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Major Advances in Nutrition: Relevance to the Sustainability of the Dairy Industry

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ABSTRACT

The typical cow has a maintenance requirement of about 10 Mcal of net energy for lactation (NE_L) per day. Each kilogram of milk takes an additional 0.7 Mcal of NE_L. Thus, the cow producing 45 kg of milk per day needs 4 times as much total energy as she needs for her maintenance requirement alone. The elite cow producing 90 kg/d needs 7 times as much total energy as she needs for maintenance alone. Consequently, the efficiency of using feed energy is much greater for the elite cow than it was for the cow of 100 yr ago consuming a diet of mostly forage. With increased productivity has come the need for fewer cows to produce milk on a per capita basis and increases in net income per cow. However, compared with energetic efficiency, the efficiency of using feed protein to make milk protein has not increased as dramatically, partly because cows are often fed protein in excess. This nitrogen waste is an environmental concern; N losses in manure contribute to water pollution and ammonia emissions from dairy farms. However, the complexities of protein nutrition and limitations in measuring feed N fractions make accurate specifications for feed protein fractions difficult. The economic risk of underfeeding protein is greater than the risk of overfeeding protein, so protein efficiency has not been maximized in the past, nor is it likely to be maximized in the near future. Most cows also are fed excess P, a notable contaminant of surface waters, but several recent studies have shown that feeding P above NRC recommendations has no utility for milk production or fertility. The goal of this article is to examine the impact of nutrition on productivity, efficiency, environmental sustainability, and profitability of the dairy industry.
Key words: nutrition, efficiency, productivity, profitability

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INTRODUCTION

Humans have long used the capability of a cow's digestive system to process fibrous plant material into the high quality nutrients of milk. At one time, the cow obtained most of her nutrients from fresh or stored forage and produced enough milk for perhaps one family. But with genetic selection and progressive management, production has steadily risen in the last 100 yr (Figure 1). The modern high-producing dairy cow will produce about 40 to 50 kg of milk per day in early lactation; production as high as 60 kg/d is not uncommon. In fact, the current world-record Holstein produced >30,000 kg of milk in a year—that's almost 90 kg/d on average—enough to feed more than 100 people. Certainly genetics is a major reason for the rise in milk production per cow over the past 50 yr, but proper nutrition and management are critical to enable the modern high-producing cow to meet her production potential.

The major goal for most dairy farms is to maximize profits. Because feed accounts for up to half of all costs on a dairy farm, many farmers are tempted to lower feed costs, especially when feed prices are high. However, feed for lactating cows is obviously not a frivolous expense but an investment. Good dairy farmers continually seek feed sources that cost less but yield the same returns. Often they are successful, but sometimes they are not, and without proper nutrition cows are unable to achieve their genetic potential for milk production. Milk yield is one of the most important factors in determining profitability of dairy cows, and high milk production is almost always more important for high profitability than is low feed cost. Level of milk production of a cow is determined by 1) the ability of the mammary gland to produce milk, 2) the ability of the cow to provide the mammary gland with nutrients, and 3) the ability of the farmer to manage and care for the cow.

Another important objective in farming is to practice good stewardship. There are 4 major areas to consider in agricultural stewardship. A good steward in dairy farming is one who 1) is environmentally friendly, 2) makes efficient use of the earth's natural resources, 3) produces quality milk and meat, and 4) practices good

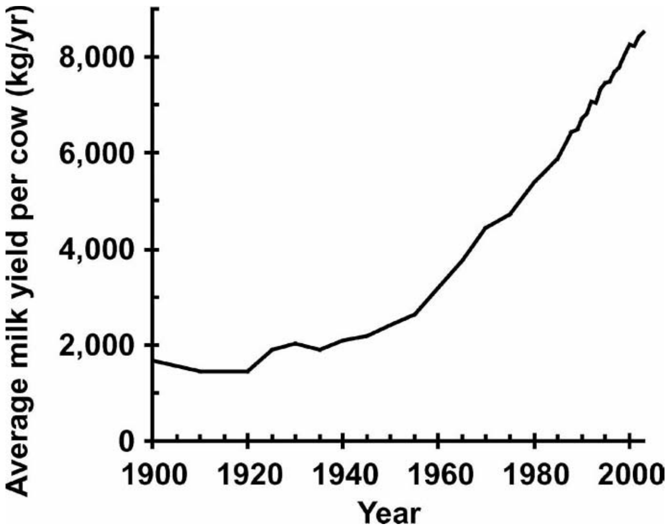

Figure 1. Milk production per cow in the United States over the past 100 yr.

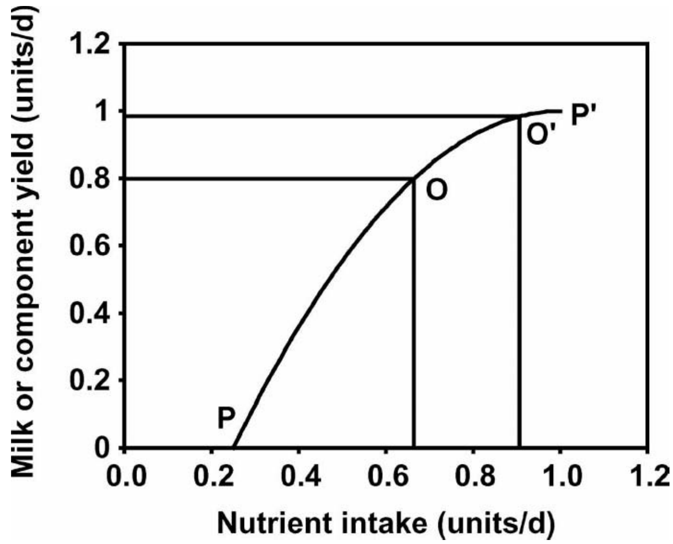

Figure 2. Nutrition and the law of diminishing returns. Animals respond in a curvilinear fashion to increased intake of a nutrient. The maximum physical efficiency is attained at point ○, whereas prevailing market prices determine the nutrient intake to maximize profits. With normal markets where the unit price of milk is greater than the unit cost of the nutrient, profits are maximized at point ○′ corresponding to a significantly greater dietary nutrient intake than at point ○. Thus the efficiency of utilization of the nutrient (units milk per unit nutrient intake; line P–P′) at the point of highest profits is less than at the point of maximum efficiency.

animal husbandry. Nutrition influences each of these stewardship goals. Excess feeding of N and P contributes to air and water pollution as ammonia emissions, N contamination of groundwater, and P-induced eutrophication, and oxygen consumption of surface waters. Proper nutrition is also important in using the earth's resources efficiently; higher milk production is associated with a greater portion of feed nutrients being converted to milk. Nutrition has less of a role in milk quality but nutrition can alter the fatty acid profile of milk fat. Finally, nutrition will impact animal health and well being. Malnutrition may exacerbate stressful situations such as weaning and calving. Animals that are fed properly have fewer metabolic diseases and better immune function.

NUTRITION AND PRODUCTIVITY

Numerous studies over the past 100 yr have demonstrated that nutrition has a major impact on productivity. Compared with an all-forage diet, a diet of forage with grains and protein supplements increases diet digestibility, daily DM intake, energy available to the cow, and milk production per cow. Fat supplementation may also increase milk yield. Moreover, ensuring adequate amounts of rumen-degradable and rumen-undegradable proteins also maximizes milk yield. However, with increasing the nutritional quality of a diet, each successive increase in nutrient intake generally results in less milk response, so that production responses follow the law of diminishing returns (line P–P′ in Figure 2). Thus, diets that maximize milk yield usually are not the most profitable, and there is usually an optimal nutrient intake or density for maximizing the efficiency and profitability of milk production. Unfortunately, the dietary intake or density of a nutrient at which efficiency is maximized is different than that which maximizes profits. In other words, it generally pays to increase the dietary intake or concentration of the nutrient above that at which efficiency is maximized as long as the return from the last unit added exceeds its costs. This paradox was studied extensively for dietary CP density by St-Pierre and Thraen in 1999. For a herd with an average potential of 35 kg/d, the maximum physical efficiency is achieved at a CP of 14.9%, whereas maximum economic efficiency is achieved at a CP of 18.0%. The additional CP generates more net income, approximately $1.4 billion more per year for the national dairy herd, but with a side effect of 150,000 additional metric tons of nitrogen being excreted. If, and when, society assigns an economic cost to N excretion from livestock through new government regulations, the maximum economic efficiency likely will occur closer to the point of maximum physical efficiency.

PRODUCTION AND EFFICIENCY

In the conversion of feed energy to milk energy, several steps must occur that are associated with 4 classic

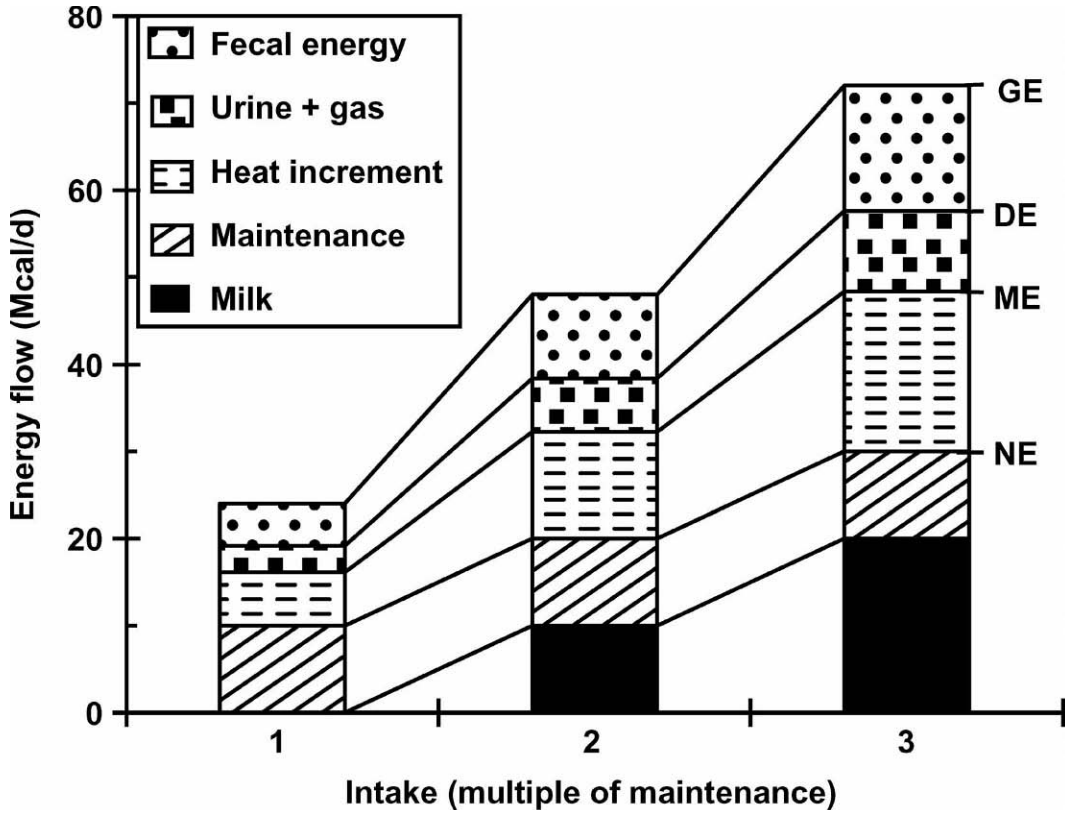

Figure 3. Level of production and energy flow. As a cow eats more and produces more milk, her total energy use, especially milk energy output, increases and the energy needed for maintenance is diluted out. This "dilution of maintenance" is the primary reason that efficiency of nutrient use has increased in the dairy industry in the past 100 yr.

ways of considering feed energy values. The gross energy (**GE**) value of a feed is the energy released during complete combustion. Not all combustible energy is useful because some of it is not digested but is lost as fecal energy. Some of the digested energy (**DE**) is lost as gaseous energy, primarily methane produced during fermentation, and as urinary energy, primarily urea produced during the catabolism of organic molecules containing nitrogen. The remaining energy is metabolized energy (**ME**). About one-third of ME is lost as the heat increment associated with the work of fermenting, digesting, and metabolizing nutrients. The remaining energy is known as net energy, which represents the chemical energy of secreted milk and accreted body tissues and conceptus and the chemical energy that is converted to heat in support of maintenance functions. In dairy cows, the efficiency of converting ME to net energy is about the same whether the ME is used for maintenance or for milk production.

A 625-kg cow has a maintenance requirement of ~10 Mcal of NE_L/d, which is associated with ~25 Mcal of GE intake/d (Figure 3). This maintenance requirement is assumed to remain constant at 10 Mcal/d; and all extra heat generated with increased intake and production is defined as the heat increment. If the cow consumes twice as much feed, or "2× maintenance" intake, she consumes 20 Mcal of NE_L/d, and 10 Mcal or 50% of NE_L will be captured in milk. If the cow consumes 3 times the maintenance intake, she will capture 67% of her NE_L intake in milk or ~27% of her GE intake. Thus, as a cow eats more feed to support greater milk production, a smaller portion of feed energy intake is partitioned toward meeting maintenance needs and a greater portion is transferred to milk. This phenomenon is the classic dilution of maintenance effect occurring with increased energy intake and milk production.

Although increased feed intake generally increases productive efficiency, it actually decreases digestive efficiency, with digestibility of a diet depending on complex relationships among rate of passage, rate of digestion, and associative effects among feeds. More than 30 yr ago, Tyrrell and Moe demonstrated at the USDA Beltsville Energy Laboratory that the conversion of GE to DE is not constant, and consequently, the NE obtained per unit of feed decreases as cows eat more. Weiss at The Ohio State University demonstrated that this is a major limitation of using feed energy values from tables and is part of the reason that tabular feed NE_L values generally overestimate the actual energy values of most feeds when fed to high-producing cows. To correct this problem, the 2001 version of the National Research Council's *Nutrient Requirements of Dairy Cattle* discounts the NE value of diets as cows eat more. Exactly what this discount should be is not clear, but the implications for the dairy industry of different assumptions for digestive efficiency on gross efficiency and profitability were examined by VandeHaar in 1998. For the remainder of this paper, we will assume that the depression in digestibility with increasing intake decreases with each successive multiple of maintenance intake, and that the digestibility discount equals 4% × (multiple of maintenance – 1)$^{0.8}$. Based on this assumption, increasing feed intake and milk yield from 1× to 4× maintenance considerably decreases fecal and urinary energy losses per unit of milk, but further increases in intake and yield per cow above 4× maintenance likely will not further decrease manure output per unit of milk and may even increase it. Increased feed intake and milk yield also increase heat production per cow, which should be considered in the management of high-producing cows during hot weather.

One of the most important dietary factors affecting feed efficiency is the source of dietary energy. When considering efficiency of different diet components, the net efficiency of converting feed to milk is conceptually more useful than the gross efficiency of converting feed to milk. Gross efficiency is captured energy (the energy of milk and accreted body tissues) divided by feed energy intake, whereas net efficiency is captured energy divided by the amount of feed energy consumed above that needed for the animal's maintenance requirement. On a GE, DE, or ME basis, the net efficiency of converting fiber to milk is less than that for starch and protein, which is less than that for dietary fat. The increased efficiency of fat is mostly due to a smaller heat increment and thus an increase in partial efficiency of converting ME to NE_L. Generally, net efficiency has received little attention in diet formulation because the impact of diet on appetite, milk production, nutrient partitioning, feed costs, and health is more important. For example, although inclusion of feeds high in fiber decreases net efficiency, fiber is generally inexpensive and some fiber is needed for proper rumen function. Thus, an overemphasis on net efficiency could decrease gross efficiency in the long term. One dietary factor that should receive more attention on farms is digestibility of fiber. Providing fiber with greater digestibility increases the DE concentration of the diet, and it may enable the cow to consume more total feed per day, both of which would result in greater DE intake and usually in greater milk production as well. Finally, high-fiber by-product feeds with small particle size, such as soy hulls or gluten feed, may limit gross efficiency. If these by-product feeds are fed in place of forage, the diet may contain inadequate long fiber particles, which may reduce fiber digestibility and gross efficiency. Conversely, if they are fed in place of grains, their lower energy value may limit milk production, again leading to reduced gross efficiency. Nonetheless, these by-product feeds often substantially decrease feed costs and increase profits.

Feed Intake and Nutrient Partitioning

Not only must the cow receive enough energy, the energy must come in the proper form. Energy is provided from cell wall carbohydrate (fiber), nonfiber carbohydrates (starch and sugar), protein, and fat. The major challenge in feeding high-producing dairy cows is to find the right balance of these nutrients to promote rumen health and maximize feed energy intake and nutrient flow to the mammary gland for milk synthesis.

Feed intake is a major determinant of energy intake and consequently of milk production. Available data support the idea that there is an optimal level of fiber at which feed energy intake will be maximized. This optimal level likely is between 25 and 30% NDF. If the diet contains a greater percentage of NDF, feed and energy intake will be reduced, as demonstrated in a study by Oba and Allen in 2000, in which cows were fed diets with 29% compared with 38% NDF (Table 1). Higher NDF diets tend to fill up the rumen and limit intake because fiber tends to digest and pass more slowly than starch. If the diet has less NDF and more starch, the rumen may become too acidic, resulting in potential health problems and decreased feed intake. Finding the right balance of starch and fiber to maximize energy intake but maintain optimal rumen health is one of the most important challenges in feeding high-producing cows. In the past 25 yr, there has been a dramatic shift toward the use of TMR, increased analysis of feeds for fiber content, and increased use of computerized systems to record ingredient weights. These tools enhance our ability to achieve both goals—adequate energy for high milk production with adequate fiber for rumen health. Other factors that can enhance feed intake and thus milk yield per cow are adequate eating space, adequate availability of feed and water over the duration of a day, long-day photoperiods, and cooling systems during hot weather.

The metabolic priority of milk production is very high for a cow in early lactation, but changes in diet composition or intake can influence the partitioning of nutrients to the mammary gland relative to other body tissues.

Table 1. Effects of altering NDF concentration and digestibility on feed intake and milk production of lactating cows[1,2]

	29% NDF		38% NDF		$P > F$	
	bm3	Control	*bm3*	Control	NDF[3]	Silage[4]
DM intake, kg/d	24.7	23.9	22.9	21.5	0.01	0.02
Est. NE_L intake, Mcal/d	37.0	36.5	33.9	32.6	0.01	0.36
Milk yield, kg/d	36.9	33.5	33.7	30.4	0.01	0.01
Milk fat, %	3.28	3.67	3.86	3.90	0.01	0.02
3.5% FCM, kg/d	35.6	34.3	35.8	32.6	0.5	0.06
Milk NE, % of NE_L intake	66.9	64.0	72.4	68.7	0.01	0.05
BW gain, kg/d	1.10	0.79	0.00	–0.02	0.01	0.5

[1]From Oba and Allen, 2000 (J. Dairy Sci. 83:1333–1341).

[2]Mid-lactation cows were fed diets with high NDF (53% corn silage, 12% alfalfa, and 3% ground corn grain) or low NDF (34% corn silage, 8% alfalfa, and 18% ground corn grain). The corn silage was the brown midrib 3 mutant (*bm3*) or an isogenic control with 56% (*bm3*) or 47% (control) in vitro NDF digestibility after 30 h of incubation.

[3]NDF: $P > F$ for the effect of NDF concentration treatment.

[4]Silage: $P > F$ for the effect of corn silage variety.

Thus, sometimes when a cow is switched to a diet high in fat or in rapidly fermentable starch, energy-corrected milk yield may not change or may decrease even though net energy intake increases. For example, in the study shown in Table 1, the high-grain, low-fiber diets increased energy intake ~10% but most of the increased energy was partitioned toward body tissue gain so that fat-corrected milk (**FCM**) yield was not increased; in contrast, feeding corn silage with greater fiber digestibility increased energy intake only slightly but caused more of the available energy to be partitioned toward milk. Such changes in nutrient partitioning are regulated at least partly by the endocrine system. For example, insulin, which is needed for glucose uptake by fat cells but not mammary cells of cattle, is increased with higher grain feeding. Dietary protein also impacts partitioning; feeding a diet with inadequate protein may limit milk synthesis and thus result in more energy partitioned toward adipose tissue. Finally, bovine somatotropin (**bST**) has been shown conclusively to increase the metabolic priority of milk synthesis, and thus its use is common in the US dairy industry.

The Lactation Cycle

Daily milk yield peaks at 40 to 60 d postpartum and then gradually declines (Figure 4). Feed intake also increases as lactation progresses but usually peaks later than milk yield. Most cows are in negative energy balance during the first 60 d postpartum. In fact, during the first month of lactation, one-third of the cow's energy needs may be derived from body stores. Some loss of body stores in early lactation and replenishment in later lactation is desirable for maximization of lactation efficiency and profitability, but excessive loss of body condition will impair fertility and prolong the calving interval. The idea that cows should calve once every 12 mo is based partly on the desirable season of calving for pasture-based dairy farming in temperate climates. In addition, with a 12-mo calving interval, the cow produces one calf per year and spends a greater proportion of her time at peak lactation than if she had a longer calving interval. Some have questioned this practice and proposed that a longer calving interval (up to 18 mo) might be more profitable for modern dairy farms using confined feeding systems and lactation enhancers such as bST, which enhances the persistency of lactation. Because most health problems occur in the first 2 wk after calving, the economic disadvantages of less milk per day during lactation and fewer calves per cow may be outweighed by fewer health problems, less difficulty getting cows bred in a timely manner, and fewer days dry relative to days being milked. Some also have

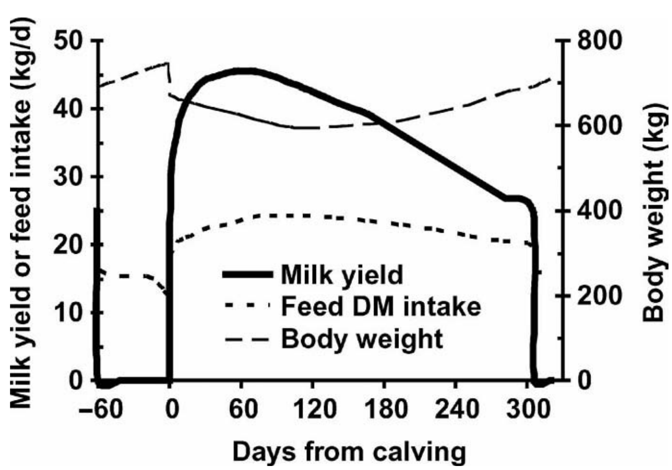

Figure 4. Milk yield, intake, and body weight curves for a typical mature Holstein cow throughout a lactation cycle.

proposed that a dry period less than 60 d might be more cost-effective than the standard 60 d.

Lifetime Gross Efficiency

Lifetime gross efficiency is defined as the capture of feed energy in milk, conceptus, and body tissues divided by total energy intake during the life of a cow, starting at birth. In this discussion, we will consider lifetime gross efficiency on a GE basis. For a cow producing 9,000 kg of milk/yr at maturity, lifetime efficiency is predicted to increase from 17% after the first lactation to 20.5% after 3 lactations and to 21.4% after 5 lactations; thus, lifetime efficiency is nearly maximized after 3 lactations. For cows producing less milk at maturity, lifetime efficiency is less, and more lactations are needed to approach maximum efficiency. For cows producing more milk at maturity, fewer lactations are needed to approach maximum lifetime efficiency.

Lifetime efficiency of GE use increases considerably as milk production increases from 6,000 to 12,000 kg/yr. However, above 15,000 kg/yr, the marginal increase in efficiency begins to approach zero so that lifetime efficiency is predicted to be maximized at about 21,000 kg/yr, when it is ~25% (Figure 5). Above 15,000 kg/yr, efficiency changes very little, but losses are partitioned differently; losses as fecal energy become slightly greater as a percentage of total GE flow, whereas percentage losses as heat become slightly smaller. These values for lifetime efficiency were predicted assuming the average cow in a herd weighs 625 kg at maturity and has a life span of 4.9 yr: 730 d as a heifer, three 305-d lactations, and two 60-d dry periods; these values also assume feeding losses of 5% and the digestibility discount mentioned earlier.

Because the typical US dairy cow has a life span of 5 yr, conversion of the GE of feed to milk, conceptus, and body tissue on US dairy farms would not be expected to improve much beyond 25% (Figure 5) unless major improvements occur in the ability of cows to digest feed. Furthermore, the positive correlation between productivity and efficiency that has existed in the past may gradually diminish in the future. At the current rate of increase in milk production, however, several decades will pass before the US dairy industry has achieved maximum efficiency on a feed GE basis. Many individual farms, however, are beginning to approach the point at which the marginal returns in energetic efficiency are small. Likewise, profits (net income) increase at a decreasing rate with lifetime production. Over the production range shown in Figure 5, the dilution of nonfeed costs compensates for the increase in marginal feed costs. At some point above 21,000 kg/yr, however, the marginal profitability (i.e., the increase in net income from one additional kilogram of milk produced) would become negative.

NUTRITION AND ENVIRONMENTAL SUSTAINABILITY

Efficiency of Protein Use

Dairy cattle obtain metabolizable protein (the amino acids that are absorbed and available for use by the cow's body tissues) from two sources: microbial protein (the protein in ruminal microbes that flush down into the small intestine), and rumen-undegraded protein or RUP (ingested protein that was not degraded in the rumen and passes to the small intestine). For most diets, more than half of the feed protein will be broken down in the rumen and provide N for microbial growth and synthesis of microbial protein; microbial protein, in turn, typically makes up more than half of the protein that passes to the small intestine. For a low-producing cow, microbial protein along with the typical amount of RUP in a diet will generally meet the cow's metabolizable protein requirement. For a high-producing cow, microbial protein plus the normal amount of RUP is often inadequate to meet the need for metabolizable protein. The 2001 version of *Nutrient Requirements of Dairy Cattle* from the National Research Council includes requirements for RUP, RDP, and even has recommendations for optimal intestinal supply of lysine and methionine. Strict adherence to the new NRC guidelines for high-producing cows results in diets with special RUP feeds, such as fish meal or expeller soybean meal, and a rumen-protected methionine supplement as well.

Protein nutrition influences productivity, profitability, and the efficiency of N use. For mature cows in zero N balance, feed N that is not converted into milk N must be excreted. The efficiency of converting feed N to milk N seldom exceeds 30%; thus >70% of feed N is typically lost with ~30% lost in feces and ~40% lost in urine, mostly as urea. Feeding cows less protein can dramatically decrease urinary N excretion and increase the efficiency of N use.

The inefficiency of using N in animal agriculture is becoming a major environmental concern. Urea in the urine of mammals is rapidly hydrolyzed to ammonia by urease enzymes in feces, and animal agriculture accounts for ~50% of total atmospheric ammonia. Atmospheric ammonia causes haze and acid rain, which decrease forest productivity and ecosystem biodiversity. Moreover, atmospheric ammonia is rapidly converted to ammonium, which contributes to small diameter (<2.5 μm) particulate matter, and small particulate matter has recently been implicated in inducing heritable mutations in mice. Other volatile N emissions from

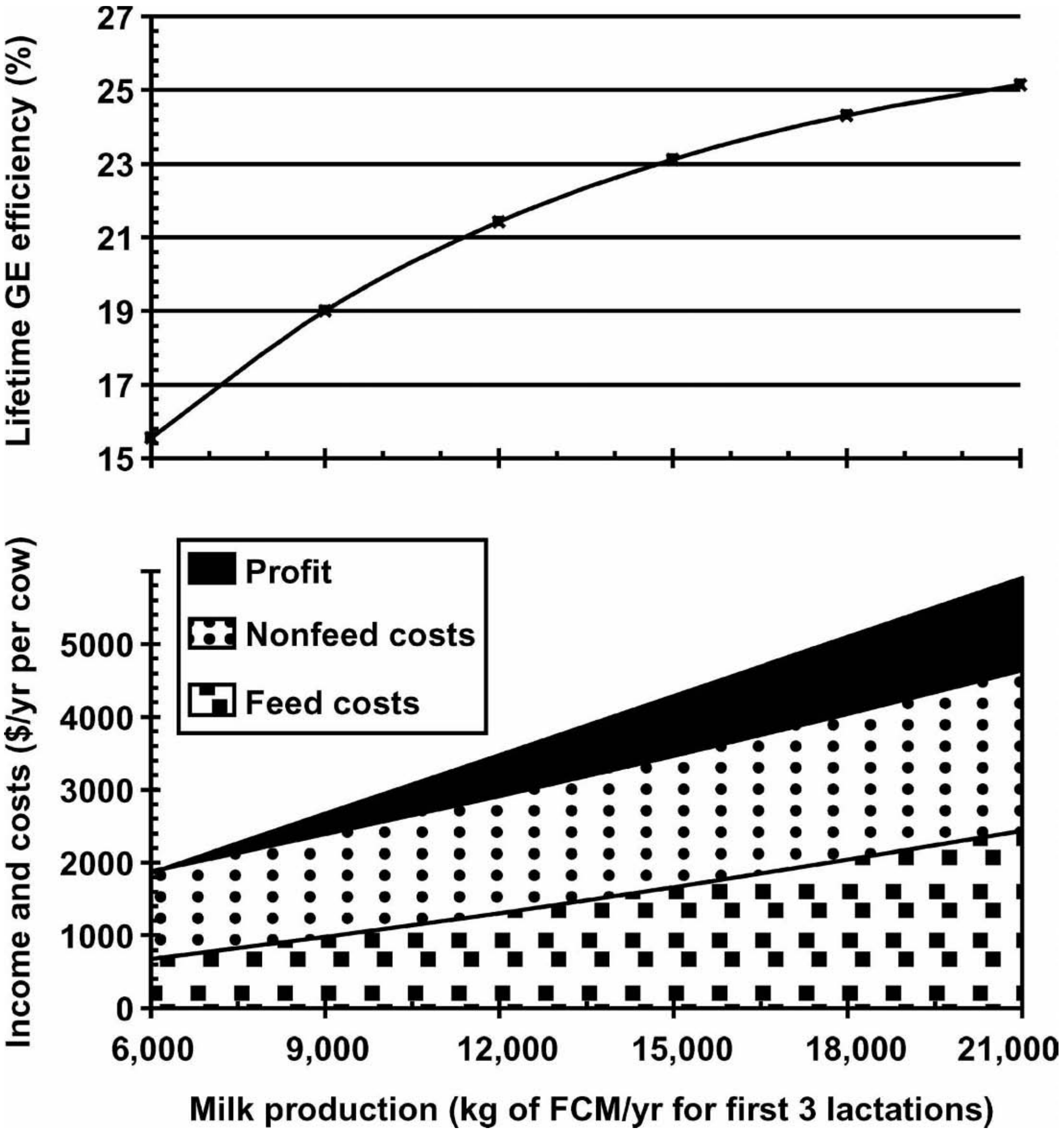

Figure 5. Projected changes in efficiency (top panel) and profitability (bottom panel) with increasing milk production. In bottom panel, the top line is milk income, and black area is income minus costs to represent total return to investment and management. From VandeHaar, 1998 (J. Dairy Sci. 81:272–282).

dairy farms include nitrous oxide (N_2O), nitric oxide (NO), and nitrogen dioxide (NO_2). These volatile nitrogen emissions have been implicated in global climate change. Increasing the efficiency of N use, particularly the efficiency of absorbed N use, per unit of milk or meat may be a major challenge for dairy farms in the future.

In the past, there has been little economic incentive to feed diets that increase the efficiency of N use. Feeding more protein than required by a cow usually increases feed costs with no financial return, but lost milk due to inadequate dietary protein is even more expensive. The economic cost in the form of lost milk due to underfeeding greatly exceeds the cost of feeding excess protein as a margin of safety. Excess protein may slightly decrease energetic efficiency, but the cost associated with the risk of underfeeding protein (reduced milk production and energetic efficiency) is much greater than the cost associated with the risk of overfeeding protein. Consequently, farms have little incentive to feed less than ~18% CP to lactating cows. Yet in some studies, feeding as little as 12% CP resulted in almost no drop in milk yield with a large decrease in urinary N excretion. If we could find ways to produce high quantities of milk per cow consistently with only 12% CP diets, we could decrease urinary N excretion by more than half on commercial dairy farms.

It is very difficult to maximize efficiency of both energy and protein use at the same time. As discussed earlier, maximum energetic efficiency occurs with highest milk production. Milk protein and energy yields are strongly and positively correlated, as are feed energy and protein intakes. So, in general, N efficiency also increases as milk production increases. In fact, if cows are fed to meet NRC requirements without excess RDP or RUP, N efficiency will increase and plateau in a pattern much like that for energy. In support of this, Kohn and coworkers at Maryland predicted N intake and efficiency on 450 farms based on milk urea N concentrations, dietary protein concentrations, and milk protein output and found that milk yield accounted for 25% of the variation in N efficiency. The fact that 75% of the variation was not accounted for by milk yield is not surprising because energy intake is generally more limiting for milk production than is protein intake. Cows are usually fed more protein than needed to ensure that protein does not limit milk yield. The excess protein is used as a fuel source. Protein is used most efficiently when it is the first limiting nutrient, so that protein is consumed below that needed for maximum milk. In 1998, Hanigan and coworkers showed that milk protein output increased in a curvilinear fashion to increasing protein intake within 3 different levels of energy intake (40, 50, and 60 Mcal of ME/d; Figure 6). For each level of energy intake, milk protein output peaked when CP intake was 4 times the yield of milk protein. Efficiency of converting feed N to milk N was as high as 35% when N intake limited milk output but was only 25% for peak milk N output within each level of energy intake, and even less when feed protein was above requirements.

With careful attention to all feed N fractions, diets theoretically can be balanced to maximize milk production and energetic efficiency while achieving acceptable protein efficiency and N excretion. Adjustments in the rumen degradability of dietary protein have allowed maximal milk yields with 1 to 2 percentage units less CP. Supplementation with the most limiting amino acids (lysine and methionine) in rumen-undegradable forms has allowed an even lower concentration of dietary CP. However, studies with diets varying in RUP, RDP, and rumen-protected amino acids are often disappointing. In a review of 108 studies conducted from 1985 to 1997, Santos and colleagues found that response in milk yield to RUP supplements was highly variable, with increased milk production occurring in only about 1 of 5 cases. The response to amino acids is also variable. Thus, our ability to accurately predict the response to protein is poor and, at least, for the foreseeable future, most cows will likely be fed more protein than needed.

Efficiency of Phosphorus Use

Phosphorus wastes from agriculture have become a major environmental concern because they accelerate the eutrophication of lakes and streams. Nutrient management plans are becoming mandatory in many states to control P runoff. Despite the fact that inorganic supplements for P are expensive and that P is a potential environmental contaminant, many farms feed P, even in inorganic supplemental forms, in excess of its requirement. Therefore, one of the simplest and most effective ways to reduce P losses from farms is to simply feed less of it. Moreover, requirements for P were reduced with the 2001 revision of NRC. Satter and colleagues recently reported results of a long-term study with 250 cows fed P at the new recommended concentration of 0.37% or at 0.57%. Consistent with earlier studies using fewer animals, milk production was not increased by feeding P above the recommendation (in fact, milk yield was identical for the 2 groups). Just as importantly, they found that P treatment had no detectable effect on reproductive performance, thus debunking the widely held view that high P diets could improve fertility (Figure 7). Based on a survey of 600 farms, Dou and coworkers reported in 2003 that the P fed to lactating cows averaged 34% above NRC recommendations, and that on 84% of these farms, P was overfed at the recommendation of a professional nutritionist. In our view, the fact that many nutritionists and veterinarians still recommend feeding excess P is unacceptable. Feeding P at its recommended level is a sound management practice both for the cow and the environment.

Efficiency of Land Use

Other issues in biological efficiency that will become more important in the future include efficiency of use of human-consumable inputs and efficiency of land use. Although the efficiency of total feed use in the US dairy industry is 20 to 25% for energy and 20 to 30% for protein, the returns on human-digestible inputs ranges from 60 to 130% for energy and 100 to 280% for protein. Increased use of by-product feeds with greater digestibility discounts may decrease the gross efficiency of total feed use, but most by-product feeds are not consumable by humans. Therefore, the use of by-product feeds in dairy diets increases efficiency of human-consumable inputs in the dairy industry. This advantage is especially important in light of the fact that one hectare of land can produce more than twice as much protein for human consumption when used to grow corn and soybeans for direct human consumption than when used for growing feeds for milk production (Table 2). Although milk output per hectare should increase with

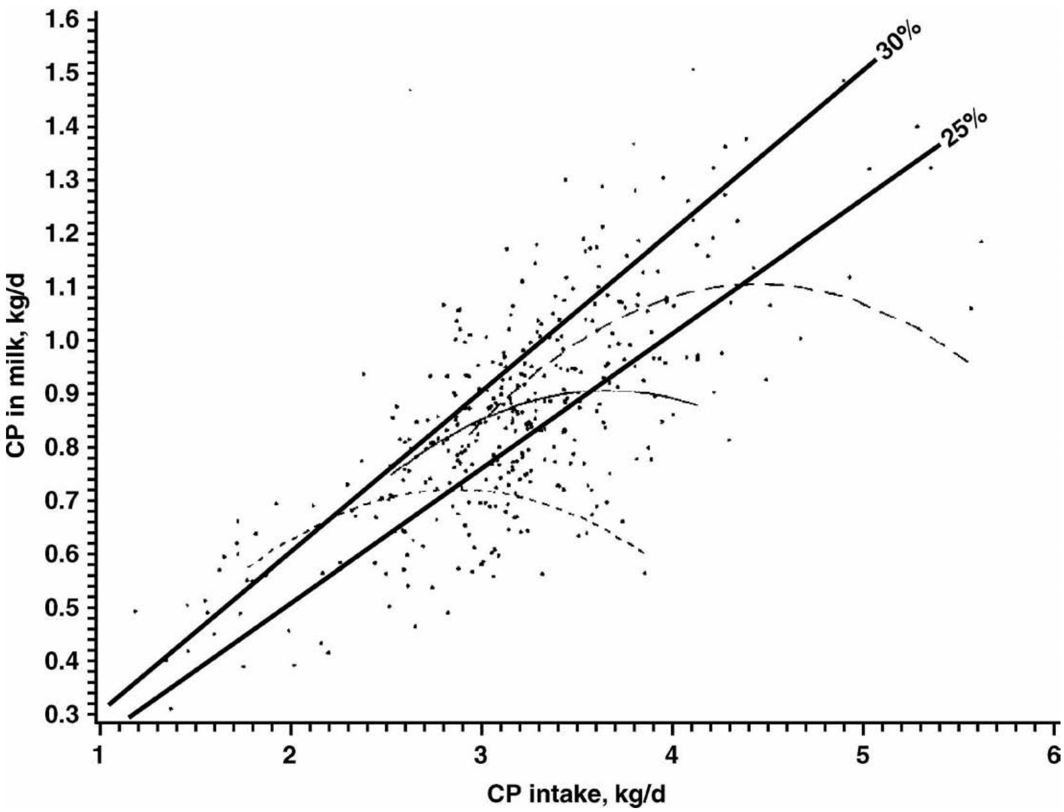

Figure 6. Milk CP output vs. CP and ME intake in a multivariate analysis of N balance data of individual cows. Best-fit curves were developed for energy intakes of 40 (dotted line), 50 (solid line), and 60 (dashed line) Mcal of ME/d. Lines designating 25 and 30% efficiency for converting feed N to milk N also are shown. From Hanigan et al., 1998 (J. Dairy Sci. 81:3385–3401).

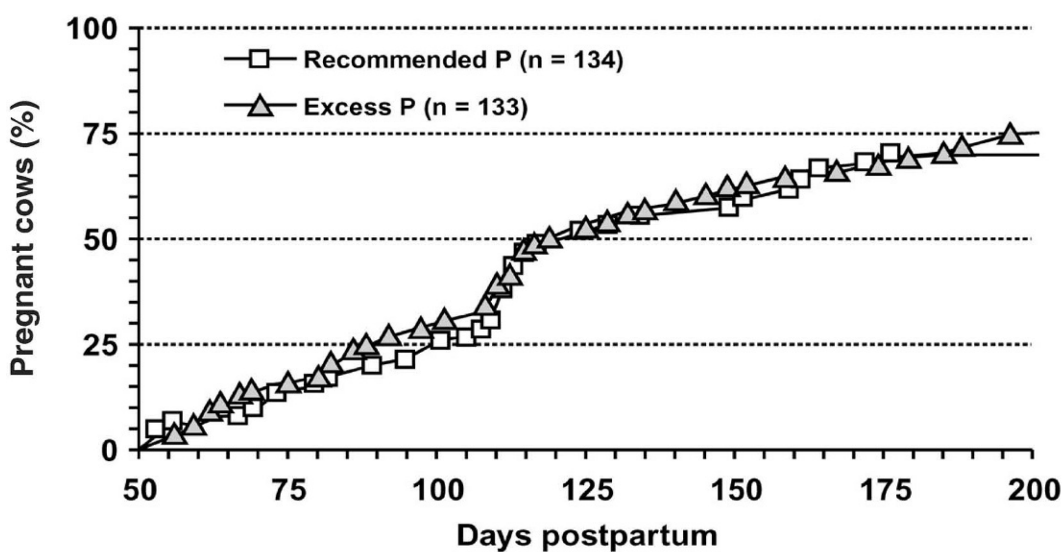

Figure 7. Survival curves ($P = 0.48$) for days open for cows fed recommended (0.37%) or excess (0.57%) concentrations of P. From Lopez et al., 2004 (J. Dairy Sci. 87:146–157).

Table 2. Effect of level of production and diet on efficiency of land use in dairy farming[1]

	Grazing system	Confined feeding without by-product feeds			Confined feeding with by-product feeds		
Milk yield, kg/yr per cow	5,000	5,000	10,000	15,000	5,000	10,000	15,000
Feed, kg of DM/yr per cow	6,050[2]	5,870	8,120[3]	10,540	5,950	8,380[4]	11,150
Land required,[5] ha/yr per cow	0.54	0.66	0.97	1.34	0.30	0.49	0.68
Protein production, kg/ha	359	295	371	392	642	731	770
Efficiency of land use,[6] %	43	35	45	47	76	88	93

[1]From VandeHaar, 1998 (J. Dairy Sci. 81:272–282).

[2]Feed DM consumed during the lifetime of cow in a grazing system consists of 99% high-quality pasture, and 1% minerals.

[3]Feed DM for 10,000 kg/yr consists of 34% alfalfa, 26% corn silage, 26% corn grain, 12% soybeans, and 2% minerals. The concentration of soybeans in the feed is decreased with lower milk production and increased with higher milk production.

[4]Feed DM for 10,000 kg/yr is 25% alfalfa, 25% corn silage, 13% corn grain, 2% soybeans, 12% corn gluten feed, 10% cottonseeds, 10% wheat middlings, 1% blood meal, and 2% minerals. The concentration of soybeans in the feed is decreased with lower milk production and increased with higher milk production.

[5]Yields (DM basis) were assumed to be 11,120 kg/ha for alfalfa, 20,210 kg/ha for corn silage, 8,150 kg/ha for corn grain, and 2,690 kg/ha for soybeans.

[6]Protein and energy yield per ha from dairy farming relative to the protein and energy yield from soybeans and corn grown for direct human consumption. Equal cropping of corn and soybeans would provide 986 kg of protein/ha with the same protein to calorie ratio as whole milk at 3.5% fat. Milk protein was considered 20% more nutritious as a source of digestible, essential amino acids than the mix of corn and soybeans.

greater milk production per cow, the use of fibrous by-product feeds with small particle size and high digestibility discounts may limit the ability of a cow to produce milk. Because efficiency of use of human-digestible inputs may become the most important justification for the continued existence of a strong dairy industry in the United States, the value of increasing productivity may decrease as more fibrous by-product feeds become available, especially if prices of grains and of land for feed production are high, but this will likely not occur in the foreseeable future. Extensive use of by-product feeds for heifers, dry cows, and cows in late lactation, along with thoughtful use for cows in early lactation, should allow continued increases in productivity and efficiency. In the process of using larger quantities of by-product feeds relatively rich in P, however, the dairy industry is acting increasingly as a recycler of excess P generated by the production of human food. This may have drastic effects on land and capital uses by the industry in the future.

NUTRITION AND PROFITABILITY

Improved productivity and biological efficiency have significantly increased profitability of dairy enterprises in the past. This relationship is not easy to study on whole-farm systems because so many factors affect profitability and thus can mask effects of productivity on profitability. For example, some studies have shown virtually no relationship between production per cow and profit per cow across farms. A major problem with these studies is they often have considered only the accounting costs and not all the costs, including the cost of the equity capital. When full-cost accounting is used, a positive relationship exists between milk production per cow and net income within breed. In examining the potential relationship of productivity to profitability in the future, two major factors must be considered. The first is that feeds generally become more expensive on a per unit energy basis as cows are fed for higher production, and the second is that fixed costs on a farm decrease relative to milk output as milk production increases. The efficiency of capital and labor use in a modern milking parlor increases with milk production because most of the tasks associated with milking are fixed per cow unit. Likewise, the capital and labor efficiency of feeding and housing increase as production increases. It is unclear which one of these two opposing forces—increased marginal cost of feeds vs. decreased fixed costs through better capital and labor efficiencies—will predominate in the long-term. History is on the side of increased production. Additionally, increased environmental regulations may increase substantially the amount of required capital per cow, putting a greater emphasis on capital efficiency, thus, favoring increased animal productivity.

Impact of Heifer Management on Efficiency and Profitability

General recommendations are that a dairy cow should calve for the first time at 22 to 24 mo of age and then once every year thereafter. A dairy calf is usually separated from its mother soon after birth and fed mostly milk or milk-based products until it is weaned between 5 and 8 wk of age. During this time, the most important goal is to keep the calf healthy and vigorous. Traditionally, calves on milk replacers are fed milk powder at about 1% of body weight per day and grain available free choice. This feeding regimen results in growth rates of 300 to 400 g/d in the first 2 wk of life with growth rate increasing as grain intake increases. However, there has been considerable interest in the last 10 yr in feeding calves higher protein milk replacers at higher rates of intake, often with milk powder at 2.2% of body weight per day. This increases growth rate to as much as 600 to 1,000 g/d but decreases grain intake and is certainly more expensive. The faster gain may enable calving at 1 mo earlier age but whether this is cost-effective remains to be determined.

After weaning, heifers should be fed to promote sound growth at a reasonable cost. General recommendations are that Holstein heifers should grow at ~800 g/d from weaning to breeding, then be bred at 363 kg, and finally grown at ~900 g/d during pregnancy. (Other breeds would be grown proportionally relative to mature body size). This growth program results in breeding at 13 to 14 mo and calving at 22 to 23 mo. However, the economic support of this general recommendation is lacking. For minimal calving problems and highest milk production, Holstein heifers should weigh ~630 kg just before calving (~570 kg after calving). Current data suggest that first-lactation milk yield will be reduced 70 kg for every 10 kg of body weight below this optimum. One way to reduce overall costs on a farm is to decrease the age at first calving. For heifers to calve earlier than 24 mo at the appropriate body weight, they must grow faster than 800 g/d.

Faster growth means less energy is used for maintenance from birth to first calving, and therefore energetic efficiency will be increased. Decreasing age at first calving from 26 to 21 mo will decrease total energy use of heifers by 10%, assuming that body weight after calving is not different. However, the amount of feed used by heifers is relatively small, so that lifetime feed energy intake for the average cow decreases less than 2% with a 5-mo earlier calving, assuming milk production is not altered. Moreover, the cost of feed per unit of energy is generally greater as heifers are fed for faster growth; for example, faster growth requires a greater protein to energy ratio, and protein calories are more expensive than nonprotein calories. Therefore, the total cost of feed to first calving is relatively unresponsive to changes in age at first calving, with a savings of ~$5 per month for earlier calving. If later calving is due to slower growth in a pasture-based system, the difference in feed costs may even favor later calving. More importantly, however, earlier calving will decrease yardage costs—costs that are directly related to time on feed, such as housing, interest, and labor. Estimates for yardage costs vary from $10 to $30 per month. Decreased yardage costs along with the decreased overall feed costs generally favor earlier calving unless timing of the expenses is different and sometimes even if subsequent milk yield is reduced. Most studies have shown that rapid growth (>900 g/d) between weaning and breeding with calving before 22 mo of age will decrease milk yield. Whether calving before 22 mo will also decrease profitability is less clear and will depend on the costs of available feeds and yardage, both of which vary with individual farms and year. The economic analysis must factor the life of the investment and the time span between the investment and the returns. This time span is shorter with younger age at first calving; that is, the animal starts returning you money earlier. When the proper time-discounting factors are applied to the flows of expenses and revenues, the optimum prepubertal rate of gain for profitability on some farms may be as high as 1 kg/d or even higher.

CONCLUSIONS

The dairy industry in the United States has undergone many changes in the past 100 yr. Milk production per cow has more than quadrupled. This increase can be attributed to improvements in genetics and in nutrition and management. Excellent nutrition is needed for a cow to express high genetic potential, but does little for a cow with low genetic potential. Advances in our knowledge of nutrition have been and will continue to be instrumental in increasing feed energy intake of cows, refining N fractions of feeds, and refining the requirements for nutrients such as P. These advances have and will continue to improve the productivity and profitability of dairy cows and the stewardship of feed resources, land, and cows by the dairy industry. Because cows can make milk efficiently from feed, especially feeds that humans cannot or will not consume, the future of the dairy industry is bright, even in a world where demand for basic food needs is increasing and most people could meet their nutritional needs without dairy products.

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