Feeding and Breeding Dairy Cattle to Improve Feed Efficiency

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INTRODUCTION

The efficiency of converting feed to milk has increased considerably I the past 50 years; in the US, efficiency has doubled since 1960 (VandeHaar and St-Pierre, 2006). This increased efficiency was achieved largely as a byproduct of selecting and managing cows for increased productivity. Increasing productivity resulted in a greater percentage of total feed intake being partitioned toward milk and less toward cow maintenance. Elite dairy cattle in the US currently partition three times more feed energy toward milk than toward maintenance, and we are not likely to continue to make major advances in feed efficiency simply by increasing productivity. Moreover, increasing competition for feed grains may limit their availability for use in feeding cows to increase productivity. Thus, we must specifically focus more on how to get more milk from each unit of feed rather than simply on how to get more milk from each cow. In summary, my points will be:

- Past increases in milk yield per cow (from genetics and grain feeding) have resulted in increased milk output per unit feed input, but this will not likely continue. In the future, we must focus directly on efficiency if we want to improve it.
- Improvements in efficiency will improve environmental stewardship.
- Optimal diets for maximizing efficiency vary by stage of lactation. Management strategies to feed cows according to lactation stage will enhance efficiency of using feed energy and protein.
- Genomic technologies may enable selection of more efficient cows.

INFLUENCE OF PRODUCTIVITY ON EFFICIENCY

Feed efficiency can be considered many ways. The simplest would be pounds of milk per pound of feed, but this does not give adequate consideration to the value of forage and fiber in dairy nutrition. In addition, feed use impacts not only current production and efficiency but also health and longevity. Moreover, one might argue that we should consider all inputs and outputs of energy and nutrients on a global scale. Such a global view would consider the efficiency of using human-edible inputs, the efficiency of using land, and the inputs and outputs of fuels and greenhouse gasses. That gets complicated, so I will discuss mostly energetic efficiency in this paper.

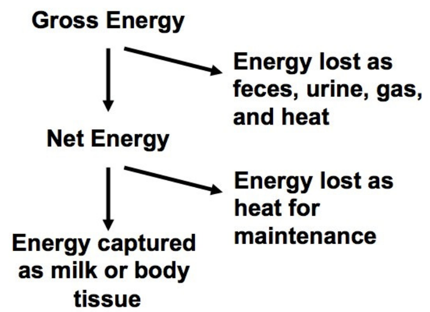

Figure 1. Energy flow in a cow.

Gross energy (**GE**) is the combustible energy of a feed and is independent of how efficiently the cow uses it. I will define energetic efficiency as ***gross efficiency***, the total milk and body tissue energy captured per unit of GE consumed. Major factors that are considered to affect gross feed efficiency on farms include a) cow body weight (**BW**), b) milk energy yield per cow, c) longevity and the percentage of lifetime a cow spends in lactation, d) nutritional accuracy in feeding, and e) the cows' net efficiency of converting feed to milk.

Not all GE is useful because some of it is not digested but is lost as fecal energy. Some of the digested energy is lost as gaseous energy, primarily methane produced during fermentation, and as urinary energy, primarily urea produced during protein breakdown. The remaining energy is metabolized energy (**ME**). About one-third of ME is lost as heat associated with the work of fermenting, digesting, and metabolizing nutrients. The remaining energy is known as net energy (**NE**), 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 NE is about the same whether the ME is used for maintenance or for milk production, and thus we use NE for lactation or **NEL** as our energy unit.

For the typical US Holstein cow, the first 10 Mcal of NEL/day (equivalent to ~25 Mcal of GE and 14 pounds of feed) is used for maintenance. At this level of intake, gross efficiency is 0% as no milk is produced. Additional feed that is consumed can be converted to milk or body tissues. If the cow eats twice as much feed—20 Mcal NEL or 2X maintenance—then only half of her feed would be used for maintenance and half would be used for production. As she eats more feed, the portion used for maintenance becomes a smaller fraction of total feed intake; this phenomenon is referred to as "***dilution of maintenance***" and it is the reason that greater productivity leads to greater efficiency.

Theoretically, if the cow's maintenance requirement is constant and the net efficiency of converting feed to milk were constant, gross efficiency would continue to increase as maintenance accounted for a smaller portion of total feed intake. However, the increase in gross efficiency is less going from 3X to 4X maintenance than from 2X to 3X, and progressively less thereafter (solid line, Figure 2). This is true whether the increase in multiple of maintenance is caused by *increased production at fixed BW* or by *reduced BW at fixed production*. However, this projection is overly optimistic, because as cows eat more feed per day, feed digestion is depressed. Eventually, as productivity increases, this depressed digestive efficiency becomes more important than the dilution of maintenance and gross efficiency may decline (dotted line, Figure 1; NRC, 2001).

This digestibility depression is not well quantified for cows consuming >4X maintenance (VandeHaar, 1998; Casper and Mertens, 2008; Huhtanen et al., 2008), and the NRC 2001 likely depresses digestibility too much at high intakes. The best estimate for gross efficiency would be a curve that is between the two curves of Figure 2. I believe a digestibility discount that diminishes with each successive multiple of maintenance is more logical and equally supported by the literature; this discount method was described in VandeHaar (1998) and is the basis for most of my discussions of efficiency. Current data on 840 Holstein cows at ~100 DIM is consistent with the idea that the true change in efficiency is somewhere between the two lines of Figure 2 (VandeHaar et al., 2012).

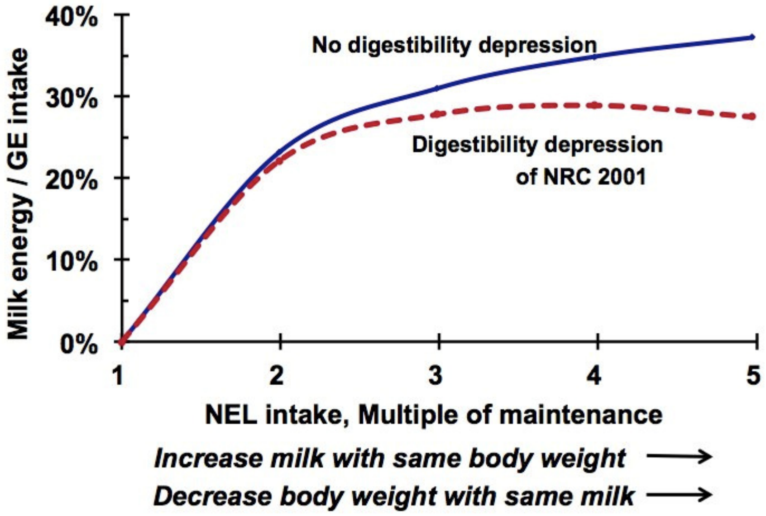

Figure 2. Gross efficiency (assuming no change in BW) vs intake as multiple of maintenance for a lactating cow with no change in digestibility (solid line) or with digestibility decreased as per the NRC 2001 system (dashed line). With NRC, the digestibility depression outweighs the dilution of maintenance as productivity increases, so gross efficiency is maximized at ~45 kg milk (3.5% fat) per day for a 1500-lb cow. The NRC system likely depresses digestibility too much at higher intakes. Regardless, producing more milk per cow will have less impact on efficiency in the future than it had in the past. The impact of diluting maintenance and digestibility are likely the same whether we achieve more milk at a specific BW, or whether we breed for smaller cows that produce the same milk.

Regardless of the discount used, the depression in digestibility at high intakes clearly does occur, and elite cows are already near, at, or possibly above the optimal multiple of maintenance for maximal efficiency. In the past 100 years, feed efficiency has increased considerably, largely as a byproduct of selection and management for increased productivity. As production increases to higher levels, however, the digestibility depression eventually becomes more important in determining gross feed efficiency than does the dilution of maintenance. Optimal milk production for a herd will be greater than for an individual cow to account for feed intake as a heifer and dry cow. However, once herds reach production levels of 10,000 kg/yr (about 3X intake for herd), we are not likely to continue to make major advances in feed efficiency simply by increasing productivity. Moreover, the competition for feed grains is increasing, so our ability to increase productivity from feeding diets enriched with starch will decrease. We must specifically focus more on how to maximize milk from each unit of feed rather than simply on maximizing milk per cow.

PRODUCTIVITY AND ENVIRONMENTAL STEWARDSHIP

Our society cares about how we do agriculture. Most consumers may not be willing to pay more for dairy foods produced in certain ways, but politicians and food retailers are increasingly impacting what practices are acceptable. There are many practices in dairy farming that contribute to good stewardship of the environment. We should strive to limit run-off of phosphorus, nitrogen, and organic materials from our farms. Phosphorus causes eutrophication of surface waters, and nitrogen can contaminate ground water. Both of these nutrients are often overfed. Ammonia losses to the atmosphere are a growing concern without easy solution. Soil erosion should be minimized in crop farming and grazing, and stream banks should be protected from grazing cattle. A good environmental steward also protects some areas of native vegetation and retains some wildlife habitat. What role, if any, do productivity and efficiency play in environmental stewardship?

As the world population continues to increase, and land resources are not expanding, efficiency of using existing land becomes more important. Much of the land currently used for growing feed grains and forages for cattle could be used to grow grains and legume seeds for humans, or could be used to grow biofuels. Measures of efficiency that consider how we use human-consumable inputs and how we use land that could be used to directly grow food for humans must be considered. Although the efficiency of total feed use in the US dairy industry is 20-25% for energy and 20-30% for protein, the returns on human-digestible inputs ranges from 60 to 130% for energy and 100 to 280% for protein (Oltjen and Beckett, 1996). 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 acre of land can produce only half as much human food when used for growing feeds for milk production at current milk production levels than when used to grow corn and soybeans for direct human consumption (VandeHaar and St-Pierre, 2006). Milk output per acre increases with greater milk production per cow. If byproduct feeds make up about one-third of a herd's diet and the cows produce 15,000 kg/year, then using land for milk production yields 90% as much food for human consumption as does corn and beans. Using land to produce corn and soybeans (or grains and legume seeds) for direct human consumption would be the most efficient way to feed people. Given that high-producing dairy cows can achieve land efficiencies almost as high suggests that the dairy industry will be part of our food production long into the future. However, the use of fibrous by-product feeds with small particle size and high digestibility discounts may limit the ability of cows to produce the highest levels of 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 US, 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 byproduct 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 for many more years.

As we consider feeding 9 billion people in a sustainable manner, and if they will consume dairy products, then we must find ways to produce milk that decreases negative environmental impacts. To do this properly, one must consider all inputs and outputs for the dairy industry, including even the fuel used to till the land to grow the crops. This is called a Life Cycle Analysis and, although it is fraught with potential inaccuracies, there is no other way to consider the big picture. Two recent studies highlight the value of increased productivity to enhance environmental stewardship. Thomassen et al (2008) compared conventional and organic Dutch dairy farms. Milk yield per cow was 8000 kg/yr for the conventional farms and 6100 kg/yr for the organic farms. When considering all inputs (which included feeds being shipped in from outside the country) on a per unit of fat and protein-corrected milk basis, conventional farms used 60% more energy and caused 50% more eutrophication, but the organic farms required 40%

more land. Acidification and climate change were not different for the two systems. In my view, the decreased need for land gives the advantage to the conventional system as the unneeded land could be used to produce biofuels or put into native habitats. Capper et al. (2008) modeled the environmental output of dairy management systems in the US to meet current USDA dietary guidelines for all Americans. If all milk was raised in organic systems, compared to our current conventional systems without bST, we would need 25% more dairy cattle and 30% more land, the cows would excrete 39% more N and 34% more P, and the US dairy industry would cause 28% more eutrophication, 15% more acidification, and 13% more global warming. In contrast, if all cows were given rbST, we would need 8% fewer cows and 5% less land, cows would excrete 5% less N and P, and the dairy industry would cause 5% less eutrophication, acidification and global warming. The major reason for these differences is that increased productivity increases efficiency, and increased efficiency generally is good for the environment—we can feed more people with less resources. We will never achieve 100% efficiency in animal agriculture, and people likely will eat fewer animal products as a percent of calories in the future than they do now. However, improving efficiency of meat and milk production by using new technologies seems the responsible thing to do for the environment.

MANAGEMENT TO IMPROVE FEED EFFICIENCY

The average US Holstein (9500 kg milk/year) currently captures ~21% of her lifetime gross energy intake as milk and body tissues. Gross efficiency during lactation is greater than this, but ~24% of the feed a cow eats in her life is during nonlactating periods (heifer, dry cow). Maximum lifetime gross efficiency of GE use is 25-30% and likely occurs around 30,000 lb of milk/year. Thus, increases in productivity will continue to improve efficiency for most US dairy farms. However, even farms with average milk near 30,000 lb/cow can improve feed efficiency at the herd level through better grouping and feeding strategies, reproduction and culling management, and diet formulation to match cow requirements. Using the model described in VandeHaar (1998), the impact of various management changes on efficiency of using energy and protein were estimated (Table 1).

Table 1. Impact of selected management changes on energy and protein efficiency for a farm with 9500 kg milk/cow/year[1]

	Energy	Protein
Base feed efficiency	21%	28%
Increase milk production 10% (2100 lb/year)	+0.7%	+0.4%
Increase longevity from 3 to 4 lactations	+0.6%	+0.5%
Decrease maintenance requirement 10%	+1.1%	+1.2%
Improve efficiency of digestion by 10%	+1.2%	+1.0%
Reduce age at first calving 2 months	+0.3%	+0.3%
Reduce calving interval 1 month	+0.4%	+0.4%
Feed cows >150 DIM a diet with 2% less CP	+0.0%	+1.3%

[1] The added benefit of any of these generally decreases with each successive improvement. This is especially true for milk productivity. Calculations are based on model of VandeHaar (1998).

It might seem counter-intuitive, but maximizing feed intake per cow helps to minimize the feed needed per unit of milk. Maximizing feed and energy intake per cow enables cows in early and mid lactation to produce more milk. More milk per cow means fewer cows are needed for the same amount of milk and thus less feed is needed for maintenance and each pound of feed on the farm results in more milk. Maximum feed intake occurs when cows are comfortable and have plenty of water and fresh, well-balanced feed available most of the day. This topic has been discussed considerably in the past 20 years, with general agreement and no need for continued discussion here. Even if some extra feed must be discarded, strategies to improve intake will yield improved efficiency, profitability, and stewardship.

Feeding to Enhance Efficiency throughout the Lactation

Nutrient requirements vary as lactation progresses, and the optimal diet for maximum efficiency will be different for a cow at 10, 60, and 200 days postpartum. In the US, however, most farms now feed totally mixed rations (**TMR**) instead of feeding grain to each cow separately and individually. Use of TMR feeding improves productivity and efficiency because cows theoretically eat the same thing in every bite and rumen pH is more consistent. However, with TMR feeding, cows are less likely to receive a diet that matches their individual requirements. In the US, there has been a trend for even large farms to feed cows the same TMR regardless of lactation stage, and this trend is a major impediment to enhanced feed efficiency on many farms. Frequently, cows may be housed in groups for purposes of managing health and reproduction, and yet the same TMR will be fed to all groups. Why? Because it is easier to do. Feeding a single TMR across lactation can never maximize production and efficiency. Precision feeding of the groups could help better allocate high energy feeds to maximize production, improve efficiency of N and P use, decrease N and P excretion, and improve sustainability (Kabreab et al., 2000;Wang et al., 2000). Several common-sense ideas should be considered when optimizing grouping strategies to maximize feed efficiency, and most are consistent with maximizing production and profitability (Figure 3).

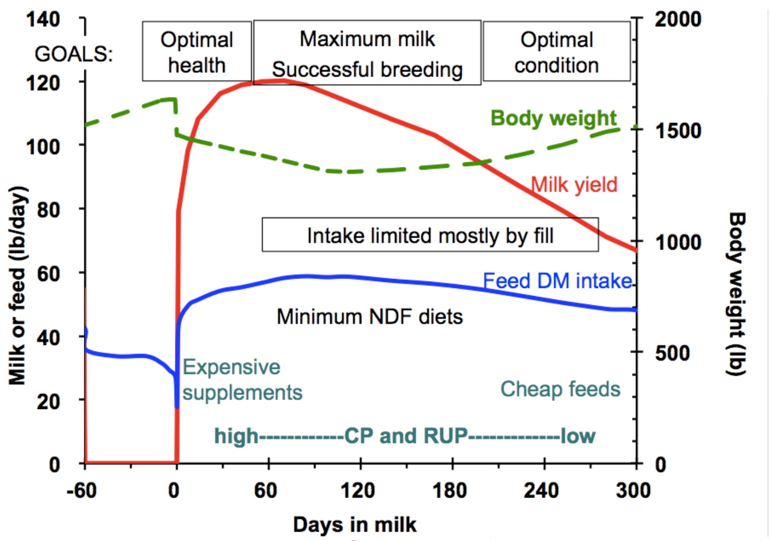

Figure 3. Considerations in nutritional grouping. Cows in the first month of lactation are less limited by rumen fill, but after the first month, most cows fed high fiber diets will be limited in how much they can eat because of rumen fill. At this time, they should be fed minimum fiber to promote maximum feed and energy intake. Once body condition exceeds 3, cows should be fed less fermentable starch and more fermentable fiber to increase gut fill and promote partitioning of nutrients toward milk instead of body tissues. Expensive supplements are most useful in early lactation, whereas cheap feeds are best allocated to late lactation. Early lactation cows should be fed more protein than those in late lactation to maximize efficiency of protein use.

If a single TMR is fed to all lactating cows, it is usually formulated for the higher-producing cows on the farm. Thus, it is more nutrient-dense than optimal for cows in later lactation, resulting in inefficient use of most nutrients in later lactation cows. For example, cows in late lactation could be fed diets with less protein than the rest of the milking herd (e.g., 15 instead of 17%). In addition, although this single TMR is formulated for the high producers, it is nearly impossible to formulate a single TMR for "maximum milk". A diet that is optimal for health and productivity during one stage of lactation is not likely optimal at other stages. Diets low in fiber and high in digestible starch optimize production and reproduction in peak lactation, but this type of diet would have inadequate fiber and increase the incidence of displaced abomasum and acidosis in fresh cows and the incidence of over-fattening in late lactation cows. Fat cows are more susceptible to health problems at next calving, resulting in less saleable milk and followed by increased body fat mobilization, impaired fertility, and extended lactation interval (Cameron et al., 1998). Consequently, cows culled in single TMR situations may be those that cannot adapt to less than optimal management, rather than those that are least efficient, productive, and profitable. Moreover, single TMR systems do not allow maximum advantage in use of supplements or expensive feeds that may profitably increase production in fresh or high producing cows but have negative return in lower producers. This is relatively obvious for supplements designed to improve fresh cow health or for protein supplements high in rumen-undegraded protein that benefit early lactation but not late lactation. This is less obvious but equally important in forage selection. Not all lactating cows benefit equally from highly digestible fiber; a single TMR prevents optimal allocation of forages. This might be especially important in tropical environments where most forages have lower digestibility.

Another impediment to feed efficiency is poor reproduction and culling management. Decisions regarding reproduction and culling determine the length of time a cow is in late lactation—a phase when she is less profitable and less efficient. Poor reproductive management exacerbates the problem of single TMR by further extending lactation interval, decreasing culling options, and impeding optimal grouping to make multiple TMR seem worth the effort.

One argument used by farmers against multiple ration groups is that milk production decreases when cows are switched to a different group with a different ration. However, many factors affect milk production during a grouping change; these factors include days in milk, pregnancy status, somatotropin timing and use, stocking density, heat stress and fan placement, and cow social interactions. These factors confound observations on farms, and farmers are quick to notice temporary drops in production and may be overly influenced by them. Moreover, replacement of starch with digestible fiber might help partition more nutrients toward milk instead of body tissues. Additionally, too often grouping decisions are made only on milk yield and reproductive status when many factors should be considered. In particular, the propensity to gain body condition in late lactation should be considered. Many nutritionists have long recommended that cows with BCS >3 should be moved to a diet with lower energy density. For maximal benefit of nutritional grouping in the long-term, grouping decisions should be determined by cow requirements (which includes body condition management) rather than by milk yield alone.

Nutritional grouping and multiple TMR undoubtedly do increase capital, management, and labor costs; however, the economic returns can be significant in both the short and long term.

Morever, feeding cows according to requirements results in less waste. If you currently feed a single TMR, I encourage you to seriously consider how you can make this work.

Managing to Enhance Protein Efficiency.

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. Ammonia and other volatile nitrogen emissions have been implicated in acid rain and global climate change.

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. However, inadequate protein risks a drop in milk production, and thus decreased energetic efficiency.

In the past, there has been little economic incentive to feed diets that increase the efficiency of N use. The economic cost in the form of lost milk due to underfeeding protein greatly exceeds the cost of feeding excess protein as a margin of safety. Maximum energy efficiency occurs with highest milk production, and, in general, N efficiency increases as milk production increases in a pattern much like that for energy. However, protein is used most efficiently when it is the first limiting nutrient, so that protein is consumed below that needed for maximum milk. Hanigan and coworkers (1998) showed that the 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 various levels of energy intake, and even less when feed protein was above requirements. Most lactating cows are fed 17-19% CP diets, which is generally above that optimal for maximizing N efficiency. If we could find ways to produce high quantities of milk per cow consistently with only 14-15% CP diets, we could decrease urinary N excretion by a third on commercial dairy farms.

With careful attention to all feed N fractions (especially RUP and RDP), diets theoretically can be balanced to maximize milk production and energetic efficiency while at the same time achieving acceptable protein efficiency and N excretion. Supplementation with the most limiting amino acids (lysine and methionine) in rumen-undegradable forms also should, in theory, enable an even lower concentration of dietary CP. However, studies to show practical value of diets varying in RUP, RDP, and rumen-protected amino acids are often disappointing (Santos et al., 1998). 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. However, grouping cows according to requirements and then feeding diets specifically formulated for each group would certainly help.

SELECTING COWS FOR GREATER FEED EFFICIENCY

A primary limitation to direct genetic selection for improved feed efficiency has been the prohibitive cost of continuously collecting feed intake data to estimate breeding values. This limitation is particularly challenging in the dairy industry because the phenotype (which requires measurement of feed intake for individual cows) must be collected on daughters of bulls that are potential selection candidates. These daughters are on commercial farms and individual feed intakes are not known. For this reason, some have suggested that the best way to select for feed efficiency is to select small cows. By selecting for both high milk and small body size, we should be selecting for improved lifetime milk per unit feed. The problem with this approach is that once a cow is above 4X maintenance intake, we cannot predict how efficiency changes with smaller size. Thus selecting for smaller size may provide no benefit, and impair our ability to select for other worthwhile traits.

Genomic selection has already been embraced by the dairy industry and minimizes the need for continuous collection of phenotypic data. The basic idea is that there is something inherent in a cow's DNA that makes her more or less efficient at converting feed to milk. Specific segments of DNA might be associated with improved efficiency and thus serve as markers for efficiency. A single nucleotide polymorphism (SNP) is a single base that varies frequently in the population and each SNP represents a whole segment of DNA. Each SNP by itself may not have a strong relationship to a trait like feed efficiency, but combining information for thousands of SNPs can correlate well with a trait.

Through a grant from the National Institute of Food and Agriculture of USDA, we currently determine if SNP genotypes are correlated with feed efficiency. The project is collaborative effort of several universities, and we are measuring individual feed intakes, BW, and production data on 8000 cows in university herds. If we find a relationship, then the SNP genotype can be used to identify potential sires that should confer higher feed efficiency to their offspring. Although we will conduct our measures only on Holsteins, we will be examining 50,000 SNPs on each cow, and our results may translate to other breeds as well. Some information on our project can be found at www.dairy-efficiency.org/ or you can search the USDA web site.

If we are to improve a trait, the first consideration is how to measure it. This is not as easy as it sounds. As mentioned above, we already are confident that higher milk yield per day will likely dilute maintenance and improve milk per unit feed. Our goal is to find cows with a better ability to digest feed or convert digested feed to NEL (meaning waste less of it as urine or heat) or with a lower maintenance requirement. We also don't want to simply select cows for better conversion of feed to milk and maintenance because we may end up inadvertantly biasing our selection for big cows, and we really don't know if a bigger cow is good or bad. We could simply examine milk per unit feed, but then we might select cows that lose too much body condition in early lactation. Adjustments must be made for body tissue gain or loss. Ideally, we would measure feed efficiency over complete lactations by placing cows in calorimetry chambers where we could measure all losses of chemical energy in feces, gas emissions, and urine as well as all heat lost; this would be impractical.

One way to measure is feed efficiency is Residual feed intake (**RFI),** which is a measure of actual versus predicted intake for an individual. Predicted intake can be determined from nutritional models based on cow and diet measurements, or it can be determined statistically as the deviation from the average intake of other cows at a similar stage in lactation that are fed and managed the same (cohorts). RFI has been heavily studied in beef cattle (Nkrumah et al., 2006;

Moore et al. 2008) and pigs (Nguyen et al., 2005; Cai et al. 2008) where long-term selection has demonstrated that RFI can be significantly altered by genetics.

In dairy cattle, estimates of heritability for RFI vary broadly across studies (0.10 to 0.75, Veerkamp et al., 1995), in part due to subtle differences in definitions of RFI, as well as the use of relatively small populations for estimation of genetic parameters. Our initial analyses on data from 840 cows shows that there is considerable variation in feed intake for a given amount of milk, even after considering differences in body weight, body condition score, and body weight gain or loss. Body weight, especially after adjusting for condition score, was not correlated with the efficiency of converting feed to milk, suggesting that efforts to breed smaller cows cannot be justified as a method to improve feed efficiency. Whether we will find that genetics plays a significant role in feed efficiency and whether SNP genotypes will be able to identify these more efficient animals is not clear. Regardless, improvements in feed efficiency must not occur at the expense of health and fertility of dairy cows. Thus, we will carefully consider relationships among measures of feed efficiency, energy balance, production and fitness traits.

RELATIONSHIP OF EFFICIENCY TO PROFITABILITY

Because feed accounts for about half of all costs on a dairy farm, trying to cut feed costs is very tempting, especially when feed prices are high. However, feed for lactating cows is obviously not a frivolous expense but an investment. As already discussed, increasing productivity leads to increased feed efficiency, and increased feed efficiency leads to greater net profits. Many factors affect profitability and can mask effects of productivity on profitability; thus, some studies have shown virtually no relationship between production per cow and profit per cow across farms. However, within a farm this relationship is clearer, and, when full-cost accounting is used, profitability and milk production per cow are strongly and positively correlated. This positive relationship is largely due to two factors: 1) the biological dilution of maintenance, which increases cow feed efficiency, and 2) the economic dilution of fixed costs, which increases efficiency of farm capital and labor use. Thus, even if we reach the optimal production per cow to maximize biological efficiency, economics still favors higher production per cow to dilute out farm fixed costs. Opposed to this is the fact that feeds generally become more expensive on a per unit energy basis as cows are fed for higher production, which can increase the marginal cost of feeds per unit of milk.

Increasing production from 6000 to 9000 kg/cow/yr has a substantial impact on efficiency, which is at least partly why such an increase generally increases profitability. Data recently presented by Luiz Rodriguez (Rodriguez et al., 2012) on the relationships of productivity, feed efficiency, and profitability on commercial California herds supports this. However, unless major improvements occur in the ability of cows to digest feed, or unless our predictions of feed digestion at high intake are very inaccurate, some farms in the US may now be approaching the predicted maximum lifetime feed energetic efficiency of ~25%.

Despite the projection that efficiency may not increase much as milk production surpasses ~15,000 kg/cow/year, profitability should continue to increase with higher production, even after considering that more expensive feeds may be required, because each liter of milk has less nonfeed fixed costs associated with it. At some point, the marginal profitability (i.e., the increase in net income from one additional kg of milk) will become negative, but increased productivity will contintue to enhance profitability on most farms for the foreseeable future. Furthermore, expected increases in environmental regulations will increase capital requirements per cow, putting an even greater emphasis on capital efficiency, and further favoring increased productivity.

Although increased productivity usually increases profitability, formulating diets to achieve maximum milk production is likely not the most profitable—feed costs do matter! With increasing the nutritional quality and cost of a diet, each successive increase in nutrient intake and cost generally results in less milk response, so that production responses follow the law of diminishing returns. Thus, there is usually an optimal nutrient intake or density for maximizing the efficiency and profitability of milk production, and the optimums for efficiency and profits are usually at different points in the milk response curve. For most nutrients except energy, it generally pays to increase the dietary concentration of the nutrient above that at which efficiency is maximized as long as the return from the last unit added exceeds its costs. Some nutrition programs attempt to formulate diets using a mathematical model for profit maximization. However, in real life, it is virtually impossible to accurately predict how a diet will affect appetite, nutrient partitioning, and milk yield and components. Thus, monitoring the actual response is essential for optimal farm management. High milk production is almost always more important for high profitability than is low feed cost, but paying attention to feed costs is still prudent.

REFERENCES

Cai, W., D. S. Casey, and J. C. Dekkers. 2008. Selection response and genetic parameters for residual feed intake in Yorkshire swine. J Anim Sci 86(2):287-298.

Cameron, R. E., P. B. Dyk, T. H. Herdt, J. B. Kaneene, R. Miller, H. F. Bucholtz, J. S. Liesman, M. J. Vandehaar, and R. S. Emery. 1998. Dry cow diet, management, and energy balance as risk factors for displaced abomasum in high producing dairy herds. J Dairy Sci 81:132-139.

Capper, J.L., E. Castaneda-Gutierrez, R.A. Cady, and D.E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. Proc Natl Acad Sci. 105: 9668-9673.

Casper, D. and D. Mertens. 2008. Depression in nutrient digestibility by lactating dairy cows when dry matter intake is expressed as a multiple of maintenance. J Animal Science 86(E-Suppl 2):618.

Hanigan, M. D. , J. P. Cant, D. C. Weakley, and J. L. Beckett 1998. An evaluation of postabsorptive protein and amino acid metabolism in the lactating dairy cow. J. Dairy Sci. 81: 3385-3401.

Huhtanen, P., M. Rinne, and J. Nousiainen. 2008. Prediction of in vivo diet digestibility in lactating dairy cows from data based on values obtained using sheep. J. Anim Sci 86(E-Suppl 2):618.

Kebreab, E., A. R. Castillo, D. E. Beever, D. J. Humphries, and J. France. 2000. Effects of management practices prior to and during ensiling and concentrate type on nitrogen utilization in dairy cows. J Dairy Sci 83:1274-1285.

Moore, S. S., F. D. Mujibi, and E. L. Sherman. 2009. Molecular basis for residual feed intake in beef cattle. J Anim Sci 87(14 Suppl):E41-47.

National Research Council. 2001 Nutrient Requirements of Dairy Cattle. 7th revised edition. National Academy Press, Washington, D.C.

Nkrumah, J. D., E. K. Okine, G. W. Mathison, K. Schmid, C. Li, J. A. Basarab, M. A. Price, Z. Wang, and S. S. Moore. 2006. Relationships of feedlot feed efficiency, performance, and feeding behavior with metabolic rate, methane production, and energy partitioning in beef cattle. J Anim Sci 84(1):145-153.

Nguyen, N. H., C. P. McPhee, and C. M. Wade. 2005. Responses in residual feed intake in lines of Large White pigs selected for growth rate on restricted feeding (measured on ad libitum individual feeding). Journal of Animal Breeding and Genetics 122(4):264-270.

Oltjen, J. W., and J. L. Beckett. 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74:1406–1409.

Rodriguez, L.A., G. Bethard, D. Tomlinson, and M. McGilliard. 2012. Impact of milk yield, herd size, and feed efficiency on economic change between and within California dairies from 2006 through 2010. Abstract. J. Animal Sci. 90(E-Suppl.1).

Santos, F.A.P., J. E. P. Santos, C. B. Theurer, and J. T. Huber. 1998. Effects of rumen-undegradable protein on dairy cow performance: a 12-year literature review. J. Dairy Sci. 81: 3182-3213.

Thomassen, M.A., R. Dalgaard, R. Heijungs, and I. de Boer. 2008. Attributional and consequential LCA of milk production. Internatl. J. Life Cycle Assessment 13:339-349.

VandeHaar, M. J. 1998. Efficiency of nutrient use and relationship to profitability on dairy farms. J. Dairy Sci. 81: 272-282.

VandeHaar, M. J. and N. St-Pierre. 2006. Major advances in nutrition: relevance to the sustainability of the dairy industry. J Dairy Sci 89:1280-1291.

VandeHaar, M.J., D. M. Spurlock, L. Armentano, R. Tempelman, K. Weigel, and R. Veerkamp. 2012. Considerations in using residual feed intake to define feed efficiency in dairy cattle. Abstract. J. Animal Sci. 90(E-Suppl.1).

Veerkamp, R. F., A. R. Cromie, and G. Simm. 1995. Variance-Components for Residual Feed Intake in dairy cows. Livestock Production Science 41(2):111-120.

Veerkamp, R. F. and G. C. Emmans. 1995. Sources of genetic variation in energetic efficiency of dairy cows. Livestock Production Science 44(2):87-97.

Wang, S. J., D. G. Fox, D. J. Cherney, L. E. Chase, and L. O. Tedeschi. 2000. Whole-herd optimization with the Cornell Net Carbohydrate and Protein System. III. Application of an optimization model to evaluate alternatives to reduce nitrogen and phosphorus mass balance. J Dairy Sci 83:2160-2169.