What We Have Learned About Optimizing Efficiency of Dairy Production

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Take Home Messages

- Nutrient requirements are human constructs. Proving their existence has been so far elusive.
- Various functional forms can be fitted to response-type data. Generally, many functions show similar quality of fit to the data, yet have substantially different implications. This is an area where we need some younger brains to be put to good use.
- Whenever the response function of output to nutritional input(s) is smooth (i.e., continuous first derivative) and concave (i.e., declining returns to scale) the level of input that maximizes its efficiency is always less than the level of input that maximizes profits. Consequently, efficiency maximization is always accompanied by a reduction in the economic efficiency.
- Whenever the penalty to achieve maximum efficiency is relatively small, setting maximum efficiency as an operational goal can be desirable. With nutritional inputs, however, it appears that maximum efficiency is frequently accompanied with substantial economic penalties.

Introduction

It used to be so simple: you had cows, you fed them, they gave milk, you got paid and nobody cared about manure. Those days are gone and likely will never be seen again. Nowadays much attention is being dedicated to the impact that agriculture in general and dairy production in particular have on the environment. In the process, many are attempting to optimize the efficiency of dairy production. More specifically, the objective no longer is in optimizing production, but in maximizing production per unit of a given input (e.g., maximizing milk production per unit of protein intake or per unit of N excreted). Deeply embedded into this line of thinking is the often poorly defined concept of nutritional requirements. In this paper we dispute the wisdom of using nutritional requirements for defining efficiencies and challenge the desirability of efficiency optimization.

■ Requirements versus Response-Based Systems

In a requirement-based system the level of production of the animals is an input (Figure 1). The outcome is a set of nutrient input levels believed to have the ability of supporting (sustaining) the stated level of production. There are numerous examples of such systems; one of the best known and often used is that of the National Research Council (NRC, 2001).

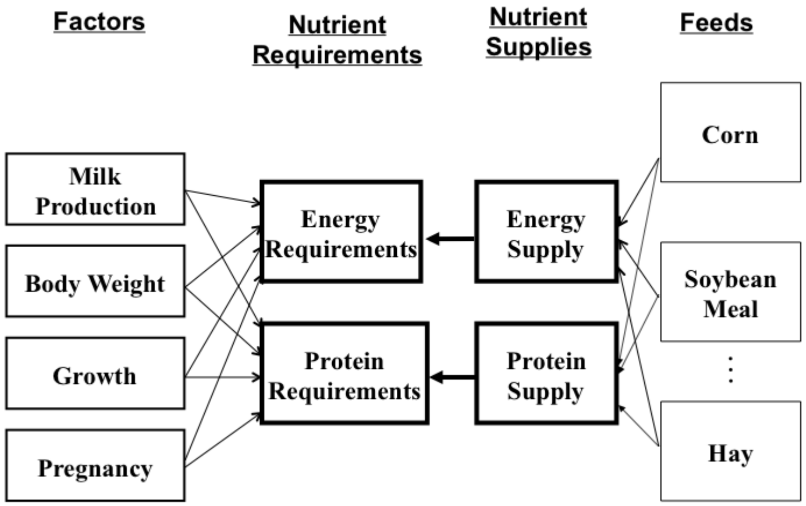

Figure 1. Requirement-based system for diet formulation. Level of productivity is an input to the system.

In a response-based system the level of production of the animals is not an input but an output of the system's evaluation (Figure 2). Although an asymptotic value for production might be used as an input, this is reflective of biological and physical limitations and not of a desired output level. The problem is that many have confused the two approaches and have mischaracterized a requirement-based system as a response-based system.

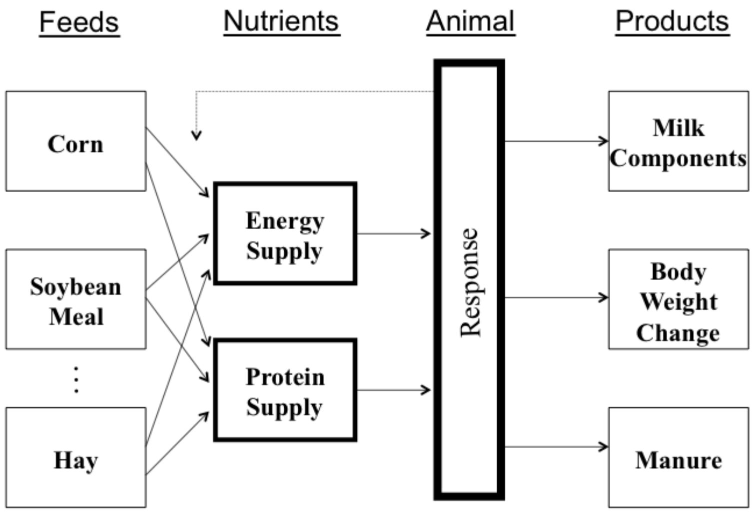

Figure 2. Response-based system for diet formulation. Level of productivity is not an input to the system.

As an example, NRC (2001) indicates that under default environmental conditions, a mature (65 month old) dairy cow weighing 680 kg at a body condition score of 3.0 and producing 35 kg of milk per day at 3.5% fat, 3.0% true protein and 4.8% lactose requires 34.8 Mcal/d of net energy for lactation (NE_L) and 2,407 g/d of metabolizable protein (MP). The requirements for an identical cow at a level of production of 25 kg/d are 27.9 Mcal/d of NE_L and 1,862 g/d of MP. The correct interpretation of these figures is that based on our current nutritional knowledge we have all reasons to believe that the first cow will continue (in the short term) to produce 35 kg/d and be in nutritional balance if the dietary supply matches the stated requirements. Nowhere do these recommendations imply that if we could stuff 34.8 Mcal/d of NE_L and 2,407 g/d of MP into the second cow her production would rise from 25 to 35 kg/d. Unfortunately, this has been the common (mis)interpretation of NE-supported and MP-supported milk in the NRC computer model output. As importantly, nowhere does it say that 34.8 Mcal/d of NE_L and 2,407 g/d of MP is the sole combination of energy and protein input levels that could support 35 kg/d. A cow is a very complex and dynamic system where energy supply and the form in which it is supplied (i.e., the substrates) affect the pathways of protein utilization (and vice-versa). Requirement-based systems are useful systems for determining feed combinations needed to achieve a pre-determined level of production (i.e., common ration balancing). They are, however, grossly incorrect at predicting animal outputs at supply levels other than “required” levels.

■ Do Animals Have Requirements?

If you come to Ohio State University for a graduate degree and if we serve on your graduate committee it is likely that you will be asked the following question either during your general examination or during your defense: do animals have requirements? In 15 years, the answer has been a unanimous "yes", but with the only justification that nutritional requirements are being taught as dogmas in nutrition classes. Even more baffling is that students are at a loss in justifying their answers; they do not know how they would prove it. A proof in this instance requires a careful definition of what "a requirement" means.

Narrow Definition

The requirement for a given nutrient is a unique level of supply for which (1) a lesser supply results in a lower level of production, and (2) a greater supply does not result in additional productivity. Mathematically, this implies a break-point in the relationship between production (e.g., milk) and nutritional supply (e.g., MP). What very few have ever considered is how one could prove the presence of a break-point, i.e., a point on a curve where the first derivative does not exist. This is an entirely different matter than demonstrating that a break-point relationship can be fitted. Many researchers have incorrectly interpreted a good fit as a proof of concept. An example will illustrate this fallacy.

Isoleucine (Ile) Requirements in Growing Swine

Results from an experiment reported by Parr et al. (2003) will be used here. In short, growing pigs were assigned to 6 different diets varying in dietary Ile concentrations. Mean average daily gain (ADG) for each of the 6 treatments is depicted in Figure 3. Results show a general trend towards greater ADG as dietary Ile level increased, but the exact, quantitative relationship between ADG and Ile is clearly not evident.

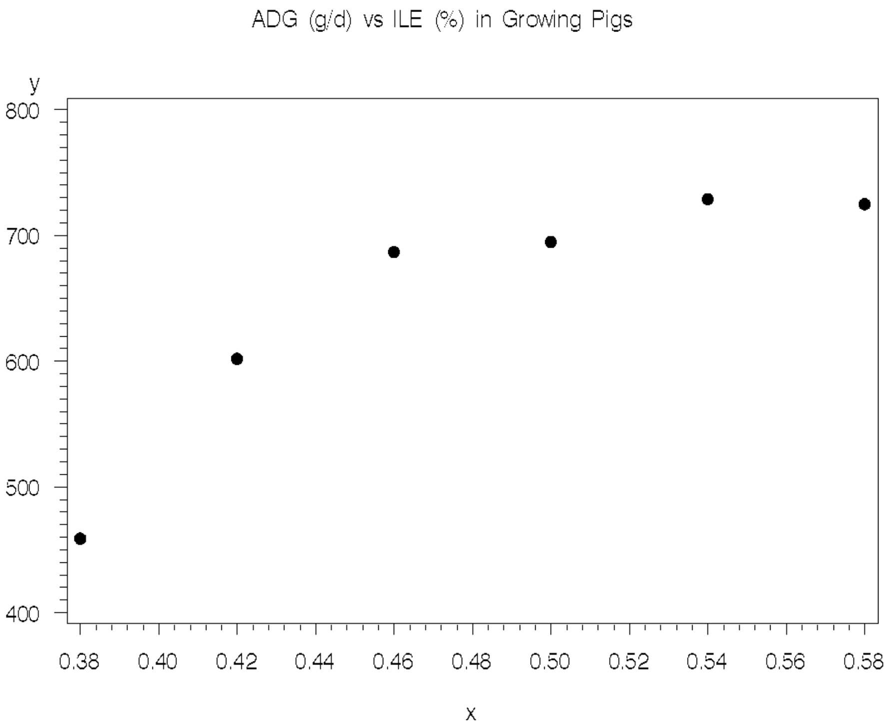

Figure 3. Average daily gain (g/d, y-axis) in growing pigs as a function of dietary Ile concentration (%, x-axis). Data from Parr et al. (2003).

Under a narrow definition of a nutrient requirement, there should be a dietary Ile concentration that (1) maximizes ADG and (2) where a first derivative does not exist. Expressed algebraically, this segmented linear model takes the following form:

$$ADG = ADG_{max} - b\,(X_0 - Ile) \quad \text{if } Ile < X_0 \qquad [1]$$
$$ADG = ADG_{max} \quad \text{otherwise.}$$

In [1], ADG_{max}, b, and X_0 are 3 parameters to be estimated. The parameter estimates that result in the best fit and the resulting model are shown in Figure 4. Just looking at these results, one would conclude that the model fits very well the data, with a very high R^2 (0.977) and low error (SE = 20.4 g/d). The requirement for Ile is then estimated at 0.47% of the diet.

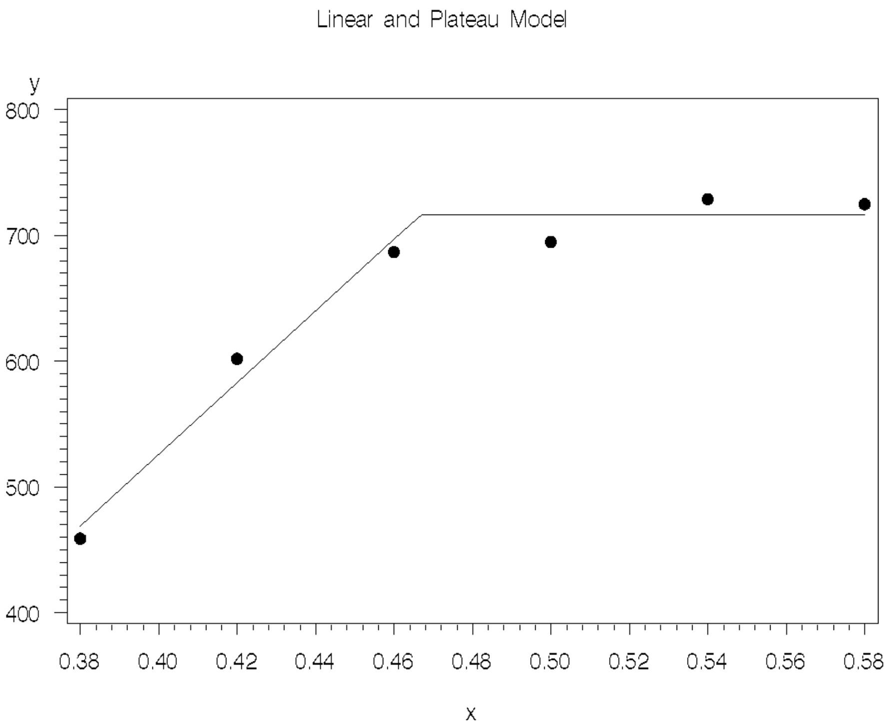

Figure 4. Linear and plateau model of ADG (g/d, y-axis) in growing pigs as a function of dietary Ile concentration (%, x-axis). Data from Parr et al. (2003).

Best fit is:

Y = 716.3 (±11.8) - 2850 (±361.0) × (0.4669 (±0.0083) – Ile) if Ile < 0.4669,
Y = 716.3 (±11.8) otherwise.
R^2 = 0.977, SE = 20.4 g/d.

Necessary Conditions to Prove Strict Requirements

This is where some people have incorrectly made a huge leap of faith and concluded from similar types of data analyses that requirements do exist and are identifiable. The problem is that the identifiability is based on the assumption that strict requirements do exist, and that the proof that strict requirements do exist is based on the identifiability. The circularity of this argument should be evident. More disconcerting is that nobody, not me, not Ronald A. Fisher, nor Einstein have been able to define (mathematically) the conditions that would prove that a break-point does exist. This would require proving that the first derivative does not exist for a certain level of X and nobody seems to know how that can be proven empirically.

Broad Definition

Under a broad definition, the requirement for a given nutrient is simply a level of supply that results in a given (desired) level of production. We no longer impose the condition that lower supply levels result in less production, and, especially, we no longer impose the restrictive concept that greater supply levels do not result in the same level of productivity. When nutrients are looked at on an individual basis, this broad definition is equivalent to fitting a response function of production levels on nutrient intake (or density). Properties of the relationship are dependent on the particular type of function being fitted. The problem is that a great many functions can be fitted (in fact there are an infinity of such functions), each implying different properties on the relationship between nutritional inputs and production levels. Here again an example should be useful.

Quadratic Response with Plateau

This model can be stated as follows:

$$ADG = ADG_{max} - b(X_0 - Ile)^2 \text{ if } Ile < X_0 \qquad [2]$$
$$ADG = ADG_{max} \text{ otherwise.}$$

With this model, the ADG response to dietary level is quadratic up to a level X_0 where it reaches a plateau. A big difference between [2] and [1] is that in [2] the function is smooth. That is, the first derivative exists for all levels of Ile. This curve does not have a breakpoint. The parameter estimates resulting in the best fit and the resulting curve are shown in Figure 5. Although it is tempting to label X_0 as “the requirement”, the economic implication of this function is that the optimal level of Ile is less than X_0 unless the nutrient is free, or the value of an additional unit of ADG is infinite – two conditions that are highly improbable in the world that we live in. So, although X_0 can be labeled as a requirement, animals would never be fed at their “requirement level”, but always at a lower level. Note also that the “requirement” calculated from this model (0.501%) is 7.3% greater than the requirement calculated from the segmented-linear model (0.467%).

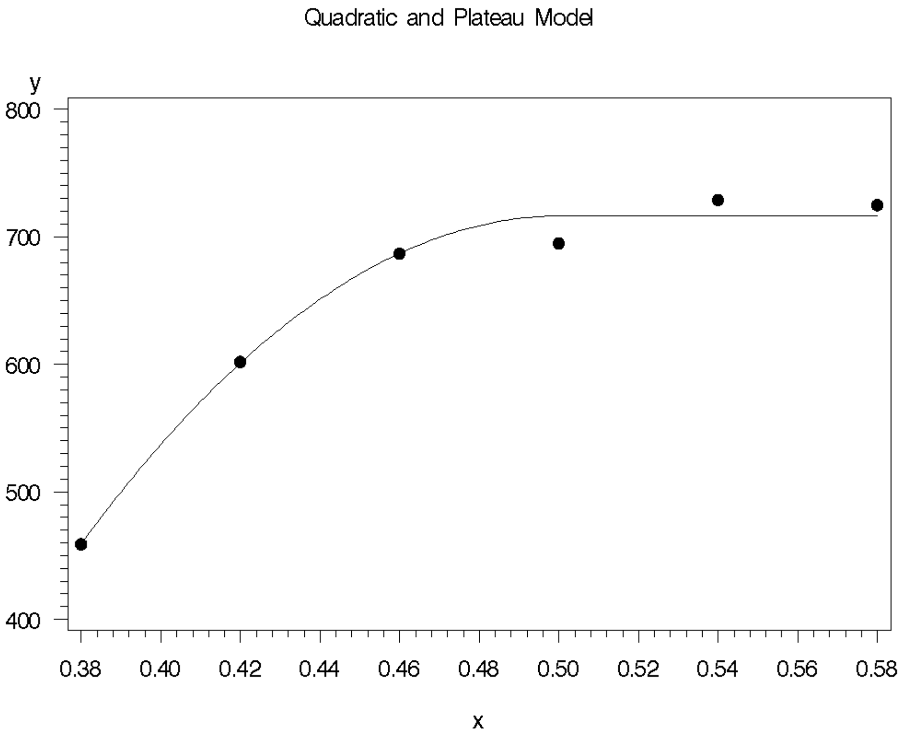

Figure 5. Quadratic and smooth plateau model of ADG (g/d, y-axis) in growing pigs as a function of dietary Ile concentration (%, x-axis). Data from Parr et al. (2003).
Best fit is:
$Y = 715.5\ (\pm 8.77) - 17{,}557\ (\pm 4260.2) \times (0.501\ (\pm 0.014) - Ile)^2$ if $Ile < 0.501$,
$Y = 715.5\ (\pm 8.77)$ otherwise.
$R^2 = 0.987$, SE = 15.2 g/d.

Monomolecular Model

The monomolecular function is similar in shape to the logistic function past its inflection point. Its algebraic form is:

$$ADG = ADG_{max} \times (1 - B \times EXP(-k \times Ile)) \qquad [3]$$

This function never reaches a plateau, but converges towards an asymptote (parameter ADG_{max} in [3]). Parameter estimates resulting in best fit and the resulting curve are shown in Figure 6. Some have argued that the level of input at which the second derivative of this function reaches a minimum can be interpreted as a "requirement". As we shall see, this interpretation is incorrect.

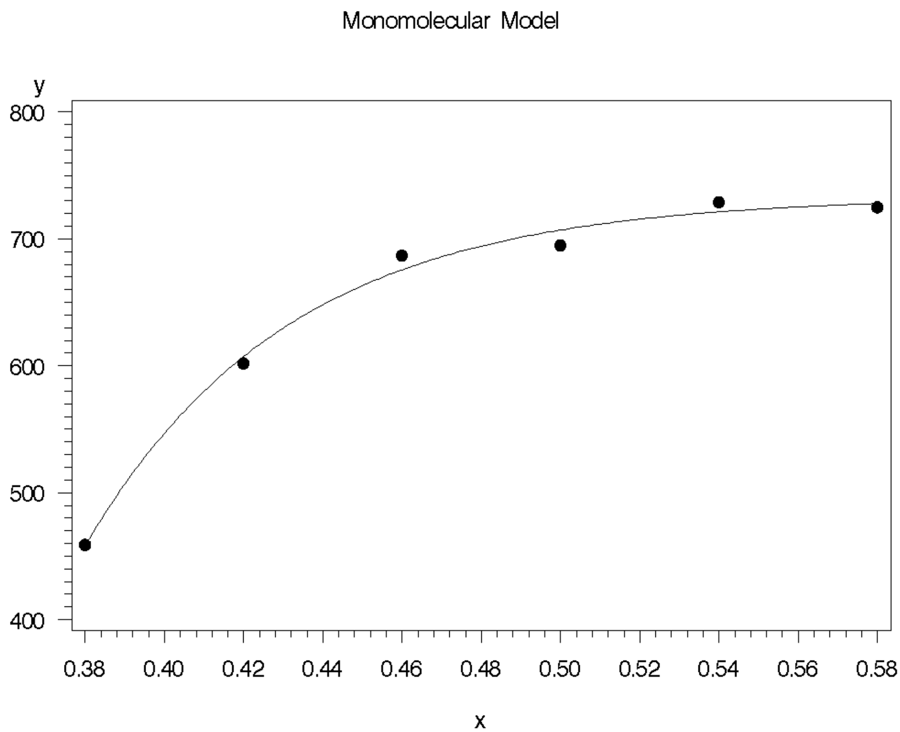

Figure 6. Monomolecular model of ADG (g/d, y-axis) in growing pigs as a function of dietary Ile concentration (%, x-axis). Data from Parr et al. (2003).
Best fit is:
Y = 733.4 (±10.2) × (1 - 627.4 (±619.2) × EXP(-19.53 (±2.62) × Ile)).
R^2 = 0.993, SE = 11.1 g/d.

Quadratic Polynomial Model

This is the simple quadratic function that we all learned in high school:

$$ADG = b_0 + b_1 \times Ile + b_2 \times Ile^2 \quad [4]$$

Best parameter estimates and the resulting curve are shown in Figure 7. Note that in spite of its simplicity (and some would say naiveté), this function also fits the data very well.

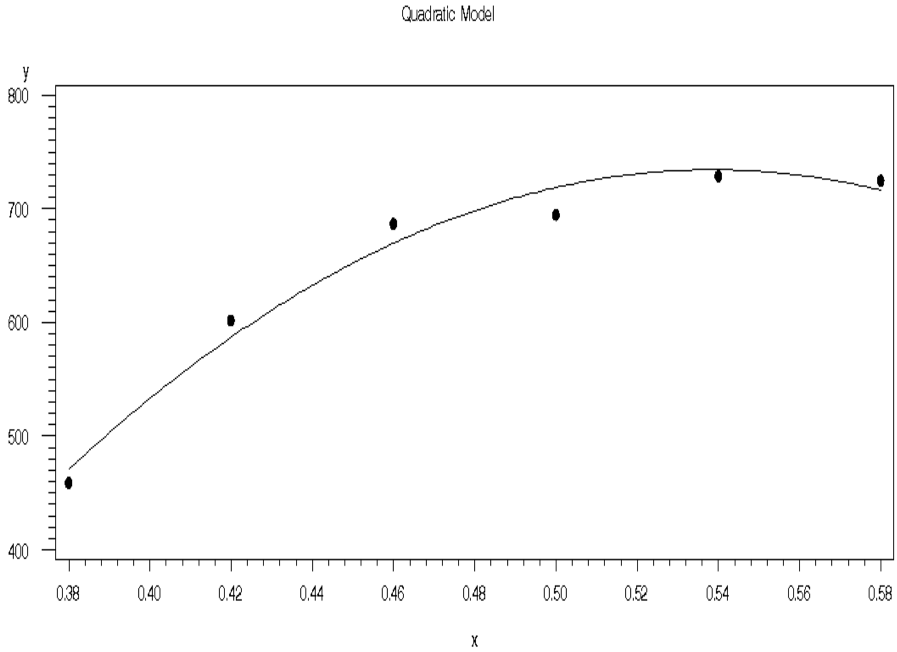

Figure 7. Quadratic polynomial model of ADG (g/d, y-axis) in growing pigs as a function of dietary Ile concentration (%, x-axis). Data from Parr et al. (2003).
Best fit is:
$Y = 2305\ (\pm 490.6) + 11{,}288\ (\pm 2073.8) \times Ile - 10{,}479.9\ (\pm 2156.3) \times Ile^2$.
$R^2 = 0.976$, SE = 21.1 g/d.

So what is the correct relationship between ADG and dietary Ile in this example? All models presented involve 3 parameters. Based on the highest R^2 and the smallest standard error, some would argue that the monomolecular model has the best fit to the data. But to argue that a difference of 0.01 between two R^2 is meaningful is ignoring the errors in the measurements. The fact is that statistics are generally of little help in assessing the comparative fit of various functions expressing the biological response of animals to dietary inputs. There are just too many alternatives and one invariably ends up with multiple functions that fit the data equally well, but that imply substantially different interpretations.

■ Population Response

The framework of a segmented-linear response model can only be theoretically valid when data are from animals of very similar genetics in near identical physiological states and environments. When measurements are made on individuals who are genetically different, or under different physiological status (e.g., stage of lactation in dairy) or environments, then the population response is expected to be smooth even if one assumes that the response function of each individual follows a model of an abrupt threshold and plateau (i.e., the segmented-linear model). The mathematical and statistical theory supporting this was developed decades ago at the University of Reading (Curnow, 1973). Figure 8 illustrates the concept.

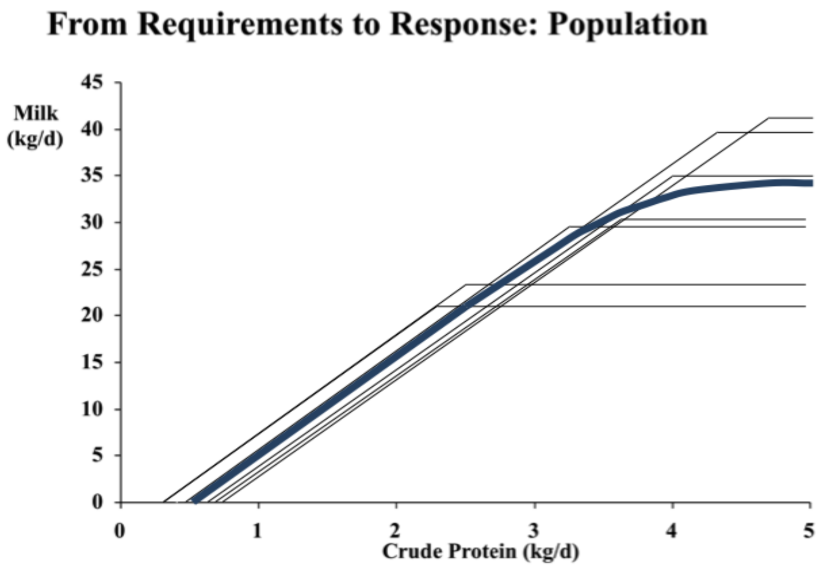

Figure 8. Illustration of a smooth population response curve (thick line) based on an abrupt threshold and plateau model (i.e., segmented-linear model) for individuals (series of thin lines).

In this figure, although the response of each individual follows a segmented-linear response (thin lines in Figure 8), the response averaged across individuals is smooth (i.e., no break-point), sigmoid, and converges toward an asymptote (the thick line). The exact mathematical form of the population response function based on some assumptions regarding the distribution of individuals is messy, somewhat complicated, and has not been expanded to multiple dimensions when the joint response to 2 or more nutrients is being investigated. The important point from this work, however, is that there is a strong theoretical basis that supports smooth and asymptotic responses to nutrients for groups of individuals even if one believes that strict nutrient requirements (as defined in a prior section) do exist for individuals. Response-type experiments in dairy are never conducted on animals of identical genotypes; physiological status always varies across individuals; and micro-environments are never identical. Therefore, although one can always fit segmented-linear models to dairy response experiments as we did in Figure 4, such models make little theoretical sense and this practice should be discontinued.

■ Nutrient Requirements For Asymptotic Models

Doepel et al. (2004) have argued in favour of (1) using a logistic function as the basis for expressing the relationship of milk protein or amino acid (AA) output to intake of various amino acids, and (2) to determine requirements as intake levels where the second derivative of the logistic function reaches a minimum (Figure 9). The logistic function is indeed a wise choice, as it closely resembles the complex theoretical function proposed by Curnow (1973) (i.e., sigmoid and asymptotic). The argument for the identification of requirements is, however, economically incorrect.

The level of input where the second derivative of the logistic function reaches a minimum is in fact the point where the average efficiency is maximized. To declare this level a requirement is not self-evident. More troublesome is that the supply level that one should target to maximize profits should be greater than the so-called requirement level; oftentimes substantially greater. We shall use a concrete example from Lorraine’s paper to illustrate what we mean.

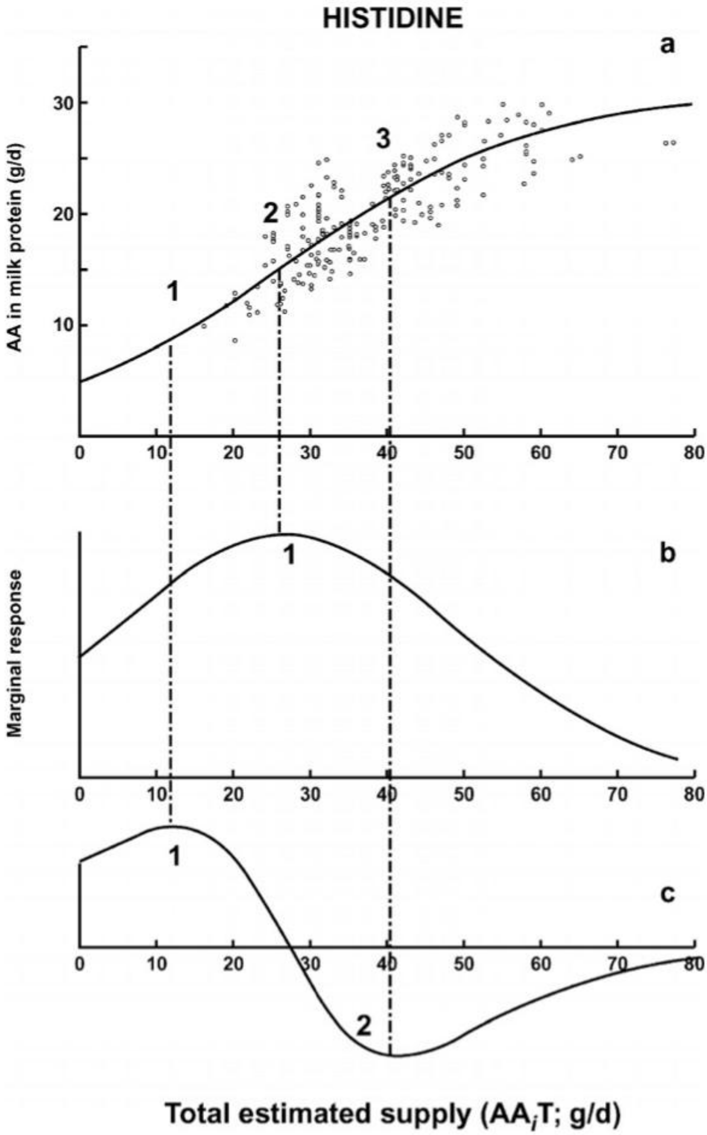

Figure 9. Representation of a logistic response to histidine supply (a), with its first (b) and second (c) derivatives. The curve (b) represents the marginal efficiency. The maximum marginal efficiency (a2, b1) is calculated from the first derivative, and the lower (a1, c1) and upper (a3, c2) critical points are calculated from the second derivative. The upper critical point is assumed to represent the requirement for duodenal AA supply. From Doepel et al. (2004).

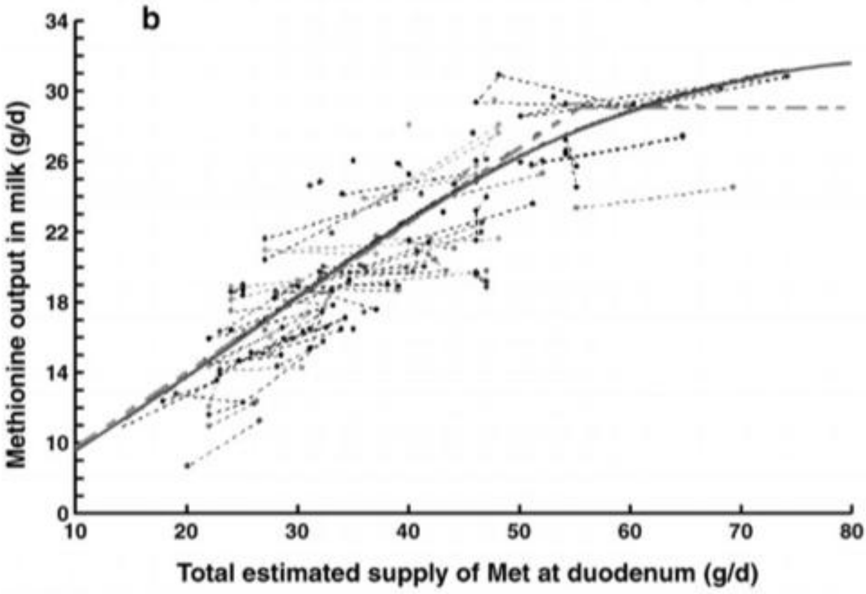

Figure 10. Relationship between Met output in milk and supply of Met at the duodenum from a meta-analysis of literature data. Data points from the same experiment are connected by dotted lines. The logistic (solid line) and segmented linear (dashed line) models are superimposed. From Doepel et al. (2004).

Figure 10 shows the relationship between methionine (Met) output in milk and the total estimated Met supply at the duodenum obtained from a meta-analysis of literature data. The Met requirement using a segmented-linear model was 50 g/d. The Met supply level where the second derivative of the fitted logistic function reached a minimum was also 50 g/d, hence reinforcing the perception that the Met requirement under the conditions summarized by this meta-analysis is 50 g/d of Met supply at the duodenum. Elementary economics, however, would indicate that the profit-maximizing supply is where the marginal value is equal to the marginal cost, i.e., the cost of the last unit added equals the value of the additional product. Expressed mathematically, the optimum Met is that where the derivative of the logistic function (i.e., the slope) is equal to the ratio of the price of dietary Met to that of milk Met.

The cost for Met supplied at the duodenum is approximately $0.02/g using commercially available rumen-protected Met. Milk protein (which contains approximately 3% Met) has averaged a market price of $2.72/lb ($6.00/kg) between 2005 and 2011 on the U.S. market. This translates to a price of about \$0.20/g of milk Met. Hence, the optimum Met supply would be found as the point on the logistic curve of Figure 10 where the slope equals 0.02 ÷ 0.20 = 0.10. This occurs approximately at a Met supply of 70 g/d, a level which is 40% greater than that designated as the “requirement”.

A Met supply of 50 g/d at the duodenum yields 26 g/d of milk Met, which translates to 867 g/d of milk protein. The Met efficiency (26 ÷ 50 = 0.52) is maximized at this level of Met supply. Pricing milk protein at \$6.00/kg, the value of the milk protein is \$5.20/d. Using a price of \$0.02/g for Met supply at the duodenum, the 50 g/d of Met costs \$1.00/d, resulting in a gross profit of \$4.20/cow per d.

A met supply of 70 g/d at the duodenum yields 31 g/d of milk Met, which translates to 1,033 g/d of milk protein. The Met efficiency at this level of supply (31 ÷ 70 = 0.44) is substantially less than at a supply of 50 g/d. The value of the milk protein, however, is increased to \$6.20/d, while the cost of the Met supplied is increased to \$1.40/d, resulting in a gross profit of \$4.80/cow per d. Thus, driving the system towards maximum Met efficiency results in a net loss of \$4.80 - \$4.20 = \$0.60/cow per day, or over \$200 per lactation compared to supplying Met for maximum economic returns.

▪ Maximum Efficiency Always Comes at a Cost

The previous example is understandably a little bit naïve, but served as an illustration of the penalty associated with using maximum efficiency of inputs as targets. A few years ago, we conducted a large study to estimate the economic penalty that would be associated with a proposed farm policy that would aim at enforcing maximum N efficiency in livestock feeding (St-Pierre and Thraen, 1999). Using an expansion of Curnow theory, we developed an empirical response model based on NE_L and crude protein (CP) inputs. The response function for cows of average genetic potential is shown in Figure 11. Note that it is smooth (continuous first partial derivatives) and asymptotic.

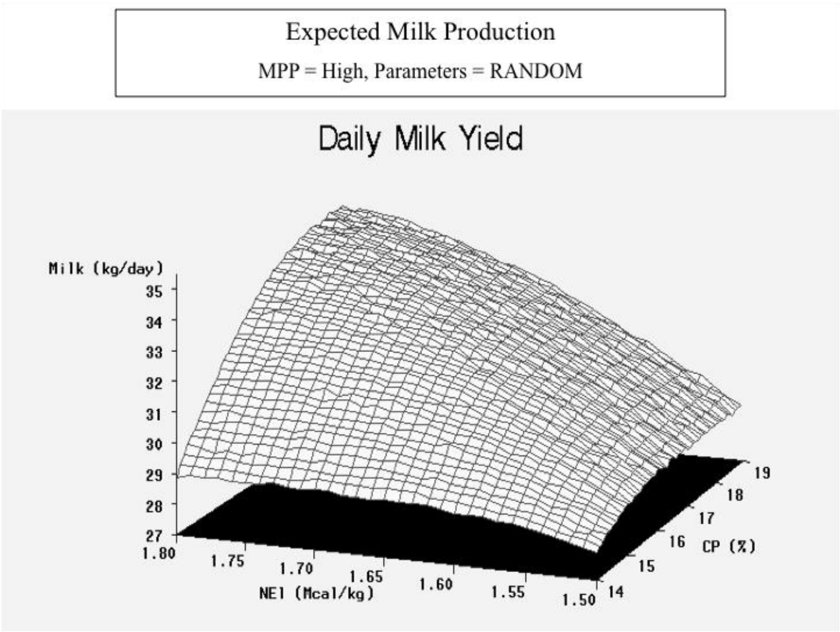

Figure 11. Response function of milk output to net energy for lactation (NEl) and crude protein (CP) concentration of the diet (St-Pierre and Thraen, 1999).

Using average feed and milk prices during the 1995-1999 period, we determined the input levels that maximized nitrogen (N) efficiency, maximized milk production, and maximized income over feed costs (IOFC). Results are shown in Figure 12.

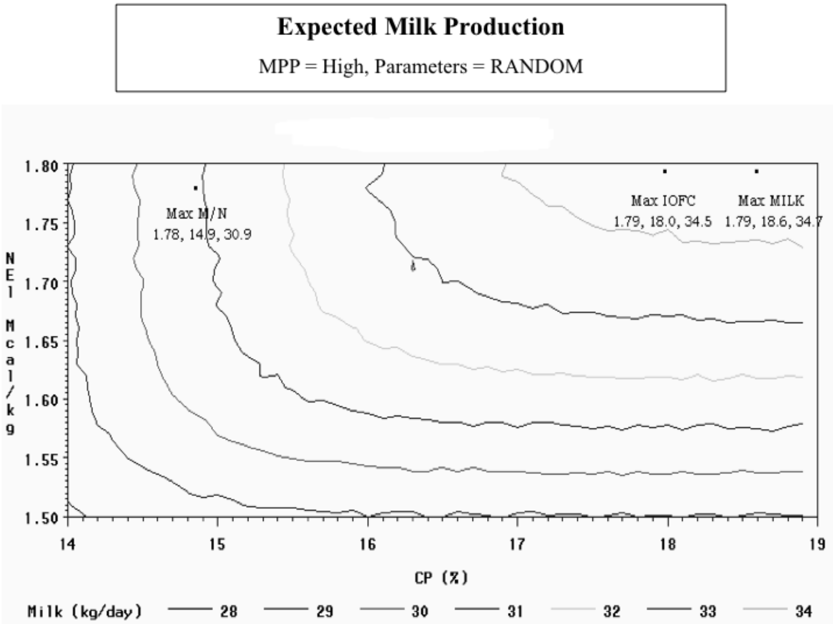

Figure 12. Contour plot showing the response function of milk production to net energy for lactation (NEl) and crude protein (CP) concentration of the diet, and the input combination leading to maximum nitrogen (N) efficiency (Max M/N), maximum milk production (Max MILK), and maximum income over feed costs (Max IOFC). From St-Pierre and Thraen (1999).

Table 1 reports results of various calculations comparing a U.S. national dairy system targeting maximum economic efficiency vs. maximum input efficiency (N in this case). The total societal cost to a policy enforcing maximum N utilization on dairy farms was estimated at $1.35 billion per year, which equated to $9.55/kg of reduction in N excretion.

Table 1. 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 (from St-Pierre and Thraen, 1999).

	MAX IOFC	MAX M/N
Actual milk production, kg/cow per year	10,955	9,812
N excretion, kg/cow per year	146	111
Income over feed costs, $/cow per year	$1,893	$1,639
Net income, $/cow per year	$622	$368
Number of cows, millions	6.39	7.13
N excretion, tonnes/year	932,940	791,430
Net income, million $/year	3975	2624
Reduction in net income per kg of reduction of N excretion, $/kg of N	.	9.55

■ Conclusions

Although it would appear desirable to thrive towards efficiency maximization in dairy, this will nearly always be accompanied with a reduction in profitability. Depending on the size of the profit reduction, maximization of input efficiency can range from being achieved at an acceptable cost to being highly objectionable.

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