Feeding and Breeding For a More Efficient Cow

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Take-Home Messages

- The efficiency of converting feed to milk has doubled in North America during the past 50 years, largely as a byproduct of selecting, feeding, and managing cows for increased productivity. However, in the future, we must specifically focus on how to get more milk from each unit of feed rather than simply on how to get more milk from each cow.
- Feed efficiency can be defined many ways, from simply considering energy inputs and outputs of the cow to considering all inputs and outputs of the dairy industry on a global scale that impact environmental stewardship. These are generally correlated because higher producing cows use less feed for maintenance.
- Optimal milk production to maximize biological feed efficiency is likely 10,000 to 15,000 kg milk/year for Holsteins that weigh ~700 kg at maturity. However, for profitability, higher production is still probably better.
- Management strategies to feed cows according to lactation stage will enhance efficiency of using feed energy and protein. Nutritionists, however, should not focus too much on efficiency; rather, the focus should be on milk income above feed cost, which requires monitoring farm management and cow responses to diet changes. In addition, farm feed efficiency can be improved by minimizing feed wastage.
- Genomic technologies likely will enable selection of more efficient cows in the future. In the meantime, breeding for small cows might improve efficiency, but if bigger cows produce more milk, they are just as efficient and probably more profitable. We should stop using size as a selection criterion, unless we want uniform body size to fit stalls. Instead we should breed for production, health, and fertility.

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■ Introduction

Feed efficiency, or the efficiency of converting feed to milk, matters on farms because it has a major influence on farm profitability and environmental stewardship in the dairy industry. Dairy feed efficiency in North America has doubled in the past 50 years, largely as a byproduct of selecting and managing cows for increased productivity. Increasing productivity results in a greater percentage of total feed intake being used for milk instead of cow maintenance. Elite dairy cattle in the US currently partition three times more feed energy toward milk than toward maintenance. We are not likely to continue to make major advances in feed efficiency simply by increasing milk per cow. Instead, we also must focus on how to get more milk from each unit of feed.

■ How Should We Define Feed Efficiency?

The simplest way to define feed efficiency is milk per unit feed, but this does not give adequate consideration to energy density of different feeds in a diet and the composition of milk, nor to gains or losses in body energy. Thus, I prefer to discuss the efficiency of converting feed energy to the energy of milk and body tissues.

Gross energy (GE) is the total chemical energy of a feed and is independent of how efficiently the cow uses it. Not all GE is useful because some of it is not digested but rather is lost as fecal energy. Some digested energy is lost as gaseous energy, primarily methane produced during fermentation, and as urinary energy, primarily urea produced to remove extra nitrogen from the body. Digested energy also is lost as heat associated with the metabolic work of fermenting, digesting, and processing nutrients. The remaining energy is known as net energy (NE; see Figure 1). Some NE is used to support maintenance functions and is all lost as heat. Some NE is the chemical energy of secreted milk and accreted body tissue and conceptus. Energetic efficiency is the energy captured in products divided by the energy consumed by a cow in her lifetime.

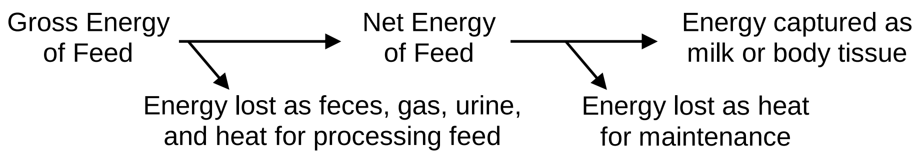

Figure 1. Flow of feed energy consumed by a cow.

At the farm level, efficiency also should account for feed wastage and the saleability of products, as well as the economic value of feed and milk components. To define efficiency on a global scale, we should consider inputs and outputs of fuels and greenhouse gasses, land use, effects on native ecosystems, and whether foods could be consumed directly by humans. For this paper, however, I will discuss mostly energetic efficiency.

■ Level of Production and Feed Efficiency

The major factors that affect feed efficiency on farms include a) milk energy yield relative to cow body weight (BW), b) the percentage of lifetime a cow spends in lactation, c) nutritional accuracy in feeding, and d) the efficiency of converting feed GE to NE.

A cow's maintenance requirement is considered to be constant and related to its BW. The typical Holstein cow has a maintenance requirement of ~10 Mcal of NE/day (equivalent to ~25 Mcal of GE and 14 kg of feed). If a cow eats at maintenance and produces no milk, her feed efficiency is 0%. Any extra feed can be converted to milk or body tissues. If the cow eats twice as much feed—20 Mcal NE or 2X maintenance, only half of her feed would be used for maintenance with the remaining half used for milk. As she eats more feed, the portion used for maintenance becomes a smaller fraction of total feed intake; this "***dilution of maintenance***" increases efficiency. However, as intake increases, the marginal increase in efficiency from diluting maintenance diminishes with each successive increase in feed intake. For example, the increase in efficiency is less going from 3X to 4X maintenance than from 2X to 3X (solid line, Figure 2). Furthermore, as cows eat more, the percentage of feed that is digested is depressed. At high intakes, the digestibility depression may even outweigh the dilution of maintenance and efficiency may decline with increased intake. In fact, according to the equations used in the NRC (2001), efficiency peaks at ~4X maintenance intake (dotted line, Figure 2), which is ~45 kg milk (3.5% fat) per day for a 680 kg cow.

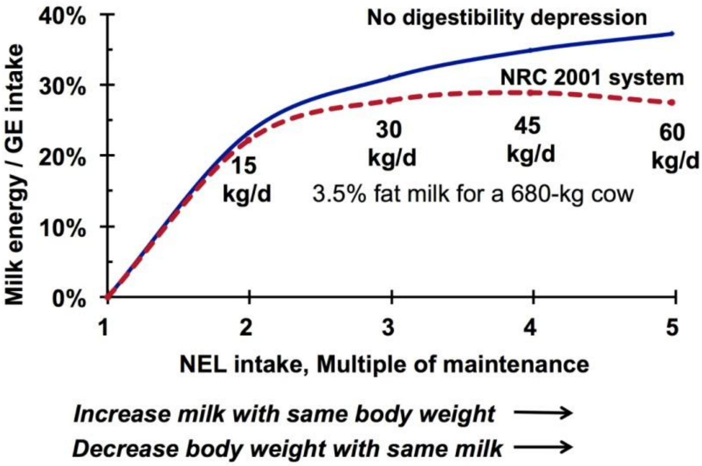

Figure 2. Efficiency (assuming no change in BW) in response to intake for a lactating cow with no change in digestibility (solid line) or with digestibility depressed as per the NRC 2001 system (dashed line).

The digestibility depression is not well quantified for cows consuming >4X maintenance (VandeHaar, 1998), and NRC (2001) likely depresses digestibility too much. Current data from our USDA feed efficiency project support the idea that the true change in efficiency is somewhere between the two lines of Figure 2. In any case, at about 4X intake, feed efficiency is close to maximum. Elite cows (>4X, or 13,000 kg/305-day lactation) are already near, at, or possibly above the optimal multiple of maintenance for maximal efficiency.

Feed efficiency at the herd level requires accounting for body tissue gain and the feed consumed by heifers and dry cows, which is 15-30% of the feed a cow eats during her lifetime. Thus, cows that average 4X intake during lactation are about 3X on a lifetime basis. The average Holstein in North America currently produces ~10,000 kg milk/year and captures ~21% of her lifetime GE intake as milk and body tissues. Many top US herds produce 15,000 kg/year and therefore are getting close to maximum biological efficiency based on multiples of maintenance. Given that 2/3 of North American Holsteins are from AI sires, the limitation to greater production and efficiency for most cows is probably feeding and management. Therefore, we are not likely to continue to make major advances in feed efficiency by simply breeding for increased milk yield relative to BW. We must do a better job of managing the cows we have to increase production and efficiency, but we must focus more on efficiency in breeding.

Importantly, the impact of multiples of maintenance on efficiency is likely the same whether we achieve more milk at a specific BW, or the same milk with smaller BW. Breeding for smaller cows is probably not going to help much, which will be discussed later.

Level of production also alters profitability and the efficiency of using human-consumable foods, on land use, and on greenhouse gas emissions.

Profitability

Because greater milk yield per cow increases feed efficiency, and because feed is a major farm expense, greater production per cow generally increases profit per cow. Data from commercial farms bears this out (Rodriguez et al., 2012). However, feed efficiency is only one factor that influences profitability. Greater production per cow decreases the proportion of total farm expenses that are fixed; 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. More importantly, the cost of feed does matter! Using expensive feeds to achieve high production or high feed efficiency will sometimes decrease profitability.

Use of Human-Consumable Foods

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). This is because cows eat many feeds that humans do not consume; examples include cottonseeds, soyhulls, and distillers grains. However, these fibrous by-product feeds are generally less digestible than grains and may limit the ability of cows to produce the highest levels of milk. Thus, maximizing total feed efficiency will not be possible at the same time as maximizing efficiency of human-consumable foods. As competition for food grains increases in the future, the ability of cows to convert non-human-consumable foods into milk and meat for people will become more important, and the optimal level of production might be less in the future than it is today. At present, however, using by-product feeds extensively for heifers, dry cows, and late lactation cows and thoughtfully for cows in early lactation should enhance efficiency of total feed and human-consumable foods.

Land Use

Using land to produce grains and legume seeds for direct human consumption would be the most efficient way to feed people. Using land to grow feeds for dairy cattle producing 10,000 kg/year results in only half as much food for people (VandeHaar and St-Pierre, 2006). However, milk output per acre increases with greater milk production per cow. More importantly, if by-product feeds make up 1/3 of the feed used by a dairy herd producing 15,000 kg/year, then using land for milk production yields 90% as much food for humans as do grains and legumes. In my opinion, an efficient dairy industry will be part of our food production system long into the future.

Environmental Stewardship

To properly consider environmental impact, 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/year for the conventional farms and 6100 kg/year for the organic farms. When considering all inputs (which included feeds being shipped in from outside the country), conventional farms used 60% more energy and caused 50% more eutrophication per kg of milk produced, 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. This is consistent with a study by Capper et al. (2009) showing that in the last 60 years, the US dairy industry has decreased greenhouse gas emissions by 60% per kg of milk produced, mostly because of the enhanced feed efficiency from higher productivity. Thus, increased productivity (up to 4X) increases efficiency, and increased efficiency generally is good for the environment - we can feed more people with less resources and less negative environmental impact. Improving efficiency of meat and milk production by using new technologies seems the responsible thing to do for the environment, at least in the foreseeable future, until average milk production exceeds 15,000 kg/year.

■ Management to Improve Feed Efficiency

The average Holstein currently produces about 10,000 kg milk/year and captures ~21% of her lifetime GE intake as milk and body tissues. Feed efficiency likely plateaus at about 15,000 kg milk for cows with mature BW of 700 kg, so increases in productivity will continue to improve efficiency for most North American dairy farms. Using a model described in VandeHaar (1998), the impacts of various management changes on efficiency were predicted. Increasing average daily milk production by 10% increases lifetime energetic efficiency 0.7%. Increasing cow longevity from 3 to 4 lactations, reducing the age at first calving from 26 to 22 months, or reducing calving interval from 14 to 12.5 months could achieve similar improvements in lifetime efficiency. Thus, how we feed and manage cows at each stage of life can increase milk yield per day of life, thereby diluting maintenance, and increasing efficiency. These management changes promote similar improvements in the efficiency of converting feed protein to milk or body protein. However, the single biggest impact farms could make on efficiency of protein use is to simply quit overfeeding protein, as is often done in late lactation. Feeding cows past 150 days postpartum a diet with 2 percent less protein (15 vs 17% CP) would increase efficiency of protein use by 1.3%.

One often-overlooked management aspect of feed efficiency is feed management. The amount of feed wasted on some farms is considerable. To minimize feed wastage requires an annual evaluation of procedures for harvesting, transporting, and storing feeds, mixing diets, and managing bunks. However, when managing bunks, it is important to remember that maximizing feed intake for lactating cows increases milk per cow and farm-wide efficiency. 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 per cow overall will yield improved efficiency, profitability, and stewardship.

▪ Feeding Cows for Greater Feed Efficiency

Nutrient requirements vary as lactation progresses, and the optimal diet for maximum efficiency and profitability changes as well. Most farms 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; this is especially true if all lactating cows (other than perhaps the fresh cows) are fed the same TMR. Feeding a single TMR across lactation can never maximize production and efficiency. A single TMR is usually formulated for the higher producing cows and is more nutrient-dense than optimal for cows in later lactation, resulting in inefficient use of most nutrients (for example, protein). In addition, although a single TMR is formulated for the high producers, it likely will not maximize milk for the herd. 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 for fresh cows and would promote 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. Consequently, cows culled in single TMR situations may be those that cannot adapt to suboptimal management, rather than those that are least efficient, productive, and profitable. Moreover, single TMR systems do not allow maximum returns from 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. Cheap by-product feeds are especially useful in late lactation to improve profitability and overall efficiency of the dairy industry. One argument used by farms 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 (examples include days in milk, stocking density, and cow social interactions), and we are quick to notice temporary drops in production.

The number of rations on any farm depends on many factors, but I recommend at least three based on feeding goals (Figure 3). Fresh cows should be fed for optimal health and expensive supplements are warranted. Cows in peak lactation should be fed for maximum milk; because their intake is limited by rumen fill, they should be fed minimum fiber diets with plenty of digestible starch to maximize energy intake. Cows in late lactation should be fed to optimize milk and body condition; they should be fed less fermentable starch to increase gut fill and more fermentable fiber to promote partitioning of nutrients toward milk instead of body tissues and thus minimize fattening. The decision on when to switch cows from the early to late lactation diet should be based on body condition, as well as on parity, milk yield, and reproductive status. Once a cow attains a body condition score of 3, she should be moved to a diet with lower energy density. In addition, late lactation cows should be fed lower protein diets to maximize efficiency of protein use. Expensive supplements are most useful in early lactation. Cheap feeds are best used in late lactation.

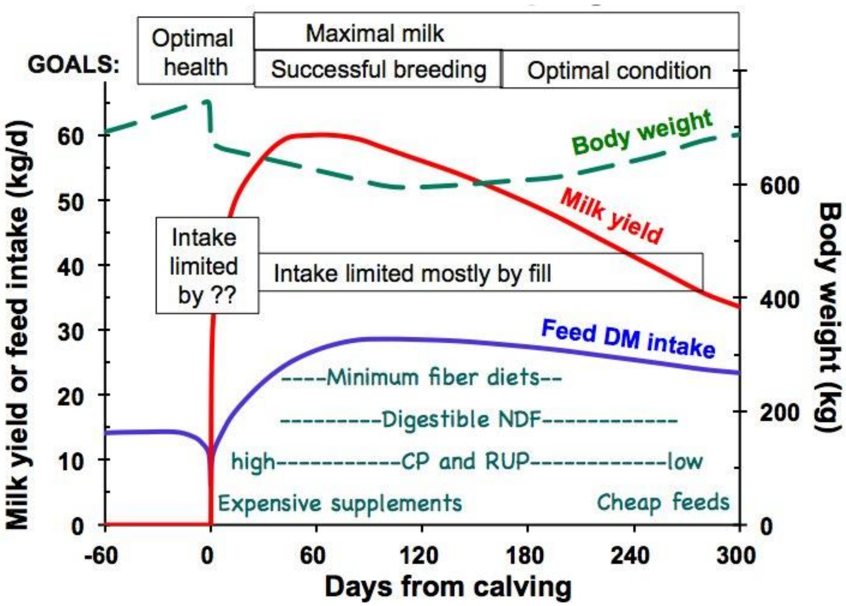

Figure 3. Considerations in nutritional grouping.

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. Moreover, feeding cows according to requirements enables feed allocation to maximize production and profitability, improves efficiency of protein use, decreases nitrogen and phosphorus excretion, and improves sustainability of the industry. If you currently feed a single TMR, I encourage you to seriously consider how you can make this work. Even small farms can devise creative methods to feed cows according to requirements. One approach might be to feed cows different supplements individually using a computerized feeding system that recognizes cows electronically and dispenses specific grain mix supplements at timed intervals throughout the day. More starch and protein could be fed to early lactation cows. More high fiber byproducts could be fed to late lactation cows.

Although poor feed efficiency usually decreases profitability, maximizing efficiency will not necessarily maximize profitability—feed costs do matter! Expensive energy sources like fats usually improve feed efficiency but sometimes decrease profitability. Cheap bulky feeds may decrease efficiency but improve profitability (especially in late lactation). Feeding extra protein usually decreases efficiency of protein use but sometimes, even if the protein is expensive, it might improve profitability if it enhances production. 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 production is almost always more important for high profitability than is low feed cost, but managing feed costs is still prudent.

■ Selecting Cows For Greater Feed Efficiency

In the past, genetic selection for milk production traits has relied heavily on quantification of the phenotype in daughters of young sires; sires with outstanding daughters are deemed genetically superior. Although milk production traits are routinely measured on many commercial farms, feed intakes of individual cows are not known. Thus, we have not been able to directly select cows for feed efficiency. Genomics may enable selection for feed efficiency in the future.

Genomic selection has already been embraced by the dairy industry as a means to more accurately find superior bulls at an earlier age. The basic idea of genomic selection for feed efficiency is that there is something inherent in a cow's DNA that makes her more or less efficient at converting feed to milk. A single nucleotide polymorphism (SNP) is a single base that varies frequently in the population and each SNP represents a whole segment of DNA. Specific SNPs might be associated with improved efficiency and thus serve as markers for efficiency. Each SNP by itself may not have a strong relationship to feed efficiency, but combining information from thousands of SNPs across the genome might be useful, as has already been proven for other traits in cattle.

Through a grant from the National Institute of Food and Agriculture of USDA, we currently are determining if SNP genotypes can be used to improve feed efficiency. We are measuring individual feed intakes, BW, and production data on 8000 cows in research dairy herds from several countries. Our goal is to characterize the relationship of SNP genotype to feed efficiency in our reference population of 8000 cows and then to use SNP genotyping to identify potential sires that should confer higher feed efficiency to their offspring. Some information on our project can be found at www.dairy-efficiency.org/ or you can search the USDA web site.

Ideally, we would measure feed efficiency on thousands (>20,000) of animals over their lifetimes, and we would employ methods to measure all losses of chemical energy in feces, gas emissions, and urine as well as all heat lost, combined with metabolic data, and diverse diets and environments, to understand why some cows are more efficient than others and how genetics interacts with diet and other environmental factors; however, that is cost-prohibitive and impractical. Instead, we are assessing feed efficiency in cows for >30 days (usually >60 days) between 50 and 200 days postpartum, with some cows observed for more than one lactation and on multiple diets. As mentioned earlier, we already know that higher milk yield per day dilutes maintenance and improves efficiency up to 4X intake. Our goal in this project is to find cows with a better ability to digest feed or convert digested feed to net energy or with a lower than expected maintenance requirement. To assess feed efficiency independent of production level, we will use residual feed intake (RFI), which is a measure of actual versus predicted intake for an individual (Figure 4). Predicted intake is 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). Two other large USDA-funded projects are using RFI to improve efficiency in beef cattle and swine.

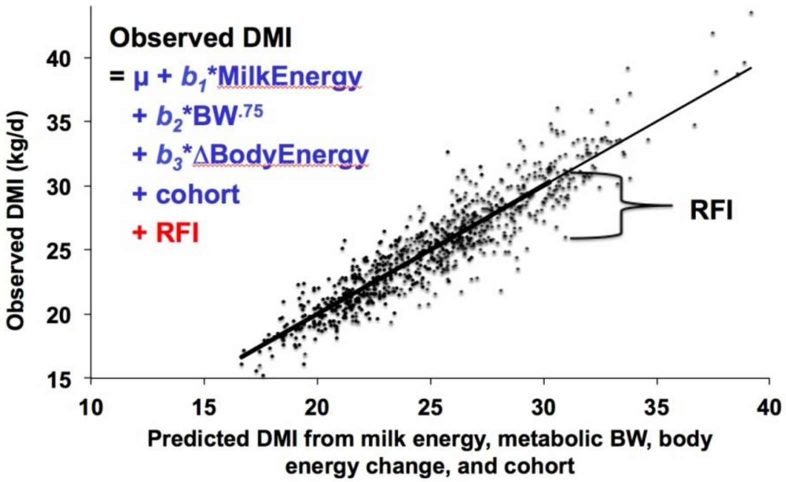

Figure 4. Residual feed intake (RFI) as a measure of feed efficiency (DMI = dry matter intake).

Our initial analyses for dairy feed efficiency are based on 4300 Holstein cows in the US, Scotland, and the Netherlands. Weekly DMI was fitted as a function of milk energy output, body weight to the 0.75 power, body condition score, change in body weight, parity, and the interaction of parity with days in milk. The residuals from this analysis provide us with a measure of RFI for each cow with the RFI term representing measurement error, variation associated with pedigree-based genetics, and other variation. Based on these data, the heritability of RFI in lactating cows is ~0.18. Previous studies, using small numbers of cows, reported values of 0.01 to 0.40 for the heritability of RFI in lactating cows (Berry and Crowley, 2013; Connor et al., 2013).

If selection for efficiency is to be realized, it is important that RFI is a repeatable trait. Our project will examine this more fully, but preliminary results from our lab and others are promising. We fed ~100 cows diets with

~14% or 30% starch in a cross-over design and found the correlation for RFI of a cow when fed a high starch diet with RFI when fed a low starch diet to be 0.7. Based on our preliminary data and others, RFI also seems to be repeatable across lactations, stages within a lactation, and stages of life (Burczynski et al., 2013; Connor et al., 2013; MacDonald et al., 2013).

Genomic selection for efficiency likely will be possible within 2 to 3 years. What measure of efficiency will be used to represent the amount of feed consumed in a breeding index is not yet decided, but it is important to note that RFI is only part of feed efficiency. Selection for optimal levels of milk production relative to body weight so that the percent of feed used for maintenance is also a key to overall farm efficiency. Moreover, 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.

Until direct selection for efficiency is possible, some have suggested we breed for smaller cows to minimize maintenance. Selecting for both high milk and small body size should enhance lifetime milk per unit feed and therefore decrease the percentage of feed used for maintenance. One problem with this approach is that once a cow is above 4X maintenance intake, we cannot predict how efficiency changes as cow size decreases (see Figure 2). More importantly, however, breeding for smaller size lessens our ability to select for traits we know to be profitable, such as milk income, health, and fertility.

Table 1 shows possible results of breeding for smaller size or for more milk in a herd that currently has large cows (800 kg mature BW) and milk production at 13,070 kg/year at maturity. The magnitude of change for each breeding scenario was chosen to give the same effect on efficiency as lifetime multiple of maintenance. Note that achieving 15% smaller BW increases lifetime income over feed cost by $310 USD per year, because of lower maintenance requirements. In contrast, achieving 11% greater milk yield increases lifetime income over feed cost by $1230 USD because of greater milk income.

Table 1. Possible results from breeding for size instead of milk[1]

	BW at maturity kg	Lifetime multiple of maintenance	Milk yield at maturity kg/year	Lifetime income over feed cost[2] $USD
Current cows	800	2.8	13,070	$8460
Select for size	680	3.0	13,070	$8770
Select for milk	800	3.0	14,530	$9690

[1]Assumes milk is 3.5% fat.
[2]Assumes milk at $0.40/kg, cull cows at $0.80/kg, and feed at 15¢/Mcal NE (~25¢/kg) for lactating cows and 12¢/Mcal NE for heifers and dry cows.

In our data, we find very little phenotypic or genetic relationship between BW and feed efficiency. The average mature cow in our study weighed 670 kg, ate 23 kg DM/d, and produced 36 kg of milk, so she was producing at 3.7 multiples of maintenance. Bigger cows within each parity produced enough extra milk so that efficiency was the same as for smaller cows. With the current milk and feed prices, the bigger cows producing more milk would be more profitable, unless they had poorer health or fertility or did not fit in the stalls! In my opinion, we should stop using size (big or small) as a criterion in sire selection, unless the goal is to have cows of a uniform size to fit stalls; instead, choose sires to produce healthy, fertile cows that give more milk income!

▪ Conclusion

We have made major gains in feed efficiency in the past 50 years as a byproduct of selecting, feeding, and managing cows for increased productivity. Improvements in management and feeding that increase milk yield to ~15,000 kg/year will likely continue to improve efficiency. However, most cows have the genetics for high production already; genomic tools should enable us to directly select for feed efficiency in the future. Greater efficiency will improve profitability and environmental sustainability, but continued focus on production, health, and fertility will still be important for farm profitability.

▪ References

Berry, D.P., and J.J. Crowley. 2013. Genetics of feed efficiency in dairy and beef cattle. J. Animal Sci. 91:1594-1613.

Burczynski, S.E., J.S. Liesman, R.J. Tempelman, J.C. Ploetz, M.S. Allen, A.L. Lock, and M.J. VandeHaar. 2013. Residual feed intake is repeatable when high and low starch diets are fed to lactating Holstein dairy cows. J. Dairy Sci. 96(E-Suppl.):397.

Capper, J.L., R.A. Cady, and D.E. Bauman. 2009. The environmental impact of dairy production: 1944 compared with 2007. J Animal Sci. 87:2160-2167.

Connor, E.E., J.L. Hutchison, H.D. Norman, K.M. Olson, C.P. Van Tassell, J.M. Leith, and R.L. Baldwin VI. 2013. Using residual feed intake in Holsteins during early lactation shows potential to improve feed efficiency through genetic selection. J. Animal Sci. 90:1687-1694.

MacDonald, K.A., J.E. Pryce, R.J. Spelman, S.R. Davis, W.J. Wales, G.C. Waghorn, Y.J. Williams, L.C. Marett, and B.J. Hayes. 2013. Holstein-Friesian calves selected for divergence in residual feed intake during growth exhibited significant but reduced residual feed intake divergence in their first lactation. J. Dairy Sci. 97:1-9.

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

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).

Tempelman, R., R. Veerkamp, M. Coffey, D. Spurlock, L. Armentano, K. Weigel, Y. de Haas, C. Staples, M. Hanigan, and M. VandeHaar. 2013. Heterogeneity across research stations in genetic variation and energy sink relationships for feed efficiency in lactating dairy cattle. J. Dairy Sci. 96(E-Suppl.):389.

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.