utilization varies across animals. With

this argument, parameter B in equation [1] would be unique for each animal. All the individual B parameters would jointly follow some unknown distribution. Also, randomness with respect to the composition of the diet actually fed cannot be ignored.

Table 5 reports the mean and standard deviation of each parameter used in the model. The NRC (39) estimates energy requirements for maintenance at 80 kcal/kg of $BW^{0.75}$. Van Es (62) reported that maintenance requirements vary by as much as 10% between cows of similar metabolic weight. We used a coefficient of variation of 6.25% on the efficiency of energy utilization for maintenance, which should approximate a 10% range under the conditions of a normal distribution. Conceptually, there should be little variance associated with the energy requirements per unit of FCM in a net energy system. This requirement represents the energy of combustion of 1 kg of FCM, a factor known with near certainty. However, there are two components responsible for variation around the value 0.74 Mcal/kg of FCM reported by the NRC (39). First, the composition of milk is never known with certainty. Milk fat shows substantial daily variation. Therefore, although the coefficient 0.74 might be accurate, its multiplicand (FCM) is uncertain, and, therefore, random. Second, uncertainty undoubtedly occurs for the efficiency of conversion of metabolizable energy (ME) to NE. The NRC (39) assumes a conversion factor of 0.6 based on results obtained at Beltsville (33, 34). Other systems (2, 60, 61, 62), vary the ME to NE conversion factor by up to 8% based primarily on ME concentration. Based on these references, we assumed a conservative coefficient of variation of 4% for the net energy requirement per unit of FCM.

Variances of parameter estimates of protein requirements are difficult to estimate. The NRC (39) used a factorial approach to estimate the require-

TABLE 3. Effect of nutrient costs on optimum allocation of NE_L and CP, expected milk production, N excretion, N efficiency, and income over feed costs (IOFC).

| Nutrient Costs ¹ | Optimum | | Milk Production (kg/d) | N Excretion (g/d) | N Efficiency ² (kg/kg) | IOFC (\$/d) |
|-----------------------------|------------------|--------|------------------------|-------------------|-----------------------------------|-------------|
| | NE_L (Mcal/kg) | CP (%) | | | | |
| Mean | 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 | 1.770 | 17.9 | 35.8 | 432 | 82.9 | 7.70 |

¹Mean is from 1982 to 1997 at two markets from 23 feed ingredients. H = high, A = average, and L = low NE_L and CP costs, respectively.

²Milk production per kilogram of N excreted.

TABLE 4. Effect of herd production potential on optimum allocation of NE_L and CP, expected milk production, N excretion, gross N efficiency, and kilograms of milk produced per kilogram of N excreted (MN:NEX).

| | Herd production potential ¹ | | |
|--|--|-------|----------------|
| | High | Low | Difference (%) |
| Optimal NE _L , Mcal/kg | 1.75 | 1.70 | 2.9 |
| Optimal 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 |
| MN:NEX, kg/kg | 83.9 | 77.2 | 8.7 |

¹High = 11,350 kg/yr; low = 9100 kg/yr.

ments in units of absorbed proteins. The origin of the crude protein requirements in Table 6-3 of NRC (39) is poorly documented. We assumed that both parameters used to estimate CP requirements have a coefficient of variation of 5%.

Roseler et al. (46, 47) reported that the best equations to predict DMI of individual cows result in a residual error of at least 2 kg/d, or approximately 10% of daily DMI. We used a coefficient of variation of 10% for both the parameter related to metabolic BW and the parameter related to FCM. Coefficients of variation for diet [NE] and [CP] were set at 2.5% of expected levels. All parameters were modeled as normal random variates. The resulting stochastic model recognizes that animals vary in BW, MPP, efficiency of utilization of NE and CP for maintenance, efficiency of utilization of NE and CP for lactation, and dry matter intake capacity. Additionally, the model

acknowledges that the nutritional composition of diets is never known with certainty. A rigorous, standardized lab analysis program would reduce this variability (56).

The resulting milk response surface is shown in Figure 4c. 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%. With average nutrient costs, IOFC was maximized at [NE] = 1.79 Mcal/kg and [CP] = 18.0%. Table 6 compares optimal levels of inputs, milk production, N excretion and efficiency, and IOFC for random and fixed parameter models. Uncertainty in model parameters results in higher [NE] and [CP] optima even though expected milk production was 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 MN:NEX. Consequently, uncertainty of parameter estimates reduced IOFC by \$0.42/d, or \$133 per lactation.

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 (30). In animal production, taxes on N and P excretion have been proposed to force

TABLE 5. Mean and standard deviation of parameters used for Monte Carlo simulation with uncertain parameters.

| Parameter | Mean (μ) | SD (σ) |
|---|----------------|----------------------------|
| NE _L Req. for maintenance, Mcal/kg of BW ^{0.75} | 0.08 | 0.005 |
| NE _L Req. per unit of FCM, Mcal/kg of 4% FCM | 0.74 | 0.03 |
| CP for Maintenance, g/kg of BW ^{0.75} | 3.35 | 0.15 |
| CP Req. per unit of FCM, g/kg of 4% FCM | 90 | 4.5 |
| DMI—Metabolic BW coefficient, kg/kg of BW ^{0.75} | 0.078 | 0.0078 |
| DMI—FCM coefficient, kg/kg of 4% FCM | 0.35 | 0.035 |
| NE _L of Diet, Mcal/kg | μ_{NE}^2 | $\sigma_{NE} \times 0.025$ |
| CP of Diet, % | μ_{CP} | $\sigma_{CP} \times 0.025$ |

¹Dry matter intake coefficients are those from the regression DMI = (0.078 × BW^{0.75}) + (0.35 × FCM) derived from Table 6-1 of NRC (39).

² μ_{NE} and μ_{CP} are the mean NE_L and CP concentrations, respectively.

TABLE 6. Effect of random compared with fixed model parameters on optimum NE_L and CP, expected milk production, N excretion, kilograms of milk produced per kilogram of N excreted (MN:NEX), and income over feed costs (IOFC).

| | Random | Fixed | Difference (%) |
|-----------------------------------|--------|-------|----------------|
| Optimum NE _L , Mcal/kg | 1.79 | 1.75 | 2.3 |
| Optimum 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 |
| MN:NEX | 75.0 | 84.0 | -10.7 |
| IOFC, \$/d | 5.96 | 6.38 | -6.6 |

TABLE 7. 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 11,350 kg/yr per cow.

| | MAX IOFC | MAX M/N |
|--|----------|---------|
| Actual milk production, kg/yr per cow | 10,955 | 9812 |
| N excretion, kg/yr per cow | 146 | 111 |
| Income over feed costs, \$/yr per cow | \$1893 | \$1639 |
| Net income, \$/yr per cow ¹ | \$622 | \$368 |
| Number of cows, millions | 6.39 | 7.13 |
| N excretion, metric tonnes/yr | 932,940 | 791,430 |
| Net income, million \$/yr | 3975 | 2624 |
| Reduction in net income per kilogram of reduction of N excretion, \$/kg of N | ... | 9.55 |

¹Assumed fixed costs of \$3.50/d per cow.

livestock enterprises towards maximum N and P efficiency (16). 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. (11) used three concentrations 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/d, which was 109 g less than that from cows fed the 18.3% CP diet, but they produced 32.8 kg of milk/d, which was 1.4 kg/d less than the cows fed the high CP diet. Nevertheless, the low CP diet had the highest MN:NEX, 98.1, compared with 77.7 for the high CP diet. With 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 per day, a reduction of \$0.44/cow per 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.

Similar results are deduced from our model. Table 7 reports the immediate consequence of a national dairy herd (with a MPP = 11,350 kg/yr) moving away from a maximum IOFC feeding strategy to a maximum MN:NEX strategy. Average milk production per cow is reduced by 10.4% or 1143 kg/yr, but N excretion is reduced by 24% or 35 kg/yr 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 United States to maintain the current supply of 70 billion kg 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 national cost of 1.35 billion dollars per year, or \$9.55/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 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 by 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 (39), a RDP/RUP system can reduce N intake by 6 to 7% compared to a CP system at identical milk production. Also, it is likely that improved knowledge of AA 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 11,350 kg/yr, 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.

GROUPING STRATEGIES

So far, we have assumed herds are fed a single diet. Intuitively, N excretion should be lowered by the adoption of multiple group feedings, assuming a proper grouping strategy. This concept raises the issue of optimal grouping criteria and how the number of groups affects milk production and N excretion.

Various grouping strategies have been proposed (32, 53, 57, 69). We chose to compare the following four strategies to group milking cows: 1) grouping by actual FCM, 2) grouping by estimated NE_L concentration requirements, 3) grouping by estimated CP concentration requirements, and 4) grouping by cluster (57). Only the results from the cluster method are presented and discussed here. This method outperformed all others under the various conditions of our Monte Carlo simulation experi-

TABLE 8. Effect of the number of groups on the optimum allocation of NE_L and CP, expected milk production, N excretion, and income over feed costs (IOFC).¹

| Number of groups | Group ² | NE_L (Mcal/kg) | CP (%) | Milk (kg/d) | N Excretion (g/d) | IOFC (\$/d) |
|------------------|--------------------|------------------|--------|-------------|-------------------|-------------|
| 1 | 1 | 1.784 | 17.7 | 35.1 | 432 | 6.12 |
| 2 | 1 | 1.792 | 18.0 | 41.4 | 473 | 7.54 |
| | 2 | 1.732 | 16.9 | 29.3 | 371 | 4.95 |
| | Mean | 1.762 | 17.5 | 35.3 | 423 | 6.24 |
| 3 | 1 | 1.794 | 18.2 | 44.0 | 495 | 8.12 |
| | 2 | 1.758 | 17.3 | 35.0 | 410 | 6.23 |
| | 3 | 1.713 | 16.3 | 27.5 | 343 | 4.63 |
| | Mean | 1.754 | 17.3 | 35.5 | 416 | 6.33 |

¹From the cluster method of grouping cows (32).

²Group are sorted in descending order of cluster.

ments. Table 8 reports the results obtained when cows were grouped into one, two, or three clusters. Additional groups reduced the variance of requirements within groups. Therefore, the optimal allocation of nutrients on a whole herd basis was reduced, whereas the expected milk production was increased. Consequently, N excretion was reduced by 3.7% and MN:NEX was increased by 5.8% from using three clusters as opposed to one. The excretion of N was minimized, whereas MN:NEX and milk production were maximized with six clusters. Additional clusters did not lead to further reductions in N excretion because, with additional clusters, the uncertainty of feed composition became the predominant component of the variance of response. At that point, only an intensification of quality control procedures would yield further declines in N excretion. Nevertheless, optimal grouping reduced N excretion by 5.8% and increased N efficiency (MN:NEX) by 8%.

Lead factors have long been recognized as important in ration optimization of groups of animals under uncertainty (26). Lead factors are multiplicative factors applied to the mean production of a group of animals to calculate an adjusted milk production used for ration formulation. For example, adjusted milk production would be 36 kg/d if the lead factor is 1.2 and mean milk production is 30 kg/d. Stallings and McGilliard (57) proposed a series of lead factors based on an 83rd-percentile method. This percentile was chosen because it is the percentile calculated from the mean plus one standard deviation of a normal distribution. This criterion, however, has little economic basis. That is, no implicit or explicit argument that a lead factor corresponding to a one standard variation in milk production yields higher economic returns than, say, 0.8 standard deviation, exists. Table 9 reports the optimum economic lead factors derived for [NE] and [CP] separately, which were compared to those of Stallings and McGilliard

(57). Interestingly, these results would support the use of different lead factors for [NE] and [CP]. In general, lead factors proposed by Stallings and McGilliard (57) are of the same magnitude as ours derived by economic optimization but are lower for the lowest group. The question of optimum lead factors needs to be looked at in much more detail because of its significant impact on resource allocation and farm profitability.

CONCLUSIONS

Numerous practices can reduce excretion and improve N utilization on dairy farms. The contribution of nutrition and management to reduction in N excretion while maintaining the total national supply of milk can be funneled through one or more of five routes. First, N reduction can be achieved from a better definition and targeting of optimum allocation of inputs (i.e., operate at optimum). Second, continued improvements in animal productivity can

TABLE 9. Economic optimum lead factors for NE_L and CP of diets.

| Number of groups | Group number | Optimum lead factors ¹ | | Previous recommended lead factors ² |
|------------------|--------------|-----------------------------------|------|--|
| | | NE_L | CP | |
| 1 | 1 | 1.33 | 1.26 | 1.32 |
| 2 | 1 | 1.19 | 1.13 | 1.17 |
| | 2 | 1.30 | 1.25 | 1.23 |
| 3 | 1 | 1.15 | 1.11 | 1.14 |
| | 2 | 1.21 | 1.17 | 1.10 |
| | 3 | 1.29 | 1.24 | 1.21 |

¹The mean production of a group is multiplied by the appropriate lead factor to determine an adjusted milk production used for diet formulation. For example, in a one group situation with a mean production of 35 kg/d, the adjusted milk is $35 \times 1.33 = 46.5$ kg/d for NE_L , and $35 \times 1.26 = 44.1$ kg/d for CP formulation.

²Lead factors of Stallings and McGilliard (57).

result in a reduction of 8% in national N excretion. Third, improved knowledge of the biology involved and of the nutrient content of inputs could result in an additional 8% reduction in N excretion. Fourth, feeding larger herds with larger and more numerous pens would result in an estimated reduction of 8% in N excretion from feeding six groups vs. a one-group TMR. Lastly, new technologies (e.g., protected AA) can produce a substantial reduction in N excretion from technical shifts of the response surface linking milk production to animal N inputs.

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