Can We Use Residual Feed Intake to Enhance Dairy Production Efficiency?

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Summary

Reducing feed costs associated with milk production has major implications for improving profitability of the dairy industry. Evidence indicates that genetic variation exists in residual feed intake **(RFI)** among dairy cattle, and it is a heritable trait. Selection for lower RFI in dairy cattle should result in reductions in feed intake while maintaining milk production and weight gain, and produce concomitant reductions in methane and manure outputs. Thus, due to its potential economic and environmental benefits, it appears that RFI should be considered for future inclusion in multi-trait genetic selection of dairy cattle. However, there are many potential impacts of selection for RFI and its interaction with environmental, physiological, and genetic factors that influence or contribute to variation in RFI that require further evaluation.

Introduction

In the last few years, we have seen changes in the dairy industry that have driven cost of production highest it has ever been as a result of high feed, fuel, and fertilizer costs. Producers and consultants are interested in ways to enhance efficiency on the farm as a strategy to reduce the cost of production. Improvements in feed efficiency **(FE)** may also reduce the impact of livestock on emissions of greenhouse gasses, such as methane, and a reduced N excretion that has benefits to the environment and the dairy industry as a whole. Past genetic selection practices have also resulted in improvements in feed utilization by dairy cows through selection of cows for higher yields. It is possible that direct selection may improve feed utilization traits more rapidly. There are many ways to define FE. Dry matter intake efficiency **(DME)** is generally defined as pounds of milk yield per pound of dry matter intake **(DMI)** and are generally correlated with higher yield and smaller body size. Gross efficiency, however, can be misleading as cows mobilize tissue in early lactation and this can be impacted by their condition prepartum. Residual feed intake is a measure of FE. Residual feed intake is independent of yield, body weight **(BW)**, and (sometimes) body condition. Heritability estimates are generally higher for DME than for RFI and both measures of efficiency can be unfavorably correlated with reproductive performance and other economically important traits if not formulated properly.

Recently, measures of residual yield have been considered. This is similar to the concept of RFI, expect that yield is regressed on DMI, BW, and body condition.

Regardless of the definition we prefer for FE, underfeeding of cows with high genetic merit for yield limits FE. This is particularly true for large cows and those that usually carry more condition. Direct selection for feed utilization is now closer to becoming feasible due to the advent of genomic selection techniques that will allow selection for novel

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traits that we cannot measure on a whole-population basis. Gains in parameters such as digestive efficiency, or lower maintenance costs at similar BW, are the theoretical goals of selecting for RFI. However, it is also possible to have an improvement in RFI but an actual increase in the amount of feed required producing a unit of milk. Therefore, it is critical to understand the factors that affect feed efficiency prior to utilizing this measure for future selection criteria in the dairy industry. This paper describes opportunities for improving milk production efficiency for lactating dairy cattle using RFI for milk production and its potential benefits to the dairy industry for reducing production costs and negative impacts on the environment.

What Is Feed Efficiency?

Feed efficiency (or DME) is a simple measure of a cow's ability to convert feed nutrients into milk or milk components. In the simplest terms, it is the pounds of milk produced per pound of DM consumed. This measure should always be a consideration of dairy diets and becomes increasingly important during times of decreased profit margins (high input and low returns). An added benefit to increasing cows' FE is that fewer nutrients will be excreted in manure, so FE affects both economic and environmental efficiency.

There are two ways to improve FE. One is to increase milk yield with the same DMI, and the other is to decrease DMI and maintain the same milk yield. Many diet modifications that increase milk yield will also increase FE. In general, as the cow produces more milk, the proportion of nutrients used for maintenance becomes smaller. In other words, the fixed costs of the animal are spread out over more pounds of milk, making the animal more cost and energy efficient. Once the fixed costs are achieved in a dairy cow, producing additional milk takes less energy and protein. *However, a problem arises with these "fixed costs," as they are not exactly fixed.* As DMI increases, there is a decrease in feed digestibility, and the cow becomes somewhat less efficient at extracting energy from the ration. This decrease in digestibility grows larger as intake increases and becomes a real issue in high producing dairy cows with high intakes. Therefore, it is important to optimize rather than maximize DMI in the cow. In many situations, getting more DMI in a high producing dairy cow is an economically sound practice. However, in some circumstances , the cost of having a more energy dense or digestible diet may be more expensive than the return from increased milk. This would result in a lower income over feed cost **(IOFC)** and would not be advised.

It is very common to standardize FE by using energy corrected milk **(ECM)** yield. This standardization allows for comparison across breeds or dairy farms that vary substantially in milk composition. The following formula should be used to convert to ECM yield (Tyrrell and Reid, 1965): ECM = (12.82 × fat lbs) + (7.13 × protein lbs) + (0.323 × milk lbs). Calculations that use ECM are slightly different from those using actual milk values, and both methods can be found in the literature. Both have value, and the results are often similar. To further improve the accuracy of calculating FE, intake could also be corrected for energy content. Correcting feed DM to a standard Mcal/lb would increase the accuracy of calculating DME and allow for comparisons between rations of different compositions. More precisely, perhaps DME could be calculated as the Mcal of milk produced per Mcal of feed consumed. Determining DME this way would eliminate the variability associated with the energy density of the TMR and forage digestibility. This method would put a greater focus on the cows' ability to produce milk efficiently, rather than DME being a product of the feed. This would be a more effective approach when comparing animals for genetic selection.

Though DME is used in the dairy industry, it does not bring out other costs to the cow related to digestive efficiency, mainly because it is highly correlated with yield and body size. This makes it more difficult to make comparisons of cows at different yield and BW. In addition, we know that cows are more efficient in very early lactation compared to post peak production. In early lactation, production is partly supported by body tissue mobilization, and therefore, a cow with high DME may not be efficient but simply mobilizing a relatively large proportion of body tissue. Such a cow may actually be very inefficient because more energy is required to deposit body tissue than is available to support milk yield. In one recent study, cows were evaluated for DME before and after adjustment for body condition score **(BCS)** and changes in BCS (Vallimont et al., 2011). Failure to account for body condition biased the evaluation of efficiency toward those cows that peaked higher and earlier.

Gross feed efficiency has been evaluated in a number of studies (Van Arendonk et al., 1991; Veerkamp et al., 1994; Vallimont et al., 2011) to determine its heritability and association with other production traits. Heritability estimates have been observed ranging from 0.14 to 0.37 (Van Arendonk et al., 1991; Vallimont et al., 2011). Gross efficiency has a high genetic correlation with milk yield (0.79; Oldenbroek, 1989), indicating that selection for greater milk yield alone should result in an improvement in efficiency without having to measure individual animal feed intake. Gross feed efficiency is also correlated with BW (Van Arendonk et al., 1991; Vallimont et al., 2011), indicating that smaller cows or those that lose more BW during lactation are more efficient.

However, Frigo et al. (2010) found that loss in BW during early lactation had strong positive genetic correlations with the incidence of metabolic diseases during early lactation. Because gross feed efficiency does not differentiate between energy used for milk yield originating from the diet and that which was available from mobilization of body reserves, cows that mobilize a greater proportion of tissue reserves will appear more efficient relative to cows that do not lose significant body condition. In addition, Vallimont et al. (2011) found a strong negative genetic correlation (i.e., 0.70) between gross feed efficiency and BCS during lactation. Reduced BCS is associated with poor fertility (Berry et al., 2003), and it is also genetically correlated with ketosis (Gillund et al., 2001), clinical mastitis, and lower calf survival during first calving (Bastin et al., 2010) in dairy cows.

Residual Feed Intake as a Measure of Feed Efficiency

A phenotype of interest related to milk production efficiency is RFI which is a measure of the animal's ability to utilize nutrients provided for productive purposes. The RFI is calculated as the difference between actual energy intake and the expected feed energy intake based on performance (e.g., maintenance, growth, BW change, body composition, and milk production). However, this relationship is likely dependent upon the physiological state of the animal, season, and many other management factors that contribute to how the animal metabolizes nutrients provided. Expected intake is determined by regressing intake of cows in the herd on their metabolic BW, BW change, and ECM. Therefore, cows with a low RFI have the ability to use less dietary energy for body maintenance and to achieve an equivalent level of milk production compared to other herd mates. The more metabolically efficient animals, of course, should also not exhibit undesirable production traits.

Because RFI is most commonly derived by regressing feed intake on milk, fat and protein yields in addition to functions of BW and BW change, it is independent of yield and BW. The RFI is the most widely considered measure of feed efficiency in beef cattle production, and there has been interest in this concept by dairy cattle researchers. Whether RFI reflects true differences in digestive or metabolic efficiency has not been conclusively demonstrated.

In a study of Angus cattle (Lines et al., 2009) selected for high RFI (low efficiency) or low RFI (high efficiency) for four generations, the high efficiency line grew at the same rate and consumed less feed than the low efficiency line as predicted. However, there were important differences in the body composition among the lines. The low efficiency animals had more back fat than the high efficiency line, and the researchers concluded that there were no differences between the lines in basal metabolic rate, which was the trait researchers had hoped to improve. Body composition has been considered when deriving RFI in some more recent dairy cattle studies (Coleman et al., 2010; Vallimont et al., 2011).

Residual Feed Intake as a Measure of Efficiency in Dairy Cattle

Selection for lower RFI in beef cattle have demonstrated greater feed efficiency for growth, including reductions in daily feed intake and improved feed:gain (Herd et al., 2003). Furthermore, low RFI steers exhibited significant reductions in methane production and methane loss as a percentage of gross energy intake relative to high RFI steers. In addition, RFI was positively correlated with fecal output, methane output, and heat production, and negatively correlated with retained energy (Nkrumah et al., 2007). Thus, it appears that reductions in RFI may be profitable for the beef industry, both by improving efficiency of energy use by the animal, but also by reducing negative environmental impacts.

Yan et al. (2010) recently demonstrated that high-producing dairy cows produce less methane per unit of intake or per unit of milk output relative to lower-yielding cows, due to their greater metabolizable energy **(ME)** intake and a greater proportion of energy used for milk production over body maintenance. This information was derived from calorimetric data from 20 studies conducted between 1993 and 2007 from cows of varying merit for milk production, lactation number, and stage of lactation, Therefore, significant reductions in feed costs and environmental impacts related to dairy production may be achieved by increasing the lactation capacity per cow.

The concern of course is as production increases , other negative impacts come about such as on fertility, reductions in body condition and longevity, and increases in the incidence of diseases (Oltenacu and Broom, 2010). Selection for yield and show ring conformation has resulted in larger framed cows (Hansen, 2000), which also translates into greater maintenance costs per cow and potentially lower FE.

There is limited published research on RFI in lactating dairy cattle. Connor et al., (2012) observed differences of over 15% in mean DMI between the least and most efficient cows across all parities (n = 254 lactations), with no differences observed in BW, average daily gain, somatic cell count, or ECM yield during the first 90 days in milk. In this study, high and low RFI cows were classified as those having an RFI measure of 0.5 standard deviations **(SD)** above or below the group mean, respectively. Research in grazing Holstein-Friesian cattle indicated no differences in BCS between cows with low and high breeding value for RFI (Lopez-Villalobos et al., 2008). Therefore, there appears to be promise for improving feed conversion efficiency among dairy cows; however, many additional studies are required to determine whether health and performance characteristics are similar between cows with high and low RFI.

Coleman et al. (2010) recently pointed out some limitations of RFI in regards to dairy cattle selection schemes. Cows at the same level of production may have equivalent RFI, despite large differences in feed intake because BW is used in the calculation of RFI. Some improvement in metabolic efficiencies may occur, but the amount of feed actually required to produce a unit of milk could actually increase. This would defeat the purpose of selecting for efficiency. Moreover, a very small and low yielding animal can have a favorable RFI but would not be an economically efficient cow. The authors derived a measure of residual solids production by regression of milk solids yield on feed intake, BW, changes in BW, and body condition. This measure was correlated favorably with yield, gross efficiency, and RFI, but it needs further development.

Connor et al. (2012) indicated that there was a considerable amount of variation in RFI among dairy cattle required for selection from the limited number of studies that have been conducted. As an example, preliminary results from the Holstein herd at Beltsville indicate a SD of 4.1 Mcal ME/day. Heritability estimates for RFI from studies with fairly low samples sizes range from 0.01 to 0.38 (Van Arendonk et al., 1991; Veerkamp et al., 1995; Lopez-Villalobos et al., 2008; Vallimont et al., 2011), indicating that environmental and other management factors add variation to the estimates. Genetic correlations with other traits, such as fertility, BCS, and behavior, have yet to be investigated, primarily due to an insufficient number of RFI records from dairy herds required to make reliable genetic inferences. Impacts of genetic selection for lower RFI in lactating dairy cattle for other important production traits still require investigation (Connor et al., 2012).

Relationship Between Feeding Behavior and RFI

Slower rates of feed intake have been reported in finishing heifers selected for low RFI (Kelly et al., 2010). Robinson and Oddy (2004) reported a positive correlation between RFI and feeding rate in finishing beef cattle. Connor et al. (2012) evaluated the relationship between RFI and feeding behavior of Holstein cattle using the GrowSafe system. Low RFI was related to a slower feed consumption and less time per day spent feeding. A slower rate of feed consumption and reduced overall intake in low RFI cows may have contributed to a slightly greater feed digestibility due to reduced passage rate of feed in the rumen (Colucci et al., 1982). More studies are required to evaluate the relationship between feeding behavior and RFI in lactating dairy cows.

Relationship Between Stage of Lactation, Parity, and RFI

It is possible that assessment of RFI during a particular stage of lactation may provide better estimates of milk production efficiency during the typical 305-day lactation than another lactational stage. Changes in the energy demand on the cow occur throughout lactation due to variation in milk yield and composition, pregnancy in late gestation, and the restoration of body reserves at the end of lactation and during the dry period could influence FE (or RFI). Differences in RFI may also exist across parities. Effects of parity on characteristics such as milk yield, energy partitioning between milk yield and BW gain, BW, and DMI have been demonstrated (Oldenbroek, 1989; Berry et al., 2006), which could have a significant effect on RFI estimates. For example, first-parity cows may behave differently when grouped with more mature cows or require different management conditions, which could influence their RFI estimates.

Preliminary results from Connor et al. (2012) from 32 high-yielding Holstein cows fed a total mixed ration (**TMR)** and evaluated for RFI during a 305-day lactation indicated that Spearman's rank correlations between RFI measurements from day 1 to 100, 101 to 20, and 201 to 305 ersus RFI during the full lactation were 0.63, 0.85, and 0.81, respectively ($P < 0.001$). Although the ata are limited, results of these studies indicate that RFI measured later in lactation (i.e., after 100 DIM) may provide more reliable estimates of efficiency during the full lactation than RFI during early lactation and that evaluation periods of 100 days in length may provide sufficient information for estimating full-lactation RFI (Connor et al., 2012). Combined with results from Lopez-Villalobos et al. (2008), these results indicate that test periods during mid to late lactation lasting for 60 to 100 days are likely to provide RFI values most representative of RFI throughout lactation. However, a very limited number of animals were used in these studies, and therefore, additional research is needed to determine the recommended test duration for estimating RFI and the appropriate stage of lactation that should be evaluated.

Interactions of Feeding Management and Genetic Response

From a nutritional stand point, interactions between diet and genotype have been suggested to exist for RFI in beef cattle (Durunna et al., 2011), and the extent that different diets may have on expression of RFI in dairy cattle is unknown. A factor rarely considered in discussion of FE is the interaction of feeding management with cow genotype. In a recent evaluation of feed intake data in 11 Pennsylvania tie-stall herds, Dekleva (2010) contrasted selection response in herds with high and low levels of feed refusals. Herds were split into the six herds that had the highest rate of feed refusal and five herds with the lowest rate of feed refusal. Milk, fat, and protein yields were regressed on sire predicted transmitting abilities **(PTA)** for yield. The expectation is a 1 kg increase in yield for every 1 kg increase in PTA. The regression coefficients in the herds with high refusals ranged from 0.87 (fat yield) to 1.23 (protein yield), which indicated feeding practices were allowing cows in those herds to fully express their genetic potential. However, herds feeding to a clean bunk or with low levels of refusals had a significantly lower response, with regression coefficients ranging from 0.34 (fat and protein yields) to 0.44 (milk yield).

Dekleva (2010) also evaluated the relationships among BW, BCS, and yield in the same two groups of herds. The genetic correlation estimate between yield and BW was near 0 in the herds feeding to a high rate of refusals; whereas, the genetic correlation was strong and negative (-0.80) in the herds that fed to a low rate of refusals. The ability of a large cow to fully express her genetic potential for yield was more severely impacted by limiting feed availability than for a small cow. The relationship between yield and BCS was more unfavorable in the low feed refusal herds (-0.21) than in the high feed refusal herds (-0.63).

Genomic Markers for RFI

The primary limitation to including traits like RFI directly in genetic selection programs is a lack of feed intake data for a large population of cows. Genetic selection for yield is facilitated by DHI testing and there were over 800,000 Holstein cows born in 2008 alone contributing records to milk, fat and protein yield evaluations. Measuring feed intake on individual cows is simply too cost and labor prohibitive to be implemented on a large-scale basis. Dairy cattle breeding programs have evolved from the traditional progeny test system that required a large amount of phenotypic data to genomic evaluation systems that combine traditional progeny tests with genotypes for bulls and cows at 50,000 or more sites across the genome. Such evaluations have been available for yield, health, and type traits in the US since 2009 (VanRaden, 2009). There is some hope that we can measure intake on smaller research populations and use such information to facilitate genomic selection.

Recently, data from 1,630 cows in four European research centers were combined to determine the feasibility of pooling data from research herds into one dataset with the purpose of facilitating genomic selection for feed intake (Banos et al., 2011). The power to detect genomic effects increased substantially when data were pooled across herds and suggests potential to develop genetic evaluations for traits, like RFI, that could not otherwise be considered. Genomic evaluations for traits such as RFI will have lower reliability than traits we have traditionally considered because it requires a large number of animals to accurately estimate genomic effects. The realized reliability for Net Merit when genomic predictions were based on 1,151 sires was approximately 35% (VanRaden et al., 2009), and the evaluations of those 1,151 sires were based on many daughters. Clearly, we will need to build a significant feed intake database for genomic evaluations of RFI to have sufficient accuracy. Genomic evaluations of RFI will be an additional tool to improve FE, but will not revolutionize our current selection programs.

Physiological Basis for RFI

Herd and Arthur (2008) indicated that there are five major physiological processes that are likely to contribute to variation in RFI. These include level of intake, digestion of feed, metabolism (anabolism and catabolism associated with and including variation in body composition), physical activity, and thermoregulation. Studies on Angus steers following divergent selection for RFI estimated that heat production from metabolic processes, body composition, and physical activity explained 73% of the variation in RFI. The proportions of variation in RFI that these processes explain are protein turnover, tissue metabolism and stress (37%); digestibility (10%); heat increment and fermentation (9%); physical activity (9%); body composition (5%); and feeding patterns (2%). The physiological mechanisms identified so far are based on very few studies, some of which have small sample sizes. The genomic basis to variation in these physiological processes remains to be determined. Early studies have shown many hundred genes to be associated with differences in RFI, perhaps not surprising given the diversity of physiological processes involved. Further research is required to better understand the mechanisms responsible for the variation in RFI and to determine how the physiological basis can be evaluated along with the molecular genetics information and become the basis for commercial tests for genetically superior animals.

Summary and Conclusions

Significant improvements to milk production efficiency of dairy cattle have been made in the last 50 years, and this has resulted in a greater level of milk yield with significantly less number of cows. However, feed costs still remain the major expense in the dairy business, and methods to improve efficiency of feed conversion to milk yield is necessary to maintain profitability, as well as to enhance impacts of livestock on the environment. When considering the dairy cow, neither composition of the output, nor are differences in locomotion, disease status, or other metabolic processes that expend energy (i.e., protein turnover, tissue metabolism, and stress; 37% contribution) are considered when evaluating RFI. If energy requirements of these processes are not taken into consideration, the reduction in feed intake sought by selection for low RFI may compromise the capacity of an animal to sustain these functions. In practical terms, there is a need for improved understanding of the genetic and phenotypic relationships between feed intake and the components of production at different phases of the productive life of the animal to be able to effectively utilize RFI to optimally improve whole animal efficiency.

A decade of research in beef cattle has shown that genetic selection for lower RFI is a viable option for improving FE without significant evidence of associated negative responses in other important production traits. Similar opportunities appear to be available for improving FE of dairy cattle through selection for lower RFI. However, very few studies have evaluated RFI in lactating dairy cattle, and there is a need for research to assess this trait, including its genetic correlation to other production traits.

In conclusion, reducing feed costs associated with milk production has major implications for improving profitability of the dairy industry. Evidence indicates that genetic variation exists in RFI among dairy cattle, and it is a heritable trait. Selection for lower RFI in dairy cattle should result in reductions in feed intake while maintaining milk production and weight gain, and produce concomitant reductions in methane and manure outputs. Thus, due to its potential economic and environmental benefits, it appears that RFI should be considered for future inclusion in multi-trait genetic selection of dairy cattle. However, there are many potential impacts of selection for RFI and its interaction with environmental, physiological, and genetic factors that influence or contribute to variation in RFI that require further evaluation.

References

Banos, G., M.P. Coffey, R.F. Veerkamp, D.P. Berry, and E. Wall. 2012. Merging and characterising phenotypic data on conventional and rare traits from dairy cattle experimental resources in three countries. Animal. 6:1040-1048.

Bastin, C., S. Loker, N. Gengler, A. Sewalem, and F. Miglior. 2010. Genetic relationships between body condition score and reproduction traits in Canadian Holstein and Ayrshire first-parity cows. J. Dairy Sci. 93:2215-2228.

Berry, D.P., F. Buckley, P. Dillon, R.D. Evans, M. Rath, and R.F. Veerkamp. 2003. Genetic relationships among body condition score, body weight, milk yield, and fertility in dairy cows. J. Dairy Sci. 86:2193-2204.

Berry, D.P., R.F. Veerkamp, and P. Dillon. 2006. Phenotypic profiles for body weight, body condition score, energy intake, and energy balance across different parities and concentrate feeding levels. Livest. Sci. 104:1-12.

Coleman, J., D.P. Berry, K.M. Pierce, A. Brennan, and B. Horan. 2010. Dry matter intake and feed efficiency profiles of 3 genotypes of Holstein-Friesian within pasture-based systems of milk production. J. Dairy Sci. 93:4318-4331.

Colucci, P.E., L.E. Chase, and P.J. Van Soest. 1982. Feed intake, apparent diet digestibility, and rate of particulate passage in dairy cattle. J. Dairy Sci. 65:1445-1456.

Connor, E.E., J.L. Hutchison, K.M. Olson, and H.D. Norman. 2012. Opportunities for improving milk production efficiency in dairy cattle. J. Anim. Sci.2011-4528. J. Anim. Sci. 90(5):1687-1694.

Dekleva, M.W. 2010. Interaction of milk, fat and protein yield genotype with feeding level and indicators of cow comfort. MS Thesis. Penn State University, University Park. Available at: http://etda.libraries.psu.edu/theses/approved/WorldWideIndex/ETD-5240/index.html.

Durunna, O.N., G. Plastow, F.D.N. Mujibi, J. Grant, J. Mah, J.A. Basarab, E.K. Okine, S.S. Moore, and Z. Wang. 2011. Genetic parameters and genotype by environment interaction for feed efficiency traits in steers fed grower and finisher diets. J. Anim. Sci. 89(11):3394-3400.

Frigo, E., C.D. Dechow, O. Pedron, and B.G. Cassell. 2010. The genetic relationship of body weight and early-lactation health disorders in two experimental herds. J. Dairy Sci. 93:1184-1192.

Gillund, P., O. Reksen, Y.T. Gröhn, and K. Karlberg. 2001. Body condition related to ketosis and reproductive performance in Norwegian dairy cows. J. Dairy Sci. 84:1390-1396.

Hansen, L.B. 2000. Consequences of selection for milk from a geneticists viewpoint. J. Dairy Sci. 83:1145-1150.

Herd, R.M., J.A. Archer, and P.F. Arthur. 2003. Selection for low post-weaning residual feed intake improves feed efficiency of steers in the feedlot. Proc. Assoc. Adv. Animal Breeding and Genetics. 15:310-313.

Herd, R.M., and P.F. Arthur. 2008. Physiological basis for residual feed intake. J Anim. Sci. 87:E64-E71.

Kelly, A.K., M. McGee, D.H. Crews, Jr., T. Sweeney, T.M. Boland, and D.A. Kenny. 2010. Repeatability of feed efficiency, carcass ultrasound, feeding behavior, and blood metabolic variables in finishing heifers divergently selected for residual feed intake. J. Anim. Sci. 88:3214-3225.

Lines, D.S., M.L. Wolcott, W.S. Pitchford, C.D. K. Bottema, R.M. Herd, and V.H. Oddy. 2009. Some consequences of selection for residual feed intake in beef cattle. Proc. Assoc. Advmt. Anim. Breed. Genet. 18:604-607.

Lopez-Villalobos, N., D.P. Berry, B. Horan, F. Buckley, J. Kennedy, M. O'Donovan, L. Shalloo, and P. Dillon. 2008. Genetics of residual energy intake in Irish grazing dairy cows. Proc. N.Z. Soc. Anim. Prod. 68:97-100.

Nkrumah, J.D., D.H. Crews, Jr, J.A. Basarab, M.A. Price, E.K. Okine, Z. Wang, C. Li, and S.S. Moore. 2007. Genetic and phenotypic relationships of feeding behavior and temperament with performance, feed efficiency, ultrasound, and carcass merit of beef cattle. J. Anim. Sci. 85:2382-2390.

Oldenbroek, J.K. 1989. Parity effects on feed intake and feed efficiency in four dairy breeds fed ad libitum two different diets. Livest. Prod. Sci. 21:115-129.

Oltenacu, P.A., and D.M. Broom. 2010. The impact of genetic selection for increased milk yield on the welfare of dairy cows. Anim. Welfare 19:39-49.

Robinson, D.L., and V.H. Oddy. 2004. Genetic parameters for feed efficiency, fatness, muscle area and feeding behaviour of feedlot finished beef cattle. Livest. Prod. Sci. 90:255-270.

Tyrrell, H., and J.T. Reid. 1965. Prediction of the energy value of cow's milk. J. Dairy Sci.48:1215-1223.

Vallimont, J.E., C.D. Dechow, J.M. Daubert, M.W. Dekleva, J.W. Blum, C.M. Barlieb, W. Liu, G..A. Varga, A.J. Heinrichs, and C.R. Baumrucker. 2011. Short communication: Heritability of gross feed efficiency and associations with yield, intake, residual intake, body weight, and body condition score in 11 commercial Pennsylvania tie stalls. J. Dairy Sci. 94:2108-2113.

Van Arendonk, J. A.M., G.J. Nieuwhof, H. Vos, and S. Korver. 1991. Genetic aspects of feed intake and efficiency in lactating dairy heifers. Livest. Prod. Sci. 29:263-275.

VanRaden, P.M. 2004. Invited review: Selection on net merit to improve lifetime profit. J. Dairy Sci. 87:3125-3131.

VanRaden, P.M., C.P. Van Tassell, G..R. Wiggans, T.S. Sonstegard, R.D. Schnabel, J.F. Taylor, and F.S. Schenkel. 2009. Invited review: Reliability of genomic predictions for North American Holstein bulls. J. Dairy Sci. 92:16-24.

Veerkamp, R.F., G. C. Emmans, A.R. Cromie, and G. Simm. 1995. Variance components for residual feed intake in dairy cows. Livest. Prod. Sci. 41:111-120.

Veerkamp, R.F., G. Simm, and J.D. Oldham. 1994. Effects of interaction between genotype and feeding system on milk production, feed intake, efficiency and body tissue mobilization in dairy cows. Livest. Prod. Sci. 39:229-241.

Yan, T., C.S. Mayne, F.G. Gordon, M.G. Porter, R.E. Agnew, D.C. Patterson, C.P. Ferris, and D.J. Kilpatrick. 2010. Mitigation of enteric methane emissions through improving efficiency of energy utilization and productivity in lactating dairy cows. J. Dairy Sci. 93:2630-2638.