# CONSIDERATIONS FOR IMPROVING FEED EFFICIENCY IN DAIRY CATTLE

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## SUMMARY

Feed efficiency is an elusive concept with multiple definitions. We have made tremendous progress in gross feed efficiency by selecting for increased milk yield. Yield expressed as a multiple of maintenance is an important determinant of gross efficiency below 5x maintenance levels of production, and can be achieved by increasing yield with constant body size and maintenance requirement, or decreasing body size and maintenance requirement while maintaining production. At higher ratios of milk yield to maintenance, direct selection for improved marginal efficiency may be more important for improving gross efficiency. Genomic tools, combined with direct measure feed efficiency phenotype in a large sample of cows, provides a way to select future sires for improved marginal feed efficiency. In addition, data collected broadly on feed efficiency phenotype will allow us to test our current theories on how body size affects maintenance costs and feed conversion efficiency in modern Holsteins. Other management techniques that increase the ratio: use of feed for milk/herd maintenance use; are also important. In addition N efficiency can be increased (and inefficiency and waste decreased) using current knowledge and more precise feeding of multiple rations throughout lactation, but implementing management of cows, labor and information present some obstacles to implementing grouping and group specific feeding on all farms.

## INTRODUCTION

Intensive selection of sires is possible by using artificial insemination; coupled with accurate measurement of a potential sire's genetic value, this has markedly improved genetics for easily measured traits like milk production and type traits. Increased milk production has in turn increased gross feed efficiency through dilution of maintenance. Additional genetic gains in feed efficiency would likely be possible if feed efficiency phenotypes were widely available, but this data is virtually impossible to collect in the field, especially for cows fed in groups. Genomic information may make a more limited (but still large) data set of phenotypes useful in identifying sires capable of transmitting improved feed efficiency.(Connor et al., 2012)

Gross feed efficiency is some ratio of feed required to produce a certain amount of milk. Sounds simple, but it is not. How we define milk outputs and feed inputs leads to many different definitions of feed efficiency, many of which have different utility. Milk output (yield) can be defined in many ways: milk volume, milk fat pounds, milk protein pounds, cheese yield potential (which in fact varies depending on what cheese you are making!), milk energy, etc. Probably milk dollars makes the most sense, but this obviously involves regional and temporal market fluctuations as much as it involves the underlying biology. Likewise, feed inputs can be defined in multiple ways: mass of dry matter, Mcal gross energy, predicted Mcal of DE (or ME or NE) estimated from combining some ration model with chemical composition, etc. Once again dollars of feed might be the best, but least definable input. Even if we decide to use dollars for feed costs, many dairy farms raise part of their feed so we would need to decide if we charge the market price (opportunity cost) or the real cost of production. The former probably makes more sense so as not to confuse the dairy enterprise with the feed enterprise, but given that land for animal waste recycling is required for the dairy enterprise, and these animal 'wastes' contain fertilizer value useful to the feed production enterprise, it is not clear how to account for these synergies and separate these enterprises. So defining feed efficiency in an economic form is difficult, and not constant. It involves fluctuating market conditions, and involves biological issues related to feed production as well as to manipulations of cattle biology and herd structure. This review will focus on animal biology, but it is important to acknowledge the broader definitions of feed efficiency when interpreting this biology.

## Cow efficiency or Herd efficiency

We can define feed efficiency at a level that includes feed production operations (for feed produced on and off the farm), we can limit it to the animals in herd (replacements, dry cows and lactating cows), or we can simply consider the milking cows. It takes a herd of cows to produce milk, so the feed used to raise replacements to mature weight and maintain dry cows is part of the feed input. These can be thought of as herd maintenance costs and are in addition to feed used to maintain cows while they are lactating. Most dairy systems are dual purpose with an income stream from salvage value of cows at the end of their productive life. Therefore, the feed used to raise replacements to mature weight cannot simply be charged to milk production as much of this input is eventually recuperated in salvage value. Without doing a formal review of this, even after crediting for cull cow salvage value, a small portion of feed used to grow dairy cows to mature size contributes to the herd maintenance ledger for milk production. For a rough calculation, let us say we raise a heifer to a post calving weight of 1370 lbs at 24 months, at a roughly average daily feed cost of $2.00/day. That live body weight gain is 1300 lbs if she weighed 70 lbs at birth. So each pound of live weight gain eventually sold for cull purposes cost us about $0.89. Cows continue to grow to mature size over the first lactation or two, but assume that cost is about the same per pound of gain to mature weight. Recent culls from the UW herd were getting about $0.70 per pound of live weight (a good price considering we get nothing for culled Professors!). In addition feed costs are incurred several years before cull price is received, and the calculations above do not discount for that time value. At these cull prices, feed costs to grow replacements to mature size would have to be less than $.70/pound live weight gain before we could consider feed used in raising heifers to actually reduce herd maintenance costs. If these calculations are the similar for cows of all final mature size, then producing larger animals will not produce 'profit' in the growing phase of the dairy enterprise, and will in fact virtually always add to the herd maintenance costs. One simplification could be to assume approximately all the costs required to raise a replacement to her first calving are recovered in salvage value, and remaining growth (from weight after first calving to final mature slaughter weight), can be considered part of herd maintenance.

This has an important impact when we consider mature size and animal daily maintenance. Even if salvage cost offset total feed used for gain, it costs more feed to maintain a larger animal during lactation and dry periods. If this increased maintenance cost is not offset by additional milk yield, then feed efficiency would be lower for a larger cow, on a herd basis, annual basis, or just over the active lactation period.

## Environmental concerns and efficient use of feed energy vs. feed N and P

Environmental concerns exist surrounding nitrogen, phosphorous, and methane emissions from dairy herds. Using less feed inputs per unit of milk (and meat) output usually means that we generate less waste N, waste P and less methane per pound of milk produced (VandeHaar and St-Pierre, 2006, Capper et al., 2009, Yan et al., 2010). In addition efficient use of different nutrients is not necessarily optimized simultaneously. For example, if we select a group of animals to use less mass of feed per pound of milk, they may have a different optimum P or N concentration in their diets and we could adjust for this. Protein metabolism cannot be separated from energy metabolism, either pre-absorption or post-absorption, so efficiency of use of non-energy nutrients is intimately tied with use of feed energy and feed dry matter. The good news is that in general, higher feed efficiency is both profitable and environmentally beneficial, so many environmentally sound practices may be adopted for purely market driven reasons, which could reduce the requirement for regulation and enforcement.

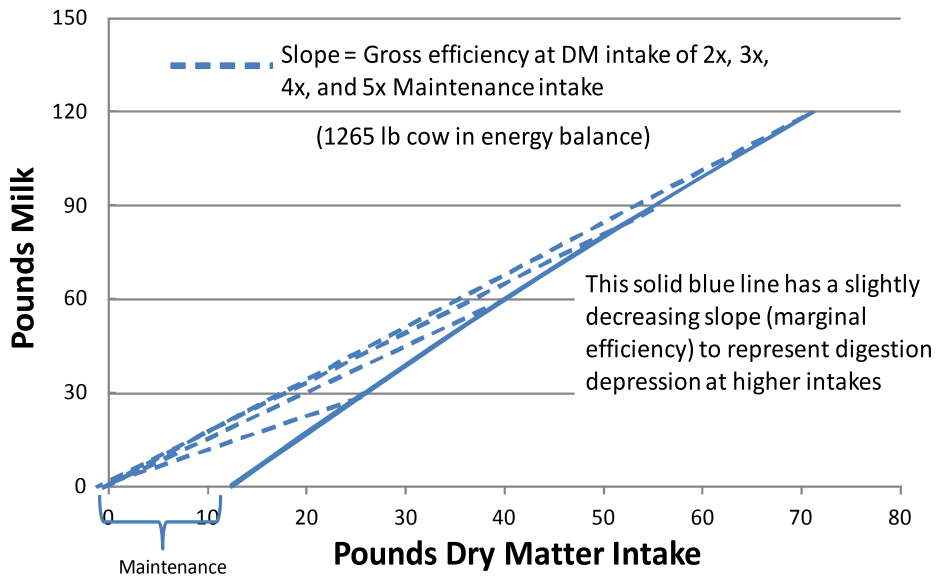
Energetic efficiency and efficiency of use of N or P are quite different. All inputs (g N, g P, Mcal) eventually become outputs, either as a useful product or waste. But most of our experience ties intake of feed energy closely to diet energy content and animal energy output. Certainly dairy cows lose body energy to support milk production and can gain excessive amounts of body condition, but over the long term energy intake will equal energy output determined largely by production and standard maintenance costs. Therefore, we increase N or P intake by increasing their concentration in the diet. If energy is in excess relative to other nutrients (or N and P are deficient relative to energy), we do not think that cows turn on some sort of heat pump to shed extra energy so they can eat more without gaining weight. There are clear mechanisms in place to excrete excess nitrogen and excess phosphorous when the intake of N or P exceeds the requirement. In short, nitrogen and phosphorous efficiency can be reduced by feeding in dietary concentrations in excess of the requirement. As the requirement for nitrogen changes throughout the lactation cycle, nitrogen efficiency is definitely susceptible to improvement by more precise delivery of high protein diets to cows with greater productivity in early lactation, and lower protein diets to cows in later lactation.

Another important difference between N efficiency and energy efficiency is that it is clear that optimal N gross efficiency (Milk N yield /N consumed) is achieved at dietary protein concentrations that yield less than maximal milk. However, it is almost always desirable to feed adequate protein for maximal milk production, so ‘suboptimal’ N efficiency is almost guaranteed (Metcalf et al., 2008). In addition, we generally feed a safety margin so that diets usually contain higher N density than required to maximize milk yield in order to account for variance in cow groups and uncertainty in diet make up. However, minimizing how much safety margin above the N actually required we feed is one way to increase N efficiency.

## Gross vs. marginal efficiency

Marginal feed efficiency, and the degree of dilution of maintenance, are the two factors that determine gross efficiency. Fixed cost and marginal costs are fundamental aspects of economics. In animal production we have herd maintenance costs consisting of the daily maintenance of a dry or lactating cow, and some small portion of growth feed costs that are not recovered as salvage value. Marginal (or net or partial) efficiency refers to the increased yield of milk we get for each additional input of feed. Traditionally this was considered fixed from below maintenance through maximum milk. This meant that the first pound of feed used for milk production gave us the same milk as the last pound. Again this is quite different than how we view protein concentration adjustments. The NRC dairy system (2001) invoked an increasing depression in DE Mcal/kg feed with increased intake above maintenance. This later adjustment means that use of NEl for milk has a constant marginal efficiency (always 100%), while use of dry matter or feed gross energy has a decreasing marginal efficiency because each increment of feed results in a lower NE concentration and therefore a smaller increment in NE intake. In either case though (constant or falling marginal efficiency), the fixed cost of maintenance has a negative effect on gross efficiency. This negative effect of maintenance decreases as production increases with fixed maintenance. As reviewed by Bauman et al. (1985), essentially all the progress made to improve the gross feed efficiency of dairy cows has come from increased milk production with unchanged marginal efficiency. The dilution of maintenance explains why a cow with twice the production of a similar cow with the same maintenance cost has higher gross efficiency. When marginal efficiency is constant, this increase in gross efficiency continues to grow, but it grows less with each increment. In figure 1, milk yield is the Y axis and intake the x axis, so a steeper slope is more efficient. Production can be measured as increments of maintenance cost. In this case a cow at 2x maintenance is eating twice what she ate at maintenance. At 3x (maintenance +2x maintenance) we attribute 2/3 of her feed for milk and 1/3 for maintenance. The production increases we have seen in the last fifty years are in this range where dilution of maintenance costs causes a marked improvement in gross feed efficiency. As we approach 4x and 5x maintenance the dilution effect diminishes even with fixed marginal efficiency. If marginal efficiency decreases (for example due to digestion depression with greater intakes) as shown by the slightly convex solid line in figure 1; then it is possible for gross efficiency to become nearly unresponsive to increased production above production levels of about 5x maintenance. This means that while much progress has been made by increasing production, it will certainly be less in the future with even the same rate of increase in productivity relative to maintenance (Bauman et al., 1985, Vandehaar, 1998, VandeHaar and St-Pierre, 2006). Increased production can occur because lactation daily yields rise within the same lactation length, shorter lactations reduce the number of low yield days, or more persistent lactations are achieved with the same peak milk yield. All of these increase milk yield relative to maintenance cost, whether maintenance includes only days when cows are in milk, or includes maintenance during days dry as well.

Figure 1: Relationship of gross efficiency (slope of dashed lines) to marginal efficiency above maintenance (solid line). Gross efficiency increases as production increases as multiple of maintenance. The increment in gross efficiency is less with each subsequent multiple of maintenance, even if marginal efficiency has a constant slope. In the figure above, marginal efficiency decreases with intake (solid line curves downward); therefore, increments in gross efficiency become even smaller with each increment of maintenance.



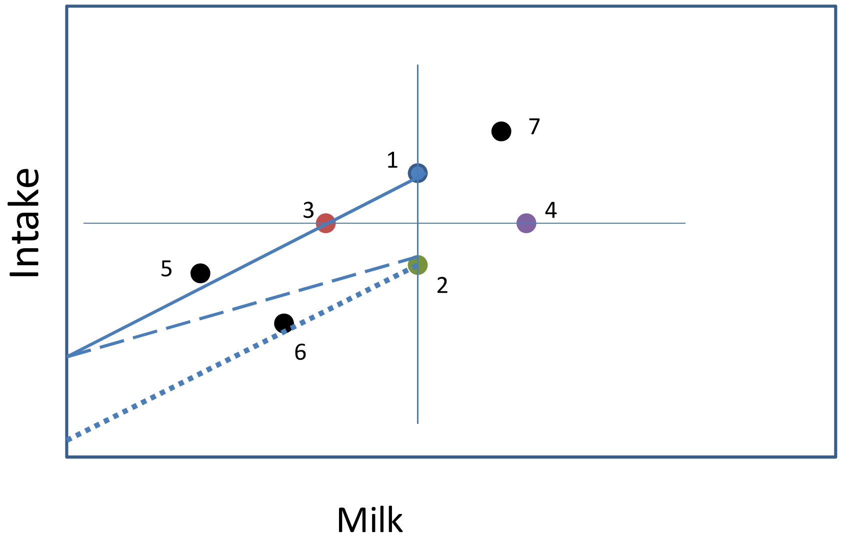
Discussing productivity in terms of multiples of maintenance is useful, but not common. Mostly we focus on absolute milk yield in estimates of herd productivity with no reference to maintenance costs. Another way to view this relationship is that at a fixed level of milk, if we reduced maintenance costs, then we would also increase gross efficiency. One predictable way to reduce animal maintenance cost (both during lactation and dry period) would be to have a smaller animal. Alternatively an animal with less NEm requirement per unit metabolic body weight (MBW or $BW^{.75}$) would do the same if we knew how to achieve that. In one way having a shorter dry period, or fewer dry days per a given lifetime milk production, is also a way to reduce maintenance cost. In reality the maintenance cost is not just the daily maintenance cost during lactation, but should also include and amount for maintenance during the dry days which are about 1 sixth of a mature cows life cycle. So if we are at 5x maintenance for the lactating cows, we are actually at some lower multiple if we include these additional herd maintenance feed costs. Shorter dry periods, with lactation cycles of constant length and milk yield, reduce this part of maintenance. Smaller cows reduce daily maintenance for both lactation days and dry days. Again, these decreases in maintenance costs at fixed absolute milk yields make less maintenance energy to dilute, so gains from this approach to improving gross efficiency should decrease to a very small value as animals pass production levels of 4x to 5x maintenance.

Maintenance is a useful concept, but defining the maintenance cost for an animal that is not at maintenance is anything but simple or obvious. We think about an animal as first meeting her maintenance requirement, then using extra feed above this requirement for milk. Cows don't really do this, do they? They really don't maintain themselves in early lactation because they lose weight and body energy. It is important to know that maintenance is usually defined as how much the animal needed to eat to just maintain itself, <u>when</u> it was just maintaining itself. So think of an animal that is eating at 4x maintenance (but the same diet as she ate when just at maintenance) and its feed digestibility is reduced from TDN1x to TDNp. Since the animal really needs the same amount of TDN (or DE or NE) for 'maintenance', this means to consume its maintenance level of digestible or net energy intake in Mcal, it increases its maintenance requirement in units of pounds DM of that feed. Therefore, multiples of maintenance could be defined in different ways. The discount factor shown in the NRC (2001) software is based on the equation: (TDN1x * feed intake during lactation)/pounds TDN1x required for maintenance; so essentially it is: total feed intake at production/ feed intake at maintenance. This is a larger number than (amount of feed used for production + maintenance)/feed eaten at the production level but required to meet maintenance energy needs (because energy content of the diet decreases above maintenance). This multiple of maintenance could also be determined as (NEm required + NEl required)/NEm required. In short, maintenance is a real thing at maintenance, but for a productive animal it is really an imaginary concept that can be defined multiple ways. But it is still a critical aspect when defining efficiency.

## Residual feed intake as a measure of marginal feed efficiency

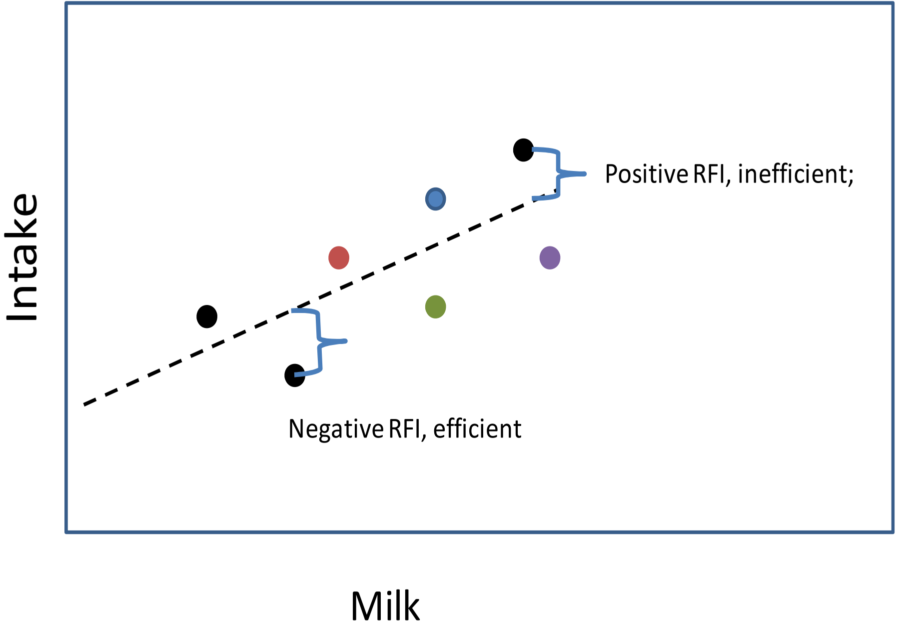
Figure 2 plots intake on the Y axis and milk production on the x axis (reverse of figure 1). For now, imagine all these cows are in energy balance, neither losing nor gaining weight. If you look at figure 2, it is easy to compare certain cows with each other. For 2 cows producing the same amount of milk (on same vertical axis), the one eating less (cow 2) is more efficient than the one eating more (cow 1). Cow 2 could be more efficient because she has a smaller maintenance requirement and the same marginal efficiency as shown in the dotted line, or the same maintenance requirement, but better marginal efficiency as shown by the dashed line (which in this plot is a shallower slope). Obviously it could be any combination of the two as well. Likewise it is easy see cow 4 is more efficient than cow 3, and hopefully even easier to see cow 6 is much more efficient than cow 5. But what about cow 6 vs. cow 7? Cow 7 makes more milk but uses more feed. We can calculate gross efficiency and make that comparison, but it would be simpler to compare them at the same level of milk

Figure 2: Note intake is now on vertical axis and milk on horizontal axis, so a shallower slope is more efficient, and differences in maintenance are shown on the Y intercept. Cow 2 is more efficient than Cow 1 because she is eating less and producing the same amount of milk (assume both are not gaining or losing body energy). This could be because cow 2 has lower maintenance cost (dotted line) or better marginal efficiency (dashed line), but we cannot tell as we just have one observation for each cow. Cow 2 has a negative residual feed intake (eats less than expected and is more efficienct) relative to the average of Cow 1 and Cow 2. Cow 1 has a positive RFI (less efficient).



production. That is what the residual feed intake calculation does. Residual feed intake compares the actual observed intake, to the predicted intake, where predicted intake is correcting for milk production. This is shown in figure 3, the negative RFI for cow 6 indicates that something about her is more efficient than for cow 7. What line do we use for the prediction? A simple regression of feed intake (in pounds DM) vs. milk energy excreted is one possibility. In this case the observed data gives the line by a statistical regression model. If all cows weighed the same and you truly knew the NEl content of the diet, then you could draw that line with an intercept based on maintenance requirement and energy density of the diet, and the slope of the line as the inverse of the NEl density of the diet. That would be using a nutritional model to predict what DMI must be to achieve what the cow is doing. Observations not on the line either have some leftover NE or not enough NE to account for what they are doing. If you are well trained in the concept of net energy, you may balk at this. Net energy cannot be created nor destroyed so where did the cow with positive RFI put the extra energy and how did the cow with negative RFI make the energy? They didn't. In reality a better way to say this is that for the cow with negative RFI, the NEl concentration of that diet <u>for her</u> was higher than for the average cow, and for the cow with positive RFI, NEl concentration was lower than for the average cow. If you assume that every cow extracts the same NE from each pound of a common diet, then the cows with negative RFI would have to be in negative energy balance, but that clearly does not need to be the case. Actual energy balance needs to be determined separately by measuring body

Figure 3: Residual Feed Intake (RFI) is a measure of feed efficiency, negative RFI is good. RFI is the deviation of observed intake from predicted for a cow measurement. The model (dashed line in this figure) used to predict Intake can be based on many things, and in turn this defines what RFI is. If Milk yield is used to estimate intake, then RFI allows comparison of cows at the same production level. Permanently high producing cows with positive RFI could still be efficient and desirable, but as lifetime feed intake and milk is not measured, and cows will be measured at different yields relative to their lifetime average, RFI is an efficiency measure that corrects for these temporary differences in yield which may be driving intake.

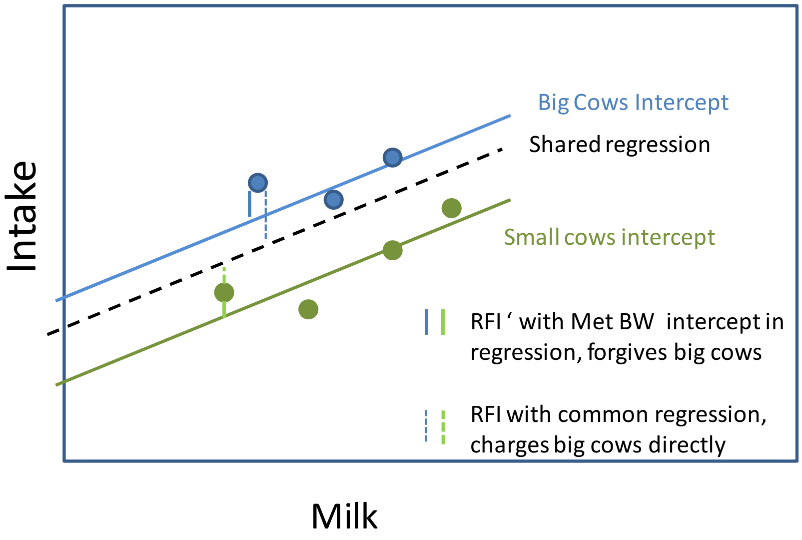


weight and condition scores. Also minimizing body energy changes during the measurement of feed efficiency might be useful. RFI does not have to be given in pounds or kilogram of DM, but if it is then the regression line gives the estimated maintenance requirement (in pounds or kg diet) and NEl concentration (as the inverse mass DM/Mcal NEl) for that specific group of cows and diet. It would be silly to do it on pounds as fed, but you could. It could be done in Mcal GE, in which case the intercept would be the maintenance requirement of the group in Mcal GE, and the slope would be the ratio of GE/ average NEl of the diet.

If we stick with the idea of comparing observed intake to intake predicted by a regression equation, we can add other factors to the intake prediction equation. We could convert maintenance and body weight changes all to a milk energy equivalent. For example using table 4-2 of the NRC (2001) we could add body weight gain in NEl units to milk energy yield or subtract body weight loss from milk energy yield, leaving us again with a simple line. Or we could plot a plane that has milk energy as a y axis independent variable and body gain/loss as a z axis independent variable. This allows us the ability to enter body weight change without fixing its conversion to milk energy, and allow the data to determine the slope.

It should be clear that RFI can be defined in many ways, depending how we predict what intake should be. Figure 4 can be used to show an additional correction that could be added. We could include metabolic bodyweight as an independent variable in the regression model used to predict dry matter intake (in addition to milk energy yield). Rather than trying to draw this as a plane, I just picked two lines, one for cows of a fixed larger body weight (upper solid line) and one for cows of a fixed smaller body weight (lower solid line). Each size group essentially gets their own intercept (difference in intercepts is determined by difference in MBW between the groups, and MBW regression coefficient). We can call this difference between observed intake and the regression that includes maintenance cost plus milk, RFI'. Now we see in this example that as compared to a common regression line (middle dashed line) where the top (bigger) cows all had a positive (inefficient) RFI and the lower (smaller) cows had negative (more efficient) RFI, now the RFI' of the big cows has been reduced and for some is negative, while the opposite happened for small cows

Figure 4: Difference between RFI calculated using common regression for DMI=milk yield (as in Figure 3); or RFI' using regression DMI= milk yield + $BW^{.75}$. RFI is likely to be more heritable and more correct, but body size can probably be determined more accurately by other means, so using RFI' and body weight in a breeding index may be most logical approach.



So by including MBW in the regression for predicting intake, we basically forgive big cows the extra feed they eat because they are big. Is this a good idea? I think it is clear that in the final analysis we must charge the larger cow for her bigger maintenance feed requirement. The question is how and using what data? Real measured feed efficiency phenotype data (needed to calculate RFI or RFI') will always be scarce. It requires thousands of measured animals to determine heritability, and genetic relationships. If we had better, more and cheaper data for body size (and we do!) it would almost certainly make sense to use a combination of body size measured on a large population, along with an RFI' measured on a smaller occupation. In this way we could avoid large cows based on size, but also nudge them up or down based on RFI’. Comparing RFI to body size and examining the slope, gives us a good idea of how much body size costs us in units identical to RFI, so we can use the smaller data set not only to predict RFI’, but also to tell us how much emphasis to put on body size relative to RFI’ as part of a feed efficiency breeding index. Even if the heritability of RFI’ is too low to be useful, this data collection and analysis is essential to tell us how to use the very heritable trait of body size to improve efficiency genetically. One way to summarize this, RFI is a deviation that includes higher or lower maintenance needs due to MBW, while in RFI’ this cost is in the regression equation and not in RFI’.

Although not considered in the example in figure 4, it is certainly possible that the large cows make up for some of their increased maintenance requirement by using feed with higher marginal efficiency. In that case we could assign a lower slope for big cows in fig. 4, (or a twist in the plane if metabolic BW and milk yield are entered as two separate axes). That can be considered in calculating RFI’ by including an interaction term (size*milk yield) to predict the DMI used in calculating residual feed intake, if the phenotypic data supports that relationship.

In many of my examples I have assumed cows are in neutral body energy status. That is almost never the case over the short term, yet must be close to the case over the long term (once growth is corrected for). It is certainly important to account for energy balance changes when calculating RFI. If not corrected for appropriately, cows constantly losing body weight would appear more efficient (have negative RFI), and cows recovering previously lost body weight would appear inefficient (have positive RFI). It is important that cows be able to regain energy lost during early lactation before the next lactation. There is also probably some optimal change that is neither so small that it restricts production, nor too large that it devastates health and reproduction. However, selecting for appropriate fluctuations in body energy is a different problem than selecting for feed efficiency per se.

## Size matters - genetics of body size

Mature body weight, which can be used to calculate metabolic body weight and estimate maintenance costs, is not a trait included in USDA AIPL animal evaluations. However, a body size composite is included, and is based on classification data that is readily available. For Holsteins, the USDA AIPL body size composite is 50% stature, 25% strength, 15% body depth and 10% rump width (VanRaden et al. 2011, http://aipl.arsusda.gov/reference/nmcalc-2006.htm#Type). Size is the most heritable trait included in the AIPL breeding indices for dairy animals, with 40% of variation due to genetics. Furthermore size does not have a positive genetic correlation with any milk production traits (Cole et al., http://aipl.arsusda.gov/reference/nmcalc.htm). This means that selecting for production does not produce big cows automatically and we could select for smaller cows without reducing production. USDA net merit $ index (NM$) places a negative (4 to 6%) on body size composite. Using net merit as a selection tool is projected to reduce the size composite index in the Holstein population by almost 1 unit (about 25 pounds live weight) in a decade. This would be a reversal of past trends.

Genetic base changes in the past decade (VanRaden et al., http://aipl.arsusda.gov/reference/base2010.htm) indicate that estimated breeding value of the average Holstein increased about 1.7 units between 1995 and 2005. This is roughly equivalent to .22 Mcal more energy required per cow per day, or about .3 lbs of feed DM. That is only about 0.5% of daily feed requirement, but it is a cost that never goes away. Holstein USA estimates that the top 100 Holstein bulls based on NM$ still have a slight positive PTA (+.19) for stature (http://www.holsteinusa.com/genetic_evaluations/ss_tpi_formula.html) while bulls selected on Holsteins TPI index will have a large positive PTA for stature (+1.28).

The Crookston Minnesota breeding experiment (Hansen et al., 1999) picked the 3 largest and 3 smallest PTA Size Holstein sires for 30 years in a controlled breeding experiment. All sires were in the top 50% for PTA for milk yield with at least 70% reliability. Over 30 years, the small line had a mature post-calving weight of 1412 pounds and the large line was 1586 pounds. For cows born between 1983 and 1994, the small line weight remained constant while the large line increased in weight, so that breeding for smallest PTA-Size merely held size constant. That means selecting average bulls by ignoring size should lead to increased size, which agrees with what the AIPL base changes and Holstein USA trends show.

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