RESIDUAL FEED INTAKE OF ANGUS CATTLE DIVERGENTLY SELECTED FOR FEED CONVERSION RATIO

A THESIS

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By

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ABSTRACT

Residual feed intake (**RFI**) is a method of measuring feed efficiency that has not yet been adopted in the beef industry. RFI is calculated as the actual feed consumed minus the feed that the animal was expected to consume based on its mid-test weight and average daily gain (**ADG**). It is known to be phenotypically independent of weight and growth rate, thus making it a better measurement tool than feed conversion ratio (**FCR**), the most widely used feed efficiency measurement. The objective of this study was to compare results obtained using RFI with those of FCR to determine the best measure of feed efficiency.

RFI was calculated using three different approaches; dry matter intake adjusted for production (**RFIp**), dry matter intake adjusted for production and backfat thickness (**RFI_{BF}**), and dry matter intake estimated with NRC net energy equations (**RFI_{NRC}**). Low RFIp and RFI_{BF} bulls consumed less feed than high RFI bulls, whereas no differences existed for weight traits or average daily gain. Both RFI_{NRC} and FCR were highly correlated with weight traits and average daily gain. RFI_{BF} proved to be the best measure of feed efficiency, as it did not have an effect on weights, gains, or backfat thickness.

Dedicated to my aunt Carolyn, rest in peace

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CHAPTER 1

INTRODUCTION

In the livestock industry, feed costs sum to approximately half of the total production cost. In the majority of beef operations, feed is the single largest expense (Wang et al., 2006). In recent years, there has been rising demand for corn based ethanol. Higher fuel prices have doubled the cost of corn, the main component of livestock feed. Because of this high expense, many beef operations have been forced to make drastic changes, from shutting down production to reducing the number of cows in the cow herd (Lutey, 2008; Yaukey, 2008). Therefore, feed efficiency is an important trait that improves the opportunity for profitability of livestock enterprises.

Improvements in feed efficiency will lead to reduced costs and better overall production system efficiency (Nkrumah et al., 2006). A 5% improvement in feed efficiency can have an economic effect four times greater than a 5% improvement in average daily gain (Gibb and McAllister, 1999). Herd (1992) discovered an important portion of variation in calf weaning weight per unit of feed consumed was independent of body size and growth rate. Therefore, any trait used to accurately measure variation in feed efficiency will need to include concern for feed requirements for both maintenance and production.

Most measures of feed efficiency are related to each other and to measures of growth. One measure of feed efficiency is the feed conversion ratio. This ratio is expressed as feed:gain. The inverse, known as feed efficiency, is also frequently used in the beef industry. The problem with these measurement tools is their close correlation with feed intake and rate of gain (Carstens et al., 2003). Therefore, selection for feed:gain ratio could lead to animals with heavier mature weights, which is usually not desirable, and animals with similar feed conversion ratios can differ greatly in their rates of gain and feed intake. In addition, ratio traits for genetic selection present problems relating to prediction of change in component traits in future generations (Gunsett et al., 1984).

Koch et al. (1963) first proposed the concept of residual feed intake (**RFI**). RFI is defined as the difference between actual feed intake and predicted feed intake required for the observed rate of gain and body weight. RFI is calculated as the actual feed consumed minus the feed that the animal was expected to consume based on its mid-test weight and average daily gain (**ADG**). This measurement, which is expressed as the difference or the residual, has been found to be phenotypically independent of growth rate and body weight in growing cattle, making it a better trait for selection than the feed conversion ratio (Kennedy et al., 1993; Archer et al., 2002; Baker et al., 2006). The concept of residual feed intake has already been adopted in other livestock industries, such as swine and poultry. Comparison of residual feed intake with feed conversion ratio in growing cattle warrants investigation to understand its potential benefits to the beef cattle industry.

The selection criterion used in the divergent feed efficiency selection experiment, conducted at the Eastern Agricultural Research Station (EARS) in the 1980s, was feed:gain ratio. The main objective of this study was to compare results obtained with RFI with those for feed:gain ratio in order to identify the best measure of feed efficiency.

CHAPTER 2

LITERATURE REVIEW

1. Economic Effects of Feed Efficiency

Genetic evaluation procedures have been developed for traits of economic relevance to beef production. Genetic evaluation models based on Henderson's mixed model equations provide best linear unbiased predictions (BLUP) of genetic merit, and now represent the standard for genetic prediction (Crews, 2005). The most broadly used technique of genetic evaluation is a statistical procedure used to accurately predict breeding values in the form of expected progeny differences (EPDs). EPDs are calculated for growth, carcass traits, milk, calving ease, gestation length, etc., and research is being conducted to incorporate additional traits of economic relevance into breeding programs. Golden et al. (2000) presented the concept of individual, economically relevant traits (ERT) as a means of guiding the process of identifying traits that should be used to calculate EPDs in the next generation of national cattle evaluation programs.

The focus of most genetic evaluation systems is on indicator traits, traits that do not directly impact revenue, because they are cheaper and easier to measure (Crews, 2005). The Golden et al. (2000) concept is to develop a breeding program for traits outside the ordinary weight and growth traits. Typically, researchers have been interested in changing the means for output traits (e.g., weight, fertility, meat yield), but recently there is growing interest in reduction of inputs. Feed costs are a large fraction of the total cost of beef production improvement programs, second only to fixed costs; consequently, reducing input costs is likely associated with traits related to feed efficiency (Archer et al., 1999; Crews et al., 2003a).

Basarab et al. (2007) suggested that the best way to decrease feed costs is to select bulls that are naturally feed-efficient, because 80 to 90 percent of genetic improvement in a herd is accomplished through the sires. An efficient bull will pass his superior genetics for feed efficiency to his progeny, in turn, resulting in feed savings for calves in the feedlot and replacement heifers entering the cow herd. The same researchers have determined that, on average, it costs $50 less to feed an efficient bull than an inefficient bull, and they have estimated that a 5 percent improvement in feed efficiency could have an economic effect four times greater than a 5 percent improvement in average daily gain.

Today, the United States is producing corn based ethanol at a rate four times greater than 8 years ago (Lutey, 2008). Because of this, corn growers are trying to keep up with the growing demand from both fuel and food (Yaukey, 2008). In 2003, corn was priced at $2.50 a bushel and a barrel of oil was $11. In the summer of 2008, corn was up to $5.65 a bushel and a barrel of oil is priced around $120. Though the price of feed is increasing, the price per pound of beef is not, thereby forcing beef cattle operations to reduce the number of cows, and feedlot operators are losing approximately $150 a head (Garber, 2008; Lutey, 2008).

2. Measurement of Feed Conversion Ratio

Feed conversion is measured as a ratio of inputs (feed consumed) to outputs (gain in weight). In the beef cattle industry, this ratio is the most frequently used measure of feed efficiency, but it will only lead to limited insight into efficiency of the entire production system (Crews, 2005). It is considered a function of gain, feed consumption, and average weight while on test, and the linear function is assumed to be gain = rate of feed:gain ratio x feed + error (Koch et al., 1963). A negative aspect of feed conversion is its inability to consider the use of feed for maintenance. Ferrell and Jenkins (1998) discovered that the relationship between feed intake and gain is not linear as originally thought for beef cattle. They showed that the maximum efficiency in daily gain may occur at less than the maximum amount of feed intake.

The Angus Sire Alliance is a United States organization established for collection of feedlot and carcass data to measure the costs and returns of a sire's progeny, to help guide mating and selection and identify the best Angus beef cattle genetics to improve profitability. They have determined that sire groups with identical feed conversion rates differ for average daily gain (Circle A Ranch, 2008).

To improve the feed to gain ratio in beef cattle, some researchers have implemented limit feeding, which restricts dry matter intake without compromising average daily gain (Okine et al., 2004). With a maximum of 15% feed restriction, there is an increase (reduction in feed:gain ratio) of approximately 9% in feed efficiency (Zinn, 1986; Plegge, 1987; Hicks et al., 1990; Gaylean, 1996). Yet, Mathison and Engstrom (1995) restricted intake by 4% and found that fat cover decreased by 22%, with only a 3% increase in improved feed efficiency measured as feed conversion ratio, which did not prove significant.

Murphy and Loerch (1994) conducted feeding trials comparing the effects of limit feeding with the effects of ad libitum feeding. During the growing phase they found ADG was reduced 0.15 kg/d and 0.24 kg/d for steers fed 90 and 80%, respectively, of ad libitum intake. During the finishing phase ADG was reduced 0.12 kg/d and 0.21 kg/d for the 90 and 80% of ad libitum intake groups, respectively, as well as feed efficiency being improved during restricted intake. It was concluded that restricting intake for growing-finishing steer calves does not adversely impact feed efficiency and may in fact improve feed efficiency.

Arthur et al. (2001) pointed out that the problem with selection using a ratio is that it is not useful in predicting change in component traits in future generations because the selection pressure is applied disproportionately to the component traits. Component traits are expressed at different rates and possible non-linearity of the component traits may exist (Herring and Bertrand, 2002). Conversely, this is not the case for a linear index that sets predetermined selection pressure on the traits, which in turn results in predictable genetic change. Gunsett (1984) prepared a method comparing efficiency of direct selection for two component traits with a linear index of the same two components. He proposed that genetic changes in feed conversion ratio do not translate to equivalent improvement in efficiency because genetic trend can result from changes in either the denominator or numerator of a ratio somewhat independent of the other. It was concluded that use of the linear index increased selection responses compared with the ratio.

Interrelationships exist among traits. Therefore, it may not be useful to select for any trait individually. The approach to calculating feed efficiency recommended by Simm et al. (1987) involves combining biological and economic information into selection indices, such as RFI, rather than ratios, such as FCR.

3. Calculation of RFI

The basis of RFI is using an animal's weight and growth rate to separate feed inputs into maintenance and growth components (Koch et al, 1963). The same researchers developed the hypothesis that feed intake could be adjusted for level of production and maintenance of body weight. They realized a robust measure of efficiency would allow for adjustment of feed intake for any of the diverse requirements that differ among industry segments. For example, where hyperplasic and hypertrophic tissue growth may be the major energy requirements for young, growing cattle, the requirements for the mature cow herd may include maintenance of body condition for reproduction and lactation (Crews, 2005).

Calculation of RFI begins with an individual record of each animal taken over a long-term feeding trial, normally lasting between 70 and 84 d. Animals may be housed individually where accurate daily measurements are taken of the amount of food offered and the amount eaten, and average daily gain and body weight monitored.

There have been several developments that allow for ease of individual feed intake measurements. One is the use of Calan gates, which involve the use of magnets attached to the animals so they can gain access to the feed bunks through electronically controlled gates. This calculates, weighs, mixes, and dispenses the rations, keeping a complete data record for each animal (Scwartzkopf-Genswein and McAllister, 1998). Another method is the development of the GrowSafe system. This system uses radio frequency technology and consists of an antenna mat lining the front of the feedbunk, a reader panel and a computer (Scwartzkopf-Genswein and McAllister, 1998). This technology monitors the animal on an individual basis, identifying several aspects of the animal's performance, from which animal produces the best grading carcass to which animal consumes the least feed.

More recently, to determine the amount of feed an animal is expected to consume, researchers have taken the phenotypic regression approach (Archer et al., 1997; Arthur et al., 2001; Crews et al., 2003). Intake is adjusted for level of production by regressing intake on average daily gain (ADG) and mid-test body weight ($BW^{.75}$). RFI should be phenotypically independent of growth and the weight traits used in the regression procedure, because variation from those traits has been removed (Herring and Bertrand, 2002). The statistical model becomes:

$$\mathbf{Y = \beta_0 + \beta_1(ADG) + \beta_2(WT)^{.75} +} \text{ residual error}$$

where Y is expected DMI, $\boldsymbol{\beta_0}$ is the regression intercept, $\boldsymbol{\beta_1}$ is the partial regression of daily intake on average daily gain (ADG), $\boldsymbol{\beta_2}$ is the partial regression of daily intake on mid-test body weight raised to the .75 power $(WT)^{.75}$ and **RFI** is the residual. Mid-test body weight raised to the .75 power is used instead of actual weight to balance the difference in maintenance requirements of cattle caused by differences in mature size (BIF, 1986).

The properties of RFI can be defined using standard statistical procedures. One central feature is the distributional property ($RFI \sim N(0, \sigma^2_{RFI})$), showing RFI has a mean of zero (Searle, 1982). The partial regressions in the estimation model are independent of

RFI. Because the estimation method causes RFI to be independent of production, the variation in RFI is probably due to metabolic processes.

The expected intake of the animal is determined by the estimation equation. Once determined, RFI is calculated by subtracting expected feed intake from the observed feed intake. Efficient animals, with negative RFI values, have daily feed intakes less than that predicted for their level of production and body weight. Conversely, an animal with a positive RFI daily feed intake trait is greater than expected based on growth and body weight.

4. Genetic Variation in Feed Efficiency

There is substantial variation in feed efficiency, in beef cattle populations, that is independent of growth rate and size (Archer et al., 1997). The fact that selection for animals that eat less for the same weight and weight gain result in progeny that have different results for the same trait, signifies there is genetic variation in the efficiency of utilization of feed (Herd et al., 1997). Feed efficiency of animals involves several complex biological processes, and is usually measured over a certain period in an animal's life or during a particular phase of production. Measures of feed efficiency that include both liveweight and average daily gain try to explain some of the underlying variation in feed utilization for both growth and maintenance (Arthur, 2001a). Koch et al. (1963) first identified that differences in both weight maintained and weight gained affect feed requirements. The problem is that it is difficult to determine the exact causes of genetic variation in feed efficiency within breeds of cattle due to the high cost of measuring maintenance efficiency on a sufficient number of cattle to present an indication of genetic variation (Archer et al., 1999).

Though no definite biological bases for differences in feed efficiency and RFI have been identified, several suggestions have been made. Understanding the causes of variation will help to ensure there are no long term adverse effects due to RFI selection on the health or performance of the resulting progeny.

Feed Intake

The scientific basis behind RFI is that individuals of the same body weight require differing amounts of feed for the same level of production (Sainz and Paulino, 2004). Sainz and Paulino (2004) showed a trend towards increased rate of gain with greater feed intake, with some deviations from this trend. For example, if two animals have identical feed intake (7.43 kg/day), but significantly different average daily gains (1.51 vs. 0.98 kg), the animal with the higher rate of gain is more efficient and considered more profitable. As another example, assume two animals have an identical rate of gain (1.5 kg/day), but with different feed intakes (7.43 and 9.22 kg/day). Here, the animal with the lower feed intake is more efficient and is considered more profitable.

An association exists between feed intake and maintenance requirements of ruminants. As feed intake increases, the amount of energy that is expended to digest food increases (Richardson and Herd, 2004). This energy expense is partly due to the size of the digestive organs. Since selection for RFI is associated with variation in intake, animals that eat less for the same performance may be expected to have less energy expended due to digestion; this is called the Heat Increment (HI; Richardson and Herd, 2004).

Digestion

Increases in feed intake level relative to maintenance result in decreases in digestion of feed. There is genetic variation in total tract digestion of feed (Richardson and Herd, 2004). A study conducted in sheep showed ewes divergently selected for weaning weight had a difference of approximately 2 percent in organic matter digestibility favoring the high weaning weight group, and rams of the high weaning weight line had a greater digestibility (approximately 4 percent) than the low line rams (Oddy et al., 1993).

Richardson and Herd (2004) performed a divergent selection experiment for residual feed intake in Angus beef cattle progeny to help determine mechanisms underlying the variation in RFI. They found a correlation of -0.44 between RFI and digestibility, indicating that differences in digestibility accounted for 19 percent of the phenotypic variation in RFI in the animals. The direction of the correlation indicated that lower RFI (improved efficiency) was associated with greater digestibility. Because digestibility is difficult to measure precisely, they suggest that variation in RFI is no more than 10 percent.

Richardson et al. (1996) phenotypically ranked young bulls and heifers for low and high RFI. The cattle were tested on a pelleted ration with a calculated dry matter digestibility of 68 percent. They found the ability to digest dry matter differed by 1 percent between the high and low lines. This difference accounted for approximately 14 percent of the difference in intake between the high and low line.

Heat Production

Another concept behind RFI is that variation is a result of variation in three basic biological processes represented by protein turnover, ion transport, and proton leakage (Herd et al., 2004), suggesting that 2/3 of RFI variation is most likely due to the heat loss that occurs during these three processes. Similarly, Richardson et al. (1999) found that differences in energy held in the body only explained 5 percent of variation in feed intake with the rest due to heat production, and suggested a need to find the causes of variation in metabolism that effect heat production. Nkrumah et al. (2006) found more efficient beef steers (low-RFI) had lower heat production than medium or high-RFI steers, indicating RFI may be negatively correlated with maintenance energy requirements.

Several studies in mice have been conducted to determine associations between heat loss and traits such as feed intake, body fat, and activity (Wesolowski et al., 2003; Eggert and Nielsen, 2006; McDonald and Nielsen, 2007). Wesolowski et al. (2003) conducted a study with mice divergently selected for heat loss. They found high heat loss mice had 50% greater heat loss, 35% less body fat, 20% greater feed intake, 100% greater locomotor activity levels, and higher core body temperature compared with low heat loss mice. Nielsen et al. (1997) reported that low heat loss mice differed in their body composition compared to high heat loss mice; the low heat-loss line was fatter and the high heat-loss line was leaner than the intermediate control. Feed intake between high and low heat loss mice differed by 34.0 percent (McDonald and Nielsen, 2007).

Eggert and Nielsen (2006) postulated that, because animals selected for heat loss differ in feed intake and body composition, but do not differ in body size, the lines should also differ in maintenance cost per unit of size or in the cost of lean or fat gain. If they differ in the cost of maintenance per unit of body size, but not in the cost of gain, then selection to improve livestock efficiency could be aimed at lowering maintenance cost. However, heat production of livestock is too laborious and expensive to measure in a practical setting. Under this speculation, the same researchers conducted a study comparing feed energy costs between lines of mice selected for heat loss and concluded that selection for heat loss has changed the cost for maintenance per unit of size, but probably not the cost of gain.

Stress

Stress also plays an important role in variation of RFI. Stress in beef cattle is defined as ‘an abnormal or extreme adjustment in the physiology of an animal to cope with adverse effects of its environment and management’ (Frazer, 1975). Stress may require extra activation of the animal’s immune system, which may result in lower performance or poorer feed efficiency (Klasing and Leshchinsky, 2000). Several studies conducted in pigs and chickens have shown genetic variation in an animal’s susceptibility to stress (Luiting et al., 1994; Zhuchaev et al., 1996).

Cattle that are in a rigorous husbandry system (such as a feedlot) are subjected to an increased number of stressors, including transportation, sudden noise, dust, etc. (Richardson and Herd, 2004). The animal is unable to invoke stress reducing behaviors in such a limited environment. Richardson and Herd (2004) hypothesize that the greater susceptibility to stress in high RFI (low efficiency) steers may be due to these animals having a less effective mechanism to manage and adapt to stressors. They suggest observing cattle in a feedlot environment compared to a less intensive setting, on pasture, and determining if differences are observed with respect to reduced expression of variation in RFI.

Richardson et al. (2002) compared red blood and white blood cell counts in steers that were divergently selected for RFI and showed high RFI steers may be more susceptible to stress than low RFI steers. Gartner et al. (1969) conducted a study analyzing blood concentrations during the handling of cattle and found a significant, positive correlation between RFI and hemoglobin and hematocrit concentrations, suggesting high RFI steers may be, on average, more excitable or easily stressed in comparison to low RFI steers.

Body Composition and Metabolism

Residual feed intake is based on energy and energy requirements, and, because it is dependent on production traits, it may suggest that variation in RFI is due to differences in maintenance requirements (Nkrumah et al., 2006). Maintenance requirement can be defined as the feed energy required for zero body weight change or zero body energy change after allowing for different energy densities of body components (Ferrell and Jenkins, 1985). Maintenance efficiency can be defined as the ratio of body weight to feed intake at zero body weight change (Archer et al., 1999).

The gastrointestinal tract and liver contribute approximately 50% of the maintenance energy requirements in ruminants (Lobley, 2003), with 16 to 29% due to the gastrointestinal tract, and 20 to 26% due to liver metabolism (Johnson et al., 1990). Therefore, studies focusing on gastrointestinal tract and liver metabolism may also lead to better understanding of the genetic variation underlying RFI.

According to Nkrumah et al. (2006), variation in feed efficiency is primarily related to differences in dietary energy losses (fecal, methane, and urinary), heat production, and energy retention. To better understand these losses, they suggest studying pathways that are typically related to variation in the efficiency of conversion of gross energy (GE) to metabolizable energy (ME).

Ferrell and Jenkins (1998) showed that differences in water, protein, and fat deposition influence efficiency and rate of body weight gain. Even though energy expense required for fat is more than that for protein deposition, maintenance of protein requires more energy than maintenance of fat. The deposition of the same weight of lean tissue and fat has different energy costs, and this variation in efficiency is primarily due to the variation in protein turnover. Protein turnover is a process that requires high energy usage and variation in protein metabolism has been shown to be associated with genetic selection for growth and other traits in domestic animals (reviewed by Oddy, 1999).

It has been observed in several other species that the rate of protein degradation is associated with selection for growth and leanness. An example in chickens (Tomas et al., 1991) showed that protein degradation rate was associated with differences in the net efficiency of protein utilization and decreased degradation rates gave evidence of improved efficiency of protein gain.

Basarab et al. (2003) reported that approximately 4.0% of the variation in daily feed intake is due to differences in empty body fat, compared to 67.9 and 8.6% attributed to body weight and daily gain. They further showed that the rate of deposition of fat, measured as ultrasound subcutaneous fat gain and ultrasound intramuscular fat gain, increased the variance of daily feed intake explained by regression on weight and gain alone from 78% to 80.9%.

Activity

Studies on non-ruminant animals have shown that variation in heat production (energy available for maintenance and growth) is associated with an animal's activity, and with RFI. For example, in pigs, De Haer et al. (1993) found positive correlations of total feeding time (r = 0.64) and number of visits to the feeding station (r = 0.51) with RFI.

This correlation between feeding time and the number of steps taken can also be found in beef cattle. Richardson et al. (2000) reported a phenotypic correlation (r = 0.32) between RFI and daily pedometer count. Arthur et al. (2001) conducted a similar study that showed high RFI steers took 6 percent more steps, on average, than low RFI steers. High RFI steers also were assumed to spend 13 percent longer in the feeding stall and ruminating, because of their 13 percent greater daily feed intake. The increase in distance walked and time spent standing and ruminating accounted for approximately 5 percent of the increase in feed energy intake by the high RFI (low efficiency) group compared to the low RFI group.

Greenhouse Gas Emissions

Agriculture accounts for a major portion of total greenhouse gas (GHG) emissions in the United States. It is the source of approximately 80 percent of total nitrous oxide emissions and approxiametly 30 percent of total methane emissions (Brodt et al., 2007). The primary source of methane emissions is animal husbandry. Animal husbandry is the enteric fermentation in the digestive systems of ruminants and manure management.

It has been suggested by several authors that more efficient cattle will produce less methane gas for the environment (Herd et al., 2003; Nkrumah et al., 2006). Herd et al. (2003) found progeny of a low RFI selected line of beef cattle produced 15% less methane and consumed 15% less feed. Nkrumah et al. (2006) found similar results. They reported a low RFI line of cattle produced less methane emissions when compared to medium and high lines (24% and 28%, respectively).

5. Heritability of Feed Efficiency Measures and Correlations of Measures with Production and Cow Traits

Variance in RFI appears to be moderately heritable. Pitchford et al. (2004) calculated a mean heritability estimate of 0.25 for RFI based on 35 estimates obtained across seven species. Published values of heritability of RFI in beef cattle are moderate, ranging from 0.39 to 0.43 (Arthur et al., 2001), 0.26 to 0.30 (Crews et al., 2003), 0.28

(Koch et al., 1963), and 0.38 (Schenkel et al., 2004). Therefore, evidence exists that RFI is at least as heritable as early growth.

Genetic variation in RFI is dependent on genetic variance in young cattle and the magnitude of genetic correlations of RFI with other production traits (growth and feed intake during finishing, carcass and meat quality traits at slaughter, and cow traits, such as mature size, feed intake, milk production, and lifetime reproduction) (Herd et al., 2003).

For a trait to be considered as a selection criterion it must be heritable, or exhibit genetic variability, meaning variability in phenotypic expression must be dependent on additive genetic variance (Sainz and Paulino, 2004; Crews, 2005). Understanding of genetic relationships of feed efficiency traits measured in weaned calves with mature cow performance traits is necessary for breeding programs designed to improve whole herd production efficiency (Herd et al., 2003). Several studies have been conducted to determine the heritability of feed conversion ratio and residual feed intake and the correlations of efficiency traits with production and cow traits.

Feed intake and FCR are known to be phenotypically and genetically negatively correlated with measures of growth and therefore mature size. Koots et al. (1994b) published a review of a number of genetic correlation estimates of FCR with weights and gains which ranged from -0.24 to -0.95. These estimates signify that increased genetic potential for performance and size are negatively correlated with mature maintenance requirements. The same review showed strong evidence that genetic associations of feed intake with measures of growth rate and weight were positive, with genetic correlations ranging from 0.25 to 0.79. They also summarized published estimates of genetic correlations of mature weight with FCR (r = -0.14) and mature weight with feed intake (r= 0.92).

Because of large genetic correlations, selection for growth rate would be expected to result in correlated responses for both intake and FCR. The problem is that the favored correlated decrease in FCR due to increased growth rate selection is not automatically correlated specifically to improved feed efficiency (Crews, 2005).

Mature cow weight is highly heritable (h^2 = .50; Koots, 1994a). Animals with high genetic potential for growth rate are assumed to have improved (lower) FCR and have increased genetic potential for greater mature size (Crews, 2005). Mature size has high genetic correlations (r_g > 0.60; Koots, 1994b) with growth rates measured at young ages. Therefore, selection to directly increase weight and growth rate in younger cattle will be prone to result in strong positive genetic change in mature size and maintenance requirements (Crews, 2005).

FCR is an appropriate measure of feed efficiency in industry segments committed to production of growing animals, but as explained by Archer et al. (1999), if an increase in feed requirements of the breeding herd counterbalances the gains in efficiency of the market progeny, little progress will be made relative to total system efficiency. They concluded that an alternative measure of efficiency is desirable to reduce non-favorable correlated responses, which would reflect more across segment differences and enable more effective selection for efficiency.

Herd et al. (2003) found the correlation between postweaning RFI and cow RFI to be very high (r= 0.98), suggesting that selection for lower RFI in heifers has the potential to decrease feed intake and improve feed efficiency of the entire breeding herd. Archer et al. (2002) also reported a high genetic correlation (r= 0.64) between these two traits. The same researchers found genetic correlations of postweaning feed:gain ratio with cow feed intake and cow feed:gain ratio of 0.15 and 0.20, respectively. These correlations suggest that selection to reduce postweaning feed:gain ratio will cause only a small reduction in feed intake and feed:gain ratio of cows, whereas selection for low RFI will have a larger effect. Correlations of postweaning feed:gain ratio with cow size have been found by Herd and Bishop (2000) (r= -0.29 ± 0.24) and Archer et al. (2002) (r= -0 .54).

When deciding upon selection criteria in beef cattle operations, it is important that they do not negatively affect the end product. Johnston et al. (2002) found evidence to indicate that RFI selection will not affect carcass quality. From this evidence, Baker et al. (2006) designed a study to determine if RFI impacts meat quality and palatability characteristics in purebred Angus steers. They chose 54 purebred Angus steers for a 70-d postweaning feeding period, where individual feed intake and body weight were recorded to determine RFI. At the end of the 70-d period, the steers were fed a finishing diet to a similar backfat thickness and then harvested. Carcasses were randomly selected to examine the relationships among RFI, meat quality, and palatability. When the steers were divided into three groups based on RFI (low, medium, and high), high RFI steers (less efficient) showed greater DMI and feed conversion ratios (FCR) when compared to low RFI steers (most efficient). Low RFI steers consumed less feed, decreasing the amount of feed per kilogram of gain, and improving feed efficiency. The data also suggested no relationship between RFI and beef quality in these purebred Angus steers.

Basarab et al. (2003) reported low, positive genetic correlations between RFI and gain in ultrasound backfat thickness (0.22), gain in ultrasound marbling (0.22), carcass marbling (0.15), and dissectible carcass fat (0.14) and a low, negative phenotypic correlation between RFI and dissectible carcass lean (-0.21). These relationships indicate a small and positive association between RFI and carcass composition, indicating selection for lower RFI will improve carcass composition. Several other published studies show a weak, positive correlation between RFI and carcass lean content (Herd and Bishop, 2000; Arthur et al., 2001; Basarab et al., 2003). Richardson et al. (2001) found a single generation of selection for reduced RFI also resulted in reduced carcass fat content. Crews et al. (2003) estimated a genetic correlation of -.44 between finishing period RFI and carcass marbling score, indicating selection for improved RFI would be associated with favorable correlated response in carcass quality grade. Further studies of RFI's association with meat quality were suggested by the authors.

6. Divergent Selection for Feed Conversion

Bishop et al. (1991a,b) conducted a divergent feed efficiency selection experiment in the 1980s on Angus beef cattle at the Eastern Agricultural Research Station (EARS). Bulls were selected and individually fed during a 140-d postweaning performance test. At the end of the period, they were divided into groups (high, low) based on their feed conversion ratios; high conversion having the least feed required per unit of gain and low conversion having the greatest feed required per unit of gain. The three highest and three lowest bulls in feed conversion ratio were selected and randomly mated to 20 cows each. The progeny were then fed to assess postweaning and carcass performance. The purpose of the study was to compare mean responses of the two divergently selected lines of Angus beef cattle and further to calculate heritability estimates for feed conversion and the phenotypic and genetic correlations between feed conversion and other economically important traits.

The heritability estimates (0.46 for FCR adjusted for maintenance requirements; 0.26 for FCR unadjusted for maintenance) indicated that genetic variability for feed conversion exists in beef cattle populations. Bishop et al. (1991a,b) reported that the low feed:gain ratio progeny had greater subcutaneous fat than the high feed:gain ratio group, but no significant differences in other carcass traits were found. Phenotypic correlations indicated that the progeny with lower (more desirable) feed:gain ratio were fatter, gained weight at a faster rate, and yielded carcasses with higher quality grades, but less desirable yield grades.

The selection criterion used in the divergent feed efficiency selection experiment, conducted at the Eastern Agricultural Research Station (EARS) in the 1980s, was feed:gain ratio. The main objective of this study was to compare RFI results obtained using RFI with those derived using feed:gain ratio. The sub-objectives were to:

1. Determine ranking of bulls based on RFI versus feed:gain ratio;
2. Determine the phenotypic correlations of RFI with weights, gains, feed intake, feed:gain ratio, and backfat thickness of the bulls individually fed in the selection experiment;
3. Determine the best measure of feed efficiency.

CHAPTER 3

MATERIALS AND METHODS

Between 1979 and 1982 a feed efficiency experiment was conducted at EARS to compare mean responses of two divergently selected lines of Angus beef cattle.

1. Selection of Potential Sires

Between 1979 and 1982, 35 bull calves were chosen each year from the purebred Angus herd located at the Eastern Ohio Resource Development Center, Belle Valley, Ohio, which is now known as EARS. The selected bull calves, totaling 135, were individually fed in a 140-day postweaning performance test. The bulls that were selected for the performance test were randomly chosen from those available each year in the herd. Numbers of bulls completing the performance test in 1979 through 1982 were 35, 34, 35, and 34, respectively. Numbers of sires represented in 1979 through 1982 were 16, 7, 10, and 8.

2. Feeding and Management of Potential Sires

After weaning at approximately 7 mo of age, bulls were placed in a three-sided barn where they were group fed for 1 wk. Bulls were then randomly assigned to individual feed bunks, where they were tied for 2 h each morning and 2 h each afternoon, and were allowed to adjust to the tying procedure for approximately 1 wk. On-test weights were then taken and recording of individual feed consumption began. Average on-test age and weight were 222 d and 232 kg, respectively (Table 3.1).

Weights and feed consumption were recorded once every 28 d. Composition of the diet can be found in Table 3.2. Weights were recorded in the morning before feeding. The final weight was calculated as the average of two weights taken on consecutive days after the 140-d performance test was completed. On the same day as the second off-test weight was taken, hip height and ultrasound estimates of subcutaneous fat thickness over the longissimus muscle between the 12th and 13th ribs were recorded.

Each year, the three bulls with the largest feed:gain ratios and the three bulls with the smallest feed:gain ratios were selected from the individually fed bulls, and were randomly mated to 20 cows in a test herd of Angus cows also located at the Eastern Ohio Resource Development Center. Each year a different set of bulls was chosen; thus, the experiment was a single generation selection experiment replicated four times.

Table 3.1: Means and standard deviations for weaning weight and postweaning performance traits of individually fed bulls[a] from which sires were selected

Trait	Mean	SD
205-d weight, kg	232	22
On-test age, d	222	13
On-test weight, kg	232	23
Average daily gain, kg/d	1.4	.16
Final weight, kg	424	34
Feed consumption, kg	1,164	203
Backfat thickness, mm	7.6	2.54
Hip Height, cm	118	4
Feed conversion, (kg feed/kg gain)	6.0	.70
Residual feed intake, kg	.000	.60

[a] From Davis et al. (1985).

Table 3.2: Composition of experimental diet [a, b] for individually fed bulls from which sires were selected[c]

Ingredient	%[d]
Corn, shelled, crimped	30.00
Oats, crimped	25.00
Corn cobs, ground	10.00
Dehydrated alfalfa	10.00
Wheat middlings	10.00
Soybean meal	10.00
Sugarcane molasses	3.00
Dicalcium phosphate	.50
Limestone	.55
Salt, trace mineralized[e]	.50
Sodium bentonite	.40
Selenium premix	.05

[a] The diet also contained 545 to 682 IU vitamin A/kg, 45 to 68 IU vitamin D/kg, and .9 to 1.4 IU vitamin E/kg.

[b] The diet contained 68.5% TDN and 13.7% protein.

[c] From Davis et al. (1985).

[d] Dry matter basis.

[e] Contained 0.35% Zn, 0.28% Mn, 0.175% Fe, 0.035% Cu, 0.007% Co, and 0.007% I.

3. Progeny and Carcass Data

Birth weight, date of birth, sex, sire, and dam's identification number were recorded for progeny of the high vs. low feed conversion sires within 24 h postpartum. In November of each year weaning weights were obtained at approximately 7 mo of age. Calves were randomly assigned to 12 pens by sire-sex group at the Northwest Branch of OARDC and fed a pretrial warm-up diet for 2 wk. Following the warm-up period they were given ad libitum access to their diet.

The diet consisted primarily of nonprotein nitrogen (NPN) - treated corn silage and shelled corn fed at the rate of 1.0 and 0.75% of BW/d for bull and heifer calves, respectively. Soybean meal was fed as a supplement (Table 3.3) and monthly analyses were made of corn silage samples to monitor CP and DM contents.

Individual weights were obtained and pen feed consumptions were totaled at the conclusion of every 28 d until the end of the 140-d test period. At the end of the test period, weights were recorded, along with ultrasound estimates of subcutaneous fat thickness. Progeny with an estimated fat thickness of $\geq$ 8.9 mm perpendicular to the longissimus muscle between the 12^{th} and 13^{th} ribs were removed from the test and harvested, and those with less subcutaneous fat continued on test for additional 28-d periods until they reached the required minimum. Progeny were harvested at the completion of the test to obtain carcass data.

Table 3.3: Composition of progeny postweaning diet[a], %[b]

Ingredient	Bulls	Heifers
Corn silage	56.7	62.2
Whole Shelled Corn	36.9	27.9
SBM[c]	6.3	4.2
Melengestrol acetate[d]	.0	5.6
Stirofos[e]	.1	.1

[a] Bishop et al. (1991a).
[b] DM basis.
[c] Soybean Meal, 44% CP.
[d] MGA, The Upjohn Co., Kalamazoo, MI.
[e] Rabon, Diamond-Shamrock Co., Cleveland, OH.

For the current study, progeny data were not analyzed, because only pen data were available, which cannot be used to calculate RFI of individual calves using methodology that is currently available.

4. Adjustment of Feed:Gain Ratios

The Beef Improvement Federation (BIF, 1986) recommends that feed:gain ratios should be adjusted for differences in maintenance requirements, if feed consumption per unit of gain is evaluated over time-constant intervals. The adjustment was described by Bishop et al. (1991a). The adjustment was accomplished by multiplying the ratio of test group average metabolic midweight ($W_i^{.75}$) to individual metabolic midweight ($W_{ij}^{.75}$) as follows: BIF-adjusted feed efficiency = ($W_i^{.75}$/ $W_{ij}^{.75}$) (feed/gain), where subscript i refers to i^{th} year of test (1979, 1980, 1981, 1982, or 1983) and subscript j refers to the j^{th} bull within the i^{th} year. Midweights were estimated as ½ (initial weight on test + final weight off test).

This procedure adjusts the feed conversion ratios of heavier-than-average bulls downward, because the bulls would be expected to have above-average maintenance requirements and above-average metabolic weights (BIF, 1986). Feed:gain ratios of lighter-than-average bulls would be adjusted upward, because their maintenance requirements and metabolic weights would be below average. The bulls used for mating were selected based on their adjusted feed:gain ratios.

5. Statistical Analysis

5.1 Residual Feed Intake

Using the data obtained from the aforementioned study, residual feed intake (RFI) was calculated by three different approaches. In the first approach, expected intake was adjusted for production (average daily gain and metabolic midweight). On-test and off-test body weights and ADG from regression of body weight on day of test were calculated using the PROC REG procedure of the Statistical Analysis System (SAS Inst., Inc., Cary, NC) computer program. This method is used to reduce fluctuations in body weight due to gut fill.

Residual feed intake was calculated using the mixed model approach with the PROC MIXED procedure of SAS, to account for year as a random effect. This procedure accounts for the effect of the random variable (year) on the intercept and slope obtained from the regression of DMI with METWT and ADG140. The model used was:

$$DMI = b_0 + b_1 METWT^{.75} + b_2 ADG140 + RFI \text{ (i.e., residual error)}$$

where DMI is dry matter intake, METWT is metabolic midweight calculated by taking the average of on-test and off-test weights, ADG140 is average daily gain, and RFI is residual feed intake.

Variables (ONTSTAGE, A205WNWT, ADG140, ONTSTWT, WEIGHT140, DMI, FCR, BF140, HIPHT) were then adjusted for the random effect of year using the PROC MIXED procedure of SAS. Acronyms and definitions can be found in Table 3.4 This adjustment basically shifts each variable across all tests to a common mean, so that the correlation between variables is not skewed by different means among years.

In the second approach, expected intake was calculated using regression, and was adjusted for production and backfat thickness (BF140). On-test and off-test body weights and ADG from regression of body weight on day of test were calculated using the PROC REG procedure of the Statistical Analysis System (SAS Inst., Inc., Cary, NC) computer program.

Table 3.4: Acronyms and definitions of dependent variables

Acronym	Definition
A205WNWT	Weaning weight of bulls adjusted for age of dam and age of calf
ADG140	Average daily gain from beginning to end of 140-d test period
BF140	Backfat at end of 140-d on test (by ultrasonic measurement)
DMI	Dry matter intake for entire test
FCR	Feed conversion ratio for entire test
FDCON	Total feed consumption for entire test
HIPHT	Hip height at conclusion of 140 d on-test
METWT	Metabolic mid-weight
WEIGHT140	Off-test weight at end of 140-d test period
ONTSTAG	Age of bull at the beginning of test
ONTSTWT	On-test weight
RFI_p	Residual feed intake calculated from regression of DMI on METWT and ADG140
RFI_{BF}	Residual feed intake calculated from regression of DMI on METWT, ADG140, and BF140
RFI_{NRC}	Residual feed intake calculated from NRC equations

Residual feed intake again was calculated using the mixed model approach with the PROC MIXED procedure of SAS, to account for year as a random effect. This procedure also accounts for the effect of the random variable (year) on the intercept and slope obtained from regression of DMI on METWT, ADG140, and BF140. The model used was:

$$DMI = b_0 + b_1METWT^{.75} + b_2ADG140 + b_3BF140 + RFI \text{ (i.e. residual error)}$$

where METWT is metabolic midweight, ADG140 is average daily gain, BF140 is backfat at end of 140 d on test, and RFI is residual feed intake.

In the third approach, expected feed intake was calculated using the NRC Net Energy equations, taking into account the amount of energy and feed required for both gain and maintenance (Beef NRC, 1996). First, the net energy (**NE**) requirement for bulls for maintenance was calculated using the equation:

$$NE_m = 1.15\ (.077 * SBW^{.75})$$

where SBW is shrunk body weight (BW * .96) to account for gut fill and NE_m is NE for maintenance in Mcal/d. This value was then divided by the concentration of NE_m (Mcal/kg) in the diet fed to determine the feed required to meet maintenance energy requirements.

Next the NE requirement for gain was calculated using the equation:

$$NE_g = .0635\ (SBW * .891)^{.75}\ (ADG140 * .956)^{1.097}$$

ADG140 is multiplied by the constant, 0.956, and the product represents empty body weight gain. The solution (NE_g) represents the Mcal of NE_g required to achieve the specific animal's rate of gain. This value was then divided by the concentration of NE_g (Mcal/kg) contained in the diet. The dividend equals the amount of feed required to achieve the specified rate of gain. Summing the feed required for maintenance and the feed required for gain provides the total feed intake that would be expected to achieve the rate of gain observed according to the NRC NE system.

Residual feed intake was calculated by subtracting expected feed intake, derived using the three approaches described above, from the observed feed intake. Residual and rank correlations between feed:gain ratio and RFI of the individually fed bulls were determined using the CORR procedure of SAS. Rank correlations were used to determine if the bulls ranked the same for feed:gain ratio versus the three measures of RFI.

Bulls were divided into three groups based on RFI (high, mid, and low) for comparison purposes and were analyzed using the SAS computer program. Bulls were separated into groups that were <0.5, $\pm$ 0.5, and >0.5 standard deviations from the mean RFI. Bulls were divided in this manner to determine if differences in performance traits exist between efficient and inefficient animals. Least-squares means of each group, using Tukey's adjustment, were compared.

Using the PROC MIXED procedure of SAS, the three high and three low bulls by year were compared to find out whether the same three high and three low bulls would have been selected for breeding if RFI had been used instead of feed:gain ratio as the selection criterion.

CHAPTER 4

RESULTS

Means and standard deviations of the three lowest and three highest FCR bulls by year

Means and standard deviations for ONTSTWT, WEIGHT140, ADG140, FCR, RFIp, RFI_{BF}, and RFI_{NRC} are presented in Table 4.1 for the three lowest and three highest FCR bulls born in year 1979. Acronyms and definitions can be found in Table 3.4. Bulls in the most efficient group had lighter ONTSTWT (200 $\pm$ 21 kg) and lighter WEIGHT140 (392 $\pm$ 37 kg) than those in the least efficient group (243 $\pm$ 6 kg and 432 $\pm$ 10 kg, respectively, for ONTSTWT and WEIGHT140). However, the means were similar for ADG140 between groups (1.36 $\pm$ 0.12 kg/d for low bulls and 1.35 $\pm$ 0.07 kg/d for high bulls). As for feed conversion, the low bulls acquired a mean of 5.10 $\pm$ 0.08 kg feed / kg gain compared to 6.77 $\pm$ 0.42 kg feed / kg gain for high bulls. The three most efficient bulls (lowest feed conversion ratios) had a mean RFIp of -0.85 $\pm$ 0.12 kg compared to the three least efficient bulls (highest feed conversion ratios), which had a mean RFIp of 0.72 $\pm$ 0.27 kg. Similarly to RFIp, bulls of the most efficient group had a mean RFI_{BF} of -0.82 $\pm$ 0.17 kg and the least efficient group had a mean RFI_{BF} of 0.57 $\pm$ 0.18 kg.

Bulls of the most efficient group had a mean RFI_{NRC} of -1.06 ± 0.50 kg, a 25% increase compared to -0.85 ± 0.12 kg for RFIp and a 29% increase compared to -0.82 ± 0.17 for RFI_{BF}. The least efficient group had a mean RFI_{NRC} of 0.54 ± 0.52 kg compared to RFIp of 0.72 ± 0.27 and RFI_{BF} of 0.57 ± 0.18. This represents 25% and 5% decreases, respectively, from RFIp and RFI_{BF}.

Means and standard deviations for ONTSTWT, WEIGHT140, ADG140, FCR, RFIp, RFI_{BF}, and RFI_{NRC} are presented in Table 4.2 for bulls born in 1980. Means for ONTSTWT were 204 ± 15 kg for low bulls and 223 ± 29 kg for high bulls. This difference is a little less compared to the previous year. For WEIGHT140, the most efficient group was slightly lighter (407 ± 30 kg) compared to the least efficient group (409 ± 48 kg). Means for ADG140 were 1.45 ± 0.26 kg/d for low bulls and 1.33 ± 0.20 kg/d for high bulls. Mean feed conversion for the low group was 4.96 ± 0.10 kg feed / kg gain compared to 7.56 ± 0.35 kg feed / kg gain for the high group. Mean RFIp was –0.83 ± 0.54 kg and 2.19 ± 1.02 kg, respectively, for low and high bulls. RFI_{BF} was similar to RFIp with mean values of –0.89 ± 0.54 kg and 2.13 ± 1.03 kg, respectively, for low and high bulls.

Table 4.1: Means and standard deviations of the performance data for the three highest and three lowest feed conversion ratio bulls born in 1979

	ONTSTWT (kg)	WEIGHT140 (kg)	ADG140 (kg/d)	FCR (kg feed/ kg gain)	RFI_p (kg)	RFI_{BF} (kg)	RFI_{NRC} (kg)
Three Most Efficient[a]							
79190	184	361	1.26	5.18	-0.71	-0.71	-0.63
79090	224	433	1.49	5.10	-0.94	-1.01	-1.61
79181	193	381	1.37	5.02	-0.89	-0.73	-0.94
Mean	200 ± 21	392 ± 37	1.36 ± 0.12	5.10 ± 0.08	-.85 ± 0.12	-0.82 ± 0.17	-1.06 ± 0.50
Three Least Efficient[b]							
79043	258	427	1.20	6.89	0.10	0.16	-0.06
79045	221	379	1.12	7.01	0.49	0.45	0.77
79006	243	422	1.27	7.25	1.03	1.09	0.90
Mean	243 ± 6	432 ± 10	1.35 ± 0.07	6.77 ± 0.42	0 .72 ± 0.27	0.57 ± 0.18	0.54 ± 0.52

[a] Bulls with the lowest feed conversion ratios. [b] Bulls with the highest feed conversion ratios.

RFI_{NRC} was –0.88 ± 0.50 kg and 1.06 ± 1.79 kg, respectively, for low and high bulls. For the most efficient group, RFI_{NRC} exhibited a 1 percent decrease compared to RFI_{BF} and a 6 percent increase compared to RFIp. RFI_{NRC} showed a 50 percent decrease from RFI_{BF} and a similar 51 percent decrease from RFIp for the least efficient group.

Means and standard deviations for ONTSTWT, WEIGHT140, ADG140, FCR, RFIp, RFI_{BF}, and RFI_{NRC} for bulls born in 1981 can be found in Table 4.3. In this replicate, bulls in the most efficient group had lower ONTSTWT than those of the least efficient group (209 ± 32 vs. 266 ± 11 kg). The most efficient group bulls also had lighter WEIGHT140 when compared to the high group (423 ± 47 vs. 452 ± 23 kg). Mean ADG140 was 1.53 ± 0.14 and 1.32 ± 0.10 kg/d for the low and high groups, respectively. Mean feed conversion was 5.29 ± 0.15 kg feed / kg gain for the low group and 6.64 ± 0 kg feed / kg gain for the high group. Mean RFIp was -0.28 ± 0.15 kg and 0.28 ± 0.15 kg for the low group vs. the high group. The most efficient group had a mean RFI_{BF} of -0.29 ± 0.15 kg and the least efficient group had a mean RFI_{BF} of 0.24 ± 0.24 kg.

Table 4.2: Means and standard deviations of the performance data for the three highest and three lowest feed conversion ration bulls born in 1980

	ONTSTWT (kg)	WEIGHT140 (kg)	ADG140 (kg/d)	FCR (kg feed/ kg gain)	RFI_p (kg)	RFI_{BF} (kg)	RFI_{NRC} (kg)
Three Most Efficient[a]							
80115	208	373	1.18	5.07	-1.27	-1.32	-0.97
80065	188	425	1.70	4.87	-0.22	-0.29	-0.34
80117	217	422	1.47	4.93	-0.98	-1.07	-1.34
Mean	204 ± 15	407 ± 30	1.45 ± 0.26	4.96 ± 0.10	-0.83 ± 0.54	-0.89 ± 0.54	-0.88 ± 0.50
Three Least Efficient[b]							
80120	240	411	1.23	7.69	1.57	1.56	1.54
80018	190	359	1.22	7.16	1.63	1.52	-0.92
80122	239	456	1.56	7.82	3.37	3.32	2.57
Mean	223 ± 29	409 ± 48	1.33 ± 0.20	7.56 ± 0.35	2.19 ± 1.02	2.13 ± 1.03	1.06 ± 1.79

[a] Bulls with the lowest feed conversion ratios. [b] Bulls with the highest feed conversion ratios.

Both groups consumed less feed than expected based on RFI_{NRC}. The most efficient group had a mean RFI_{NRC} of -0.83 $\pm$ 0.33 kg compared to a mean RFIp of -0.28 $\pm$ .15 kg and a mean RFI_{BF} of -0.29 $\pm$ 0.15. The least efficient group had a mean RFI_{NRC} of -0.29 $\pm$ 0.25 compared to the mean RFIp value of 0.28 $\pm$ 0.15 kg and mean RFI_{BF} of 0.24 $\pm$ 0.24.

Means and standard deviations for ONTSTWT, WEIGHT140, ADG140, FCR, RFIp, RFI_{BF}, and RFI_{NRC} for bulls born in 1982 are presented in Table 4.4. Mean ONTSTWT and WEIGHT140 were lighter for the most efficient group than for the least efficient group (218 $\pm$ 39 vs. 247 $\pm$ 47 kg and 421 $\pm$ 55 vs. 424 $\pm$ 32 kg, respectively for ONTSTWT and WEIGHT140). For the low group ADG140 was greater when compared to the high group (1.45 $\pm$ 0.16 vs. 1.27 $\pm$ 0.12 kg/d). As expected, feed conversion was lower for the most efficient group (5.26 $\pm$ 0.05 kg feed / kg gain) when compared to the least efficient group (6.82 $\pm$ 0.62 kg feed / kg gain). The same can be seen for RFIp (-0.66 $\pm$ 0.46 kg for the low group and 0.41 $\pm$ 0.32 kg for the high group). This is consistent with the means for RFI_{BF}, which were -0.63 $\pm$ 0.40 kg for the low group and 0.42 $\pm$ 0.29 kg for the high group. These RFI_{BF} values were similar to the RFIp values. Mean RFI_{NRC} was -1.14 $\pm$ 0.90 kg for the low group and 0.28 $\pm$ 0.18 kg for the high group. These RFI_{NRC} values are lower compared to the RFIp and RFI_{BF} values.

Table 4.3: Means and standard deviations of the performance data for the three highest and three lowest feed conversion ratio bulls born in 1981

	ONTSTWT (kg)	WEIGHT140 (kg)	ADG140 (kg/d)	FCR (kg feed/ kg gain)	RFI_p (kg)	RFI_{BF} (kg)	RFI_{NRC} (kg)
Three Most Efficient[a]							
81048	175	369	1.38	5.18	-0.26	-0.19	-0.44
81128	211	442	1.65	5.23	-0.15	-0.23	-1.00
81002	240	458	1.55	5.46	-0.45	-0.46	-1.04
Mean	209 ± 32	423 ± 47	1.53 ± 0.14	5.29 ± 0.15	-0.28 ± 0.15	-0.29 ± 0.15	-0.83 ± 0.33
Three Least Efficient[b]							
81020	258	428	1.21	6.65	0.14	-0.03	-0.39
81112	260	452	1.37	6.64	0.43	0.44	-0.14
81053	279	475	1.40	6.64	0.26	0.30	-0.33
Mean	266 ± 11	452 ± 23	1.32 ± .10	6.64 ± 0	0.28 ± 0.15	0.24 ± 0.24	-0.29 ± 0.25

[a] Bulls with the lowest feed conversion ratios. [b] Bulls with the highest feed conversion ratios.

The overall means and standard deviations for bulls born in 1979, 1980, 1981, and 1982 can be found in Table 4.5. These means show the differences in ONTSTWT and WEIGHT140 between low and high FCR bulls. Most efficient bulls were lighter at beginning and end of test, and had greater ADG140. RFIp for low bulls was -0.65 $\pm$ 0.26 kg compared to that of high bulls, 0.90 $\pm$ 0.88 kg. Mean RFI_{BF} and RFI_{NRC} were lower for the most efficient group also, -0.66 $\pm$ 0.27 kg and -0.98 $\pm$ 0.15 kg compared to 0.84 $\pm$ 0.87 kg and 0.40 $\pm$ 0.56 kg. Differences were found in feed conversion between groups, 5.15 $\pm$ 0.15 vs. 6.95 $\pm$ 0.41 kg feed / kg gain. The most efficient group was better in terms of all RFI estimates and FCR.

Table 4.4: Means and standard deviations of the performance data for the three highest and three lowest feed conversion ratio bulls born in 1982

	ONTSTWT (kg)	WEIGHT140 (kg)	ADG140 (kg/d)	FCR (kg feed/ kg gain)	RFI_p (kg)	RFI_{BF} (kg)	RFI_{NRC} (kg)
Three Most Efficient[a]							
82003	261	474	1.52	5.22	-1.19	-1.06	-1.84
82021	208	426	1.56	5.24	-0.30	-0.27	-1.09
82064	185	363	1.27	5.31	-0.49	-0.57	-0.48
Mean	218 $\pm$ 39	421 $\pm$ 55	1.45 $\pm$ 0.16	5.26 $\pm$ 0.05	-0.66 $\pm$ 0.46	-0.63 $\pm$ 0.40	-1.14 $\pm$ 0.90
Three Least Efficient[b]							
82014	288	454	1.19	7.36	0.21	0.16	0.55
82190	196	391	1.40	6.14	0.78	0.74	0.08
82017	257	426	1.21	6.95	0.25	0.37	0.20
Mean	247 $\pm$ 47	424 $\pm$ 32	1.27 $\pm$ 0.12	6.82 $\pm$ 0.62	0.41 $\pm$ 0.32	0.42 $\pm$ 0.29	0.28 $\pm$ 0.18

[a] Bulls with the lowest feed conversion ratios. [b] Bulls with the highest feed conversion ratios.

Table 4.5: Overall means and standard deviations of the performance data for bulls born in all 4 years of the study

	ONTSTWT (kg)	WEIGHT140 (kg)	ADG140 (kg/d)	FCR (kg feed/ kg gain)	RFI_p (kg)	RFI_{BF} (kg)	RFI_{NRC} (kg)
MOST EFFICIENT[a]	208 ± 8	411 ± 14	1.45 ± 0.07	5.15 ± 0.15	-0.65 ± 0.26	-0.66 ± 0.27	-0.98 ± 0.15
LEAST EFFICIENT[b]	244 ± 18	429 ± 18	1.32 ± 0.03	6.95 ± 0.41	0.90 ± 0.88	0.84 ± 0.87	0.40 ± 0.56

[a] Bulls with the lowest feed conversion ratios.

[b] Bulls with the highest feed conversion ratios.

Comparison of simple means for the three highest FCR bulls and three lowest RFIp and RFI_{BF} bulls

The same three lowest and three highest bulls were chosen for both RFIp and RFI_{BF}. When compared to the three high FCR bulls, the three low RFIp and RFI_{BF} bulls had heavier weights for all 4 yr of the study (Table 4.6). In the years 1980 and 1981, ADG was lower for low RFI bulls than for high FCR bulls, and was similar the other 2 yr. This shows that if we select on FCR, we tend to select bulls that are lighter at the beginning of the test and have greater ADG. Also, in the years 1980 and 1981, low RFI bulls consumed less feed than high FCR bulls, whereas the values were reversed the other 2 yr. Bulls of the low RFI group had less backfat, and hip height was similar across all years.

Comparison of simple means for the three highest FCR bulls and three lowest RFI_{NRC} bulls

When compared to the three high FCR bulls, the three low RFI_{NRC} bulls had heavier weights for all 4 yr of the study (Table 4.7). In the years 1980 and 1981, ADG was lower for low RFI_{NRC} bulls than for high FCR bulls. The trend was reversed the other 2 yr. This shows that if we select on FCR, we tend to select bulls that are lighter at the beginning of the test and have greater ADG. In all 4 yr of the study, the low RFI_{NRC} bulls consumed more feed than the high FCR bulls; in turn daily dry matter intake was higher for the low RFI_{BF} bulls. Bulls of the low RFI_{NRC} group had less backfat except for 1979, and hip height was similar across all years.

Table 4.6: Comparison of simple means for the three highest and three lowest RFIp and RFI_{BF} bulls by year

	High FCR					Low RFI				
Trait	1979	1980	1981	1982	Mean	1979	1980	1981	1982	Mean
Weight, kg										
ONTST	200	204	209	218	208	218	217	253	262	238
140	392	407	423	421	411	410	402	446	469	432
ADG140, kg	1.36	1.45	1.53	1.45	1.45	1.37	1.33	1.37	1.48	1.39
FDCON, kg	935	1,080	1,099	1,064	1,045	964	1,015	1,070	1,123	1,043
RFIp, kg	-0.85	-0.83	-0.28	-0.66	-0.66	-0.93	-1.10	-0.70	-0.98	-0.93
RFI_{BF}, kg	-0.81	-0.89	-0.30	-0.63	-0.66	-0.84	-1.15	-0.66	-0.89	-0.89
FCR, kg DM /kg gain	5.10	4.96	5.29	5.26	5.15	5.23	5.07	5.74	5.45	5.37
DMI, kg	6.96	7.18	8.08	7.61	7.46	7.17	6.72	7.88	8.04	7.45
BF140, mm,	8.4	8.6	9.1	8.4	8.6	7.1	7.9	8.4	8.1	7.9
HIPHT, cm	113	116	120	118	117	119	117	121	119	119

TABLE 4.7. Comparison of simple means for the three most efficient FCR bulls and the three most efficient RFI_{NRC} bulls by year

	High FCR					Low RFI_{NRC}				
Trait	1979	1980	1981	1982	Mean	1979	1980	1981	1982	Mean
Weight, kg										
ONTST	200	204	209	218	208	224	244	268	263	250
140	392	407	423	421	411	442	447	469	465	456
ADG140, kg	1.36	1.45	1.53	1.45	1.45	1.52	1.35	1.38	1.47	1.43
FDCON, kg	935	1,080	1,099	1,064	1,045	1,109	1,195	1,142	1,180	1,157
RFI_{NRC}, kg	-1.06	-0.88	-0.83	-1.14	-0.98	-1.28	-1.55	-1.42	-1.49	-1.44
FCR, kg DM /kg gain	5.10	4.96	5.29	5.26	5.15	5.40	5.96	6.10	5.75	5.80
DMI, kg	6.96	7.18	8.08	7.61	7.46	8.21	8.00	8.38	8.44	8.26
BF140, mm,	8.4	8.6	9.1	8.4	8.6	9.1	7.9	7.9	8.4	8.3
HIPHT, cm	113	116	120	118	117	120	119	121	117	119

Comparison of A205WNWT and ONTSTWT between low, medium, and high groups across all measures of RFI

Bulls were divided into three groups (high, medium, and low) based on standard deviations from the mean RFI. The low group were consisted of bulls with RFI values < 0.5 standard deviations from the mean, the medium group consisted of bulls with RFI values $\pm$ 0.5 from the mean, and the high group consisted of bulls with RFI values > 0.5 standard deviations from the mean. Least-squares means and standard errors can be found in Table 4.8 for A205WNWT and ONTSTWT for bull groups across all measures of RFI. There was no significant difference ($P = 0.54$; $P = 0.62$, respectively) among all groups for adjusted 205-d weaning weights for RFIp or $RFI_{NRC.}$ This result is expected for RFIp, as it is known to be independent of weight traits. There was a significant difference ($P < 0.05$) among low RFI_{BF} bulls and high RFI_{BF} bulls (238 $\pm$ 3 kg and 225 $\pm$ 4 kg, respectively). No significant differences existed among groups, across all measures of RFI for ONTSTWT.

Table 4.8. Least-squares means and standard errors for A205WNWT and ONTSTWT for low, medium, and high bulls across all measures of RFI

RFI-Group[a]	A205WNWT (kg)	ONTSTWT (kg)
	P = 0.54	P = 0.65
MEAN LOW RFIp	237 $\pm$ 4	235 $\pm$ 4
MEAN MED RFIp	230 $\pm$ 3	231 $\pm$ 3
MEAN HIGH RFIp	227 $\pm$ 4	230 $\pm$ 4
	P < 0.05	P = 0.66
MEAN LOW RFI_{BF}	238 $\pm$ 3[b]	233 $\pm$ 4
MEAN MED RFI_{BF}	231 $\pm$ 3[b,c]	232 $\pm$ 3
MEAN HIGH RFI_{BF}	225 $\pm$ 4[c]	229 $\pm$ 4
	P = 0.62	P = 0.59
MEAN LOW RFI_{NRC}	235 $\pm$ 2	235 $\pm$ 3
MEAN MED RFI_{NRC}	229 $\pm$ 3	228 $\pm$ 4
MEAN HIGH RFI_{NRC}	220 $\pm$ 6	227 $\pm$ 7

[a] Low bulls are bulls with low RFI values and high bulls are bulls with high RFI values.
[b,c] Values in the same column without a letter in common are significantly different.
* There were 37 low RFIp bulls, 70 medium RFIp bulls, and 31 high RFIp bulls.
* There were 38 low RFI_{BF} bulls, 69 medium RFI_{BF} bulls, and 31 high RFI_{BF} bulls.
* There were 78 low RFI_{NRC} bulls, 48 medium RFI_{NRC} bulls, and 12 high RFI_{NRC} bulls.

Dry matter intake, RFI, and feed conversion ratios of low, medium, and high bulls across all measures of RFI

Least-squares means for dry matter intake, RFI, and FCR for the 140 d performance test are found in Table 4.9. For low bulls, RFIp was significantly lower ($P < .001$) than for medium and high bulls, -0.66 ± 0.06 vs. 0.01 ± 0.04 and 0.77 ± 0.06 kg, respectively. Feed conversion ratio was significantly lower as well for low bulls (5.62 ± 0.10 kg feed / kg gain) compared to medium (6.02 ± 0.11) and high bulls (6.60 ± 0.11 kg feed / kg gain). DMI was also significantly different ($P < .001$), with lower intake associated with low bulls (7.6 ± 0.11 kg/d) compared to medium (8.3 ± 0.12 kg/d) and high (9.1 ± 0.08 kg/d) bulls. Medium bulls were also significantly different from the high bulls. These same differences existed across all four years of the study.

Low RFI_{BF} bulls were significantly lower ($P < .001$) than medium and high bulls, -0.63 ± 0.05 vs. 0 ± 0.04 and 0.75 ± 0.06 kg, respectively. Feed conversion ratio was significantly lower as well for low bulls (5.62 ± 0.10 kg feed / kg gain) compared to medium (6.02 ± 0.11 kg feed / kg gain) and high bulls (6.60 ± 0.11 kg feed / kg gain). DMI was also significantly different among groups ($P < .001$), 7.5 ± 0.11 kg/d and 9.0 ± 0.12 kg/d for low and high bulls, respectively.

Low RFI_{NRC} bulls were significantly lower ($P < .001$) than that of medium and high bulls, -0.82 ± 0.04 vs. -0.04 ± 0.05 and 0.74 ± 0.10 kg, respectively. In addition, feed conversion ratio was significantly lower as well for low bulls (6.18 ± 0.06 kg feed / kg gain) compared to medium (6.82 ± 0.07 kg feed / kg gain) high bulls (7.40 ± 0.15 kg feed / kg gain). DMI was significantly different also ($P < .001$), 8.1 ± 0.09 kg/d and 8.9 ± 0.24 kg/d for low and high bulls, respectively.

Table 4.9. Least-squares means and standard errors for dry matter intake, residual feed intake, and feed conversion ratio of low, medium, and high bulls for all measures of RFI

RFI Group[a]	DMI (kg/d)	RFI (kg)	FCR (kg feed/ kg gain)
	$P < .001$	$P < .001$	$P < .001$
MEAN LOW RFIp	7.58 ± 0.11^{b}	-0.66 ± 0.06^{b}	5.62 ± 0.10^{b}
MEAN MED RFIp	8.25 ± 0.12^{c}	0.01 ± 0.04^{c}	6.02 ± 0.11^{c}
MEAN HIGH RFIp	9.07 ± 0.08^{d}	0.77 ± 0.06^{d}	6.60 ± 0.11^{d}
	$P < .001$	$P < .001$	$P < .001$
MEAN LOW RFI_{BF}	7.5 ± 0.11^{e}	-0.63 ± 0.05^{e}	5.62 ± 0.10^{e}
MEAN MED RFI_{BF}	8.3 ± 0.08^{f}	0 ± 0.04^{f}	6.02 ± 0.11^{f}
MEAN HIGH RFI_{BF}	9.0 ± 0.12^{g}	0.75 ± 0.06^{g}	6.60 ± 0.11^{g}
	$P < .001$	$P < .001$	$P < .001$
MEAN LOW RFI_{NRC}	8.1 ± 0.09^{h}	-0.82 ± 0.04^{h}	6.18 ± 0.06^{h}
MEAN MED RFI_{NRC}	8.3 ± 0.12^{h}	-0.04 ± 0.05^{i}	6.82 ± 0.07^{i}
MEAN HIGH RFI_{NRC}	8.9 ± 0.24^{i}	0.74 ± 0.10^{j}	7.40 ± 0.15^{j}

[a] Low bulls are bulls with low RFI values and high bulls are bulls with high RFI values.
[b,c,d,e,f,g,h,i] Values in the same column without a letter in common are significantly different.
* There were 37 low RFIp bulls, 70 medium RFIp bulls, and 31 high RFIp bulls.
* There were 38 low RFI_{BF} bulls, 69 medium RFI_{BF} bulls, and 31 high RFI_{BF} bulls.
* There were 78 low RFI_{NRC} bulls, 48 medium RFI_{NRC} bulls, and 12 high RFI_{NRC} bulls.

Feed consumption and ADG for low, medium, and high bulls across all measures of RFI

Least-squares means for FDCON and ADG140 are shown in Table 4.10. There was no difference among groups (P = 0.56; P = 0.49, respectively) for ADG140 for either RFIp or RFI_{BF}. For FDCON there was a significant difference between RFIp groups (P < 0.05), with lower overall feed consumption for the low bulls (1,068 ± 17 kg) compared to medium (1,151 ± 12 kg) and high (1,253 ± 15 kg) bulls. Similar differences were seen among RFI_{BF} groups (1,065 ± 17, 1,159 ± 12, and 1,239 ± 18 kg of dry matter for low, medium, and high bulls, respectively)

There was a significant difference for the low RFI_{NRC} bulls compared to the medium and high RFI_{NRC} bulls (P < .001) for ADG140, 1.32 ± 0.02 kg/d compared to 1.22 ± 0.02 kg/d and 1.21 ± 0.04 kg/d, respectively. There was not a significant difference (P = 0.63) among RFI_{NRC} groups for FDCON.

WEIGHT140, BF140, and HIPHT for low, medium, and high bulls across all measures of RFI

Bulls in the high RFIp group were fatter than those in the low RFIp group at d 140 (BF140; P < 0.05; Table 4.11), as measured by ultrasound. There was no difference (P > 0.05) between the high and medium groups. No difference existed among the three groups for HIPHT (P = 0.99). Means for WEIGHT140 were nearly identical among the three RFIp groups.

Table 4.10. Least-squares means and standard errors for total feed consumption and average daily gain from beginning to end of test of low, medium, and high bulls across all measures of RFI

RFI Group[a]	FDCON (kg dry matter)	ADG140 (kg/d)
	$P < 0.05$	$P = 0.56$
MEAN LOW RFIp	1,068 $\pm$ 17[b]	1.36 $\pm$ 0.03
MEAN MED RFIp	1,151 $\pm$ 12[c]	1.37 $\pm$ 0.02
MEAN HIGH RFIp	1,253 $\pm$ 15[d]	1.39 $\pm$ 0.03
	$P < 0.05$	$P = 0.49$
MEAN LOW RFI_{BF}	1,065 $\pm$ 17[e]	1.35 $\pm$ 0.03
MEAN MED RFI_{BF}	1,159 $\pm$ 12[f]	1.39 $\pm$ 0.02
MEAN HIGH RFI_{BF}	1,239 $\pm$ 18[g]	1.38 $\pm$ 0.03
	$P = 0.63$	$P < 0.05$
MEAN LOW RFI_{NRC}	1,141 $\pm$ 13	1.32 $\pm$ 0.02[b]
MEAN MED RFI_{NRC}	1,153 $\pm$ 17	1.22 $\pm$ 0.02[c]
MEAN HIGH RFI_{NRC}	1,213 $\pm$ 34	1.21 $\pm$ 0.04[c]

a- Low bulls are bulls with low RFI values and high bulls are bulls with high RFI values.
b,c,d,e,f,g- Values in the same column without a letter in common are significantly different.
* There were 37 low RFIp bulls, 70 medium RFIp bulls, and 31 high RFIp bulls.
* There were 38 low RFI_{BF} bulls, 69 medium RFI_{BF} bulls, and 31 high RFI_{BF} bulls.
* There were 78 low RFI_{NRC} bulls, 48 medium RFI_{NRC} bulls, and 12 high RFI_{NRC} bulls.

There was a significant difference for BF140 ($P < 0.05$; Table 4.11) between the low and medium RFI_{BF} groups. Least-squares BF140 means for the low and medium RFI_{BF} groups were 8.2 $\pm$ 0.33 and 9.2 $\pm$ 0.24 mm, respectively. No difference existed among the three groups for HIPHT ($P = 0.99$). Means for WEIGHT140 were similar among the groups.

There were no significant differences among RFI_{NRC} groups for BF140 ($P = 0.99$; Table 4.11). Significant differences existed between groups for HIPHT ($P < 0.05$). Least squares HIPHT means for the low, medium, and high groups were 119 $\pm$ 0.37 cm, 117 $\pm$ 0.47 cm, 115 $\pm$ 0.94 cm, respectively. WEIGHT140 was also significantly different among RFI_{NRC} groups ($P < 0.01$; Table 4.11). Low bulls (433 $\pm$ 3 kg) tended to be heavier than the medium (414 $\pm$ 4 kg) and high bulls (408 $\pm$ 8 kg).

Table 4.11. Least-squares means and standard errors for WEIGHT140, BF140, and HIPHT of low, medium, and high bulls for all measures of RFI

Year-RFIp Group[a]	WEIGHT140 (kg)	BF140 (mm)	HIPHT (cm)
	P = 0.99	P < 0.05	P = 0.99
MEAN LOW RFIp	425 ± 6	8.1 ± 0.33[b]	118 ± 0.57
MEAN MED RFIp	424 ± 4	9.0 ± 0.24[c]	118 ± 0.41
MEAN HIGH RFIp	426 ± 6	9.3 ± 0.36[c]	118 ± 0.62
	P = 0.79	P < 0.05	P = 0 .99
MEAN LOW RFI_{BF}	422 ± 6	8.2 ± 0.33[d]	118 ± 0.56
MEAN MED RFI_{BF}	427 ± 4	9.2 ± 0.24e	118 ± 0.42
MEAN HIGH RFI_{BF}	422 ± 6	8.9 ± 0.36[d,e]	118 ± 0.62
	P < 0.01	P = 0.99	P < 0.05
MEAN LOW RFI_{NRC}	433 ± 3[b]	8.8 ± 0.23	119 ± 0.37[b]
MEAN MED RFI_{NRC}	414 ± 4[c]	8.8 ± 0.30	117 ± 0.47[c]
MEAN HIGH RFI_{NRC}	408 ± 8[c]	8.9 ± 0.59	115 ± 0.94[c]

a- Low bulls are bulls with low RFI values and high bulls are bulls with high RFI values.
b,c,d,e- Values in the same column without a letter in common are significantly different.
* There were 37 low RFIp bulls, 70 medium RFIp bulls, and 31 high RFIp bulls.
* There were 38 low RFI_{BF} bulls, 69 medium RFI_{BF} bulls, and 31 high RFI_{BF} bulls.
* There were 78 low RFI_{NRC} bulls, 48 medium RFI_{NRC} bulls, and 12 high RFI_{NRC} bulls.

Phenotypic correlations of performance traits with different measures of feed efficiency

Phenotypic correlations of performance traits with FCR, RFIp, RFI_{BF}, and RFI_{NRC} are shown in Table 4.12. Negative correlations were reported for FCR with ADG140 (r = -0.56; P < 0.001) and WEIGHT140 (r = -0.17; P < 0.05). This indicates that bulls with lower feed conversion ratios (more desirable) gained weight at a faster rate and were heavier at the end of test when compared to bulls with higher feed conversion ratios. FCR was positively correlated with DMI (r = 0.29; P < 0.001) and ONTSTWT (r = 0.29; P < 0.001). So, more efficient bulls were lighter at beginning of test and ate less. FCR was not correlated with either BF140 or HIPHT, indicating selection for low FCR will not affect these traits.

As expected, RFIp and RFI_{BF} were strongly correlated with DMI (r = 0.69 and r = 0.70, respectively) and RFI_{NRC} was moderately correlated with DMI (r = 0.24; P < 0.05). Neither RFIp nor RFI_{BF} was correlated with ADG140 or any of the weight traits (Table 4.12). Conversely, RFI_{NRC} was moderately correlated with all weight traits (A205WNWT, r = -0.28, P < 0.001; ONTSTWT, r = -0.21, P < 0.05; WEIGHT140, r = -0.42. P < 0.001). This indicates that as RFI_{NRC} decreases (more desirable), animals will be heavier at the beginning and end of test. RFI_{NRC} was moderately correlated with ADG140 (r = -0.38; P <0.001). RFIp was positively correlated with BF140 (r = 0.18; P < 0.05), but no correlation existed between BF140 and RFI_{BF} or RFI_{NRC}.

Table 4.12. Phenotypic correlations of performance traits with different measures of feed efficiency

Trait	FCR	RFIp	RFI_{BF}	RFI_{NRC}
ONTSTAG	.10	-.04	-.03	-.19*
A205WNWT	.16	-.14	-.13	-.28**
ADG140	-.56**	0	0	-.38**
ONTSTWT	.29**	-.03	-.02	-.21*
WEIGHT140	-.17*	-.03	-.01	-.42**
DMI	.29**	.69**	.70**	.24*
BF140	0	.18*	.08	-.01
HIPHT	-.08	-.03	-.01	-.30**
FCR	1.00	.68**	.68**	.71**
RFIp	.68**	1.00	.99**	.74**
RFI_{BF}	.68**	.99**	1.00	.73**
RFI_{NRC}	.71**	.74**	.73**	1.00
FDCON	.23*	.57**	.68**	.11

* P < 0.05
** P < 0.001

RFIp and RFI_{BF} were not correlated with HIPHT, but a negative correlation was present between RFI_{NRC} and HIPHT ($r = -0.30$; $P < 0.001$).

All measures of feed efficiency, except for RFI_{NRC}, were positively correlated with FDCON. RFIp and RFI_{BF} were both strongly correlated ($r = 0.57$ and $r = 0.68$, respectively), indicating that, as RFI values increases, feed consumption, as well as dry matter intake, also increases. FCR had a moderate correlation with FDCON ($r = 0.23$). All measures of RFI were strongly correlated with FCR, indicating that selecting for RFI will in turn improve feed conversion ratio.

Phenotypic correlations among performance traits

Phenotypic correlations among the performance traits are presented in Table 4.13. DMI was strongly correlated with ADG140 ($r = 0.59$; $P < 0.001$), ONTSTWT ($r = 0.44$; $P < 0.001$), and WEIGHT140 ($r = 0.69$; $P < 0.001$). BF140 was moderately correlated with DMI ($r = 0.38$; $P < 0.001$) and ADG140 ($r = 0.32$; $P < 0.001$). HIPHT was also moderately correlated with DMI ($r = 0.37$; $P < 0.001$) and ADG140 ($r = 0.38$; $P < 0.001$).

Table 4.13. Phenotypic correlations among performance traits

	ADG140	DMI	BF140	HIPHT
A205WNWT	0.11	0.32*	0.12	0.47*
ADG140	1.00	0.59**	0.32**	0.38**
WEIGHT140	0.10	0.69**	0.33*	0.56**
ONTSTWT	0.10	0.44**	0.17	0.45**
DMI	0.59**	1.00	0.38**	0.37**
BF140	0.32**	0.38**	1.00	0.13
HIPHT	0.38**	0.37**	0.13	1.00

* P < 0.05
** P < 0.001

Rank correlations between feed conversion and different measures of RFI

The rank correlation of 0.65 indicates that ranking of bulls from best to worst would have been similar, but there would have been some differences in ranking, whether based on RFIp or feed conversion ratio. Similar rank correlations existed between FCR and RFI_{BF}, and between FCR and RFI_{NRC} (r = 0.65 and r = 0.67, respectively). Tables 4.14 and 4.15 present the three most efficient and three least efficient bulls that would have been selected in the divergent selection experiment if the selection criterion had been RFIp, RFI_{BF}, or RFI_{NRC}, rather than FCR. These results show that ranking of bulls for RFIp and RFI_{BF} were nearly the same each year; order only changed by one in 1980 for both the most efficient and least efficient groups (Tables 4.14 and 4.15, respectively). Bulls chosen for FCR and RFI_{NRC} had a few similar to those for RFIp and RFI_{BF}, but many differences did exist.

Table 4.14. Three most efficient bulls by year based on FCR, RFIp, RFI_{BF}, and RFI_{NRC}

YEAR	FCR	RFIp	RFI_{BF}	RFI_{NRC}
1979	79190	79113	79113	79063
	79090	79090	79090	79090
	79181	79181	79181	79167
1980				
	80115	80115	80115	80116
	80065	80144	80035	80034
	80117	80117	80117	80117
1981	81048	81104	81104	81104
	81128	81027	81027	81027
	81002	81035	81035	81115
1982	82003	82003	82003	82003
	82021	82070	82070	82024
	82064	82142	82142	82065

Table 4.15. Three least efficient bulls by year based on FCR, RFIp, RFI_{BF}, and RFI_{NRC}

YEAR	FCR	RFIp	RFI_{BF}	RFI_{NRC}
1979	79043	79095	79095	79120
	79045	79097	79097	79085
	79006	79006	79006	79124
1980	80120	80118	80120	80104
	80018	80135	80135	80038
	80122	80122	80122	80063
1981	81020	81129	81129	81078
	81112	81051	81051	81042
	81053	81058	81058	81116
1982	82014	82197	82171	82184
	82190	82190	82190	82063
	82017	82103	82103	82167

CHAPTER 5

DISCUSSION

Our results are in agreement with those of Arthur et al. (1996) that variation exists among individual animals for feed efficiency. On average, high RFIp bulls consumed 18.5% more feed than low RFIp bulls and high RFI_{BF} bulls consumed 14% more feed than low RFI_{BF} bulls. Selection for bulls with low RFI will therefore lower overall feed consumption and in turn lower feed costs. There was no difference in feed consumption between RFI_{NRC} groups, and the low phenotypic correlation between FDCON and RFI_{NRC} may suggest selection for reduced RFI_{NRC} will not have an affect on FDCON.

The strong correlations between FCR and growth traits are in accordance with published estimates (Brody, 1935; Koch et al., 1963; Koots et al., 1994; Arthur et al., 2001). Feed intake was not reduced and ADG140 was higher in low FCR bulls (more desirable) when compared to bulls from the high FCR group. The phenotypic relationships among ADG140, DMI, and FCR found in this study are in agreement with others indicating selection against FCR will reduce the amount of feed required for growth and will be valuable to feedlot operations. However, FCR's strong correlation with growth leads to increases in mature BW, resulting in an increase in the cost of maintaining breeding herds (Archer et al., 1999).

The strong correlations with growth rate and size were not the case for RFIp or RFI_{BF}. Both were independent of weight gain and weight traits, which is expected because of the linear regression of DMI on ADG140 and METWT. There were strong correlations between RFI and DMI (r = 0.69 and r = 0.70, respectively for RFIp and RFI_{BF}) and DMI with FCR (r = 0.68). Similar relationships have been published by other authors (Herd and Bishop, 2000; Johnson et al., 2004).

The present study showed that animals with high RFIp generally had greater feed to gain ratios (18% greater) and consumed more feed compared to animals with low RFIp, even though there was no difference in ADG140. Similar relationships were found for RFI_{BF}. No difference existed among groups for ADG140 and bulls in the high RFI_{BF} group had a 20% greater feed:gain ratio. These results agree with those reported by Arthur et al. (2001b). They conducted a divergent selection experiment for RFIp for two generations and reported that the progeny from low RFIp parents consumed 11.3% less feed and had a 15.4% improvement in FCR compared to the progeny of parents with high RFIp.

RFI_{NRC} exhibited a significant difference in ADG140 ($P < 0.05$), where low bulls were favored (1.32 $\pm$ .02 kg/d) compared to medium (1.22 $\pm$ .02 kg/d) and high (1.21 $\pm$ .04 kg/d) bulls. These results are similar to those of FCR; strong correlation with growth rate that may result in increase in mature BW.

As expected, there was a strong phenotypic correlation between RFIp and FCR (r = 0.68). This is an indication that selection for low RFIp will get the same performance outcome of the progeny, but will not have the negative effects of unwanted weight gain and growth because of RFIp's independence with these traits. Also, the rank correlation between FCR and RFIp (r = 0.65), signifies that the animals will still rank in a similar fashion from best to worst based on feed efficiency, although some differences in ranking will be found.

The phenotypic correlations of DMI and RFIp with each other and with growth and BW reported in this study were significantly different from zero. The strong phenotypic relationship of DMI with growth rate (ADG; r = 0.59) and body size (OFFTSTWT; r = 0.69) suggest selection for faster growth rate and greater finish weights would lead to greater maintenance energy requirements and greater overall feed consumption as reported by Archer et al. (1999).

Phenotypic correlations indicate that selection for low RFIp may correspond with less accretion of subcutaneous fat (BFAT; $P < 0.05$). Schenkel et al. (2004) reported a similar, positive phenotypic correlation (r = 0.17) between RFIp and backfat thickness. These results may suggest a relationship between RFIp and meat yield. Brody (1935) suggested animals with greater fat deposits would be less efficient than animals with greater amounts of protein and water, due to fat having a higher gross energy content than protein. Therefore, selection for lower RFIp will produce animals that are more efficient with less fat. A small relationship between RFI and overall meat yield may exist as well.

The correlations of DMI and FCR with ADG are similar to published estimates as reviewed by Koots et al. (1994), as well as those reported by Schenkel et al. (2004).

However, these correlations are in contrast with earlier reports (Gill et al., 1986; Meissner et al., 1995, Gibb and McAllister, 1999), which indicated that the correlations between feed intake and gain or between intake and feed conversion ratio are typically low in feedlot cattle.

When determining the best measure of feed efficiency, several aspects of the beef cattle industry must be taken into consideration. Feed conversion ratio, as expected, will improve feed efficiency, but will likely have negative impacts on mature body weight. Similar results were found when residual feed intake was calculated using NRC expected feed intake equations. RFI_{NRC} was strongly negatively correlated with weight gain and weight traits with no correlation with actual feed consumption. This study supports the conclusion that RFIp and RFI_{BF} proved to be more beneficial estimates of feed efficiency. RFIp did have a weak correlation with backfat thickness, suggesting selection for low RFIp will also be accompanied by a small decrease in fat. If this is not desirable, RFI_{BF} would be the better measurement, as expected intake is adjusted for both production and backfat thickness.

CHAPTER 6

CONCLUSION

Residual feed intake proved to be a better measurement of feed efficiency than feed conversion ratio. RFIp and RFI_{BF} were better measurements than RFI_{NRC}, because of RFI_{NRC}'s strong correlations with weight traits and average daily gain. This RFI measure showed similar effects to those of selecting for feed conversion ratio. Selecting for low RFIp or RFI_{BF} will result in lower dry matter intake and overall feed consumption which may in turn lower feed costs of the production system. This selection should have no adverse effects on weight traits and gains, as RFI is phenotypically independent of these traits. RFI_{BF} may be the better measurement tool for feed efficiency, as it does not have an affect on subcutaneous backfat.

Further research should be performed to assess the actual economic effects of selecting for residual feed intake versus feed conversion ratio, to predict actual savings on feed costs due to such selection.

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