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Enhancing Nutrient Efficiency Through Genetic Selection: Opportunities and Challenges

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Introduction

Intensive animal agriculture has lead to public and legislative concern about environmental and health risks from manure (Meyer and Mullinax, 1999). Solutions to nutrient management issues require an understanding of the flow of nutrients on livestock farms (Koelsch and Lesoing, 1999). Of the nutrients present in manure, nitrogen, phosphorus, sodium, potassium, copper and zinc cause the greatest concern (NRC, 1998). Nutrient inputs to the farm are purchased feed, fertilizer, purchased animals, nitrogen fixed by crops and nitrogen in irrigation water. Nutrients may exit the farm as managed outputs such as animals, milk, or crops. The difference between nutrient inputs and managed nutrient outputs is the imbalance and is an indication of environmental risk. A systems effort that incorporates all components of the farming enterprise is needed to minimize environmental risk. Engineering solutions for the handling, treatment and application of manure and systems of cropping and soils management have received most of the scientific attention (NCSU, 1999). Improving the efficiency of nutrient utilization by animals is also a feasible approach. Feeding programs that influence nutrient excretion have also been extensively studied and described (Prince et al., 2000; Galyean, 2001; Satter et al., 2002). Genetic selection is another method that can be utilized to improve efficiency of nutrient utilization by animals thereby decreasing amount of nutrients excreted in urine and feces and reducing total nutrient output from the farming enterprise and increasing efficiency of production. The objective of this article is to review genetic opportunities to influence nutrient efficiency for concentrated animal feeding operations.

Areas of Opportunity

Efficiency of Nutrient Utilization

The efficiency of using feed N and other minerals by growing pigs, and cattle is generally lower than 0.4 and 0.3, respectively (Verstegen, 1995). Genetic selection to improve the efficiency of nutrient utilization should focus primarily on feed efficiency. It has been reported (Coffey, 1996) that an improvement in feed efficiency of 0.01 results in a 3.3% reduction in nutrient excretion assuming similar growth rate and nutrient retention. Feed conversion is a complex, highly aggregate trait (Figure 1) that is the net result of the interaction of many different component traits (Emmerson, 1997). In general, feed conversion represents a rather crude measure of biological efficiency and consequently, selection for feed conversion influences the underlying component traits in a relatively undirected manner

Historically, genetic selection for improved feed conversion at the farm level can be attributed to increases in growth potential and selection for lean. Rate of growth is the prime determinant of efficiency because of savings in feed used to meet the maintenance requirement (Whittemore, 1993). Maintenance energy costs occur daily, utilizing feed but yielding no economic product. An animal growing slowly will incur the same daily feed maintenance costs as one growing fast, but will have less product to offset the nutrient cost of that feed. The ratio of lean to fat in growth is second only to growth rate as a controller of feed efficiency because the feed energy cost of fatty tissue growth is about four times that of lean tissue growth due to the differing water content of these two tissues (Whittemore, 1993). Several experiments have demonstrated that selection for an index of average daily gain and backfat thickness resulted in correlated improvements in efficiency without significant reduction in genetic potential for feed intake (Sather and Freeden, 1978; Vangen, 1980; Cleveland et al., 1983). However, feed efficiency has been recorded on family groups or on an individual basis in central testing stations since the early 1920s (Ollivier, 1998). Direct selection for feed efficiency has been more recently applied use electronic feeding systems (Eissen et al., 1999; Hyun and Ellis, 2001).

Quantitative genetic approaches have been very successful in improving feed efficiency and its component traits. In a summary of reported parameter estimates for postweaning performance traits in swine (Clutter and Brascamp, 1998), heritability estimates for feed efficiency, average daily gain, daily feed intake and backfat thickness were mostly moderate averaging across studies 0.30, 0.31, 0.29, and 0.49, respectively. Clutter and Brascamp (1998) also reported that the average reported genetic correlations between feed efficiency and average daily gain, daily feed intake and backfat thickness were –0.53, -0.41, and 0.30, respectively, revealing that selection for each of these traits should also improve efficiency. Observation of changes that have occurred in body composition of Large White and Landrace pigs over time is possible by comparing reports of body weight, fat and muscle mass from studies occurring 47 yr apart (McMeekan, 1940; Susenbeth and Keitel, 1987). These data indicate that there has been increased body weight and muscle mass concurrent with decreased body fat over this period of time. There has been a major shift in the rate of muscle accretion between 20 and 30 wk of age. What is not clear is whether the overall rate of muscle protein synthesis has been altered, whether accelerated growth rate is reflected in increased fiber number or in an acceleration of ribosome accretion, or whether there has been an impact on the regulatory links between the diet and the anabolic responses that they mount (Reeds et al., 1993).

Improvements have been observed in swine for increasing lean mass. The National Pork Board (2003) has summarized USDA data since 1955 that indicate a phenotypic trend of 0.28 kg/yr for retail meat produced per pig. A genetic trend of 0.21 kg/yr for kg of lean at 113 kg of body weight in the U.S. Yorkshire population from 1992 to 2002 (National Swine Registry, 2003) indicates that a sizable contribution to observed increases in meat produced per animal is genetic. However, reported genetic correlation between lean percentage and age of puberty (0.40 ± 0.10; Rydhmer et al., 1994) suggests that selection for a greater percentage of lean will delay sexual maturity. In addition, genetic trends in the Yorkshire breed for d to 113 kg, -.42 d/yr, and fat depth, -.58 mm/yr, will substantially contribute to improvements in lean efficiency. Chen et al. (2002) reported results based on the National Swine Registry data that the average genetic trend for lean growth rate was 2.35 g/yr for the Yorkshire, Duroc, Hampshire, and Landrace breeds.

Selection for lean growth efficiency in a closed herd significantly improves growth and carcass traits with increased efficiency, decreased backfat and increased percentage lean cuts when compared to the control (Cameron and Curran, 1995; Lonergan et al., 2001). However, meat quality in the selection line significantly declined with higher Warner Bratzler shear values and less lipid in the longissimus dorsi (Lonergan et al., 2001). A more striking observation is the consistent effect of selection for lean growth efficiency on the ability of fresh pork to hold water. Percentage drip loss was significantly increased in the selection line over the control in the longissimus dorsi, semimembranosus and semitendinosus. It is likely that this effect is a direct result of selection line difference in postmortem pH decline and lactate production by 15 min postmortem (Lonergan et al., 2001).

For dairy cattle, increasing milk production so more nutrients are partitioned to milk formation relative to maintenance will impact the amount of dietary protein that ends up in milk or in feces and urine (Satter et al., 2002). For dairy cattle heritability estimates have been reported (Veerkamp and Brotherstone, 1997) for milk yield, dry matter intake, average live weight, and average condition score as 0.27, 0.44, 0.44, 0.35, respectively. The annual genetic trend of milk yield of Holsteins has accelerated with time and selection goals continue to place major emphasis on yield traits. Hansen (2000) reports that the consequences of selection for milk yield are an additional 115 kg/yr of milk, improved udder conformation, increased body size and a more angular appearance. However, selection for increased milk yield has also resulted in reduced reproductive rates and increased levels of inbreeding in the Holstein breed. Lucy (2001) also reports that selection for milk production has resulted in decreasing reproductive efficiency in dairy cows worldwide. An increased level of inbreeding within Holsteins has approached that point that concern is warranted and may result in crossbreeding dairy cattle becoming a routine practice (Hansen, 2000). Jones et al. (1994) reported that the health care costs during first lactation total $65 for cows in a line selected for milk yield compared to $40 for cows in the control line. Feed intake has been largely ignored until recently, however, there is a fairly strong genetic correlation between yield and gross efficiency (Simm, 1998) indicating that selection for yield should lead to improvements in feed efficiency.

From an extensive review of published parameter estimates in beef cattle (Koots et al., 1994a, b) the weighted mean estimates of heritability for feed conversion ratio, feed intake, postweaning gain, and backfat depth were 0.32, 0.34, 0.31, and 0.44, respectively. However, genetic improvement in beef cattle has been directed primarily toward traits such as fertility, live weight and carcass quality with little emphasis placed on efficiency (Arthur et al., 2001). However, the genetic correlation between yearling weight and feed efficiency of –0.60 (Koots et al., 1994b) and the reported genetic trends of beef cattle breeds for yearling weight would indicate that some improvements in feed efficiency should have occurred without direct selection. Residual feed intake, the difference between actual feed intake and the expected feed requirements for maintenance of body weight and some level of production has also been proposed as an alternative measure of feed efficiency (Koch et al., 1963).

A series of studies (Havenstein et al., 1994a, b; and Quereshi and Havenstein, 1994) have been reported that asses the contribution changes in genetic selection and diet formulation have made on the performance, carcass yield and immune performance of broilers. Influence of genetic selection for several key traits are summarized in Table 1. The 1991 males were 3 times larger in body weight and had a 13% advantage in feed conversion than the 1957 males at the same age. In addition, the 1991 males had a greater carcass yield and more total breast meat at the same age. However, the 1991 broilers had 40 times more tibial dyschondroplasia. The faster the growth rate and the heavier the body weight, the higher the incidence of leg problems and the more difficulty the broilers experienced in movement. The 1991 broilers also experienced 4.4 times more mortality at 42 d of age than the 1957 broilers and they reported that most of the mortality after 21 d of age was associated with flip-overs, ascites, and leg problems. Significant differences were also observed between strains in antibody production. These results suggest that successful genetic selection toward growth and efficiency traits has negatively influenced leg problems, mortality, and the immune system of the broiler.

Reduced Nutrient Excretion

Relatively little is known about genetic differences in nutrient output. Wiener (1979) found that genetic groups of sheep vary in plasma copper levels, indicating that genetic differences in nutrient utilization exist. Crocker and Robison (2002) demonstrated genetic differences in nutrient excretion. They compared maternal and paternal composite lines that had each been selected for 10 generations for number of pigs born alive and lean growth, respectively. The maternal line excreted significantly less P, Ca, Cu, Zn, and Fe than the paternal line or an F1 composite of the two lines. In addition, the F1 pigs excreted ($P < 0.05$) more Ca than either selection line. Crocker and Robison (2002) also compared two Duroc lines divergently selected on testosterone for 10 generations. They found that the high testosterone line excreted greater amounts of all measured nutrients being significantly higher in Cu, K, Ca, and P. Further research is needed to examine genetic differences in nutrient excretion. However, these studies provide convincing evidence that selection could be used as a tool to alter utilization or requirements of nutrients.

Quantitative Trait Loci

Molecular genetic markers are being developed that should augment the quantitative methods that are currently applied. Several genes have been identified that may contribute to efficiency of lean growth or its component traits. Insulin-like growth factor II (*IGF2*) is a paternally expressed QTL affecting muscle mass in pigs and has been identified at the distal end of Chromosome 2p (Amarger et al., 2002). The *PIT1* gene, found on pig chromosome 13, is a positive regulatory gene of growth hormone, prolactin, and thyrotroph-stimulating hormone β (Yu et al., 1995). Significant associations between *PIT1* genotype and birth weight and measures of fat thickness have been reported (Yu, et al., 1995; Brunsch et al., 2002). Porcine melanocortin-4 receptor (MC4R) is a receptor expressed in the brain and mediates the effects of leptin, one of the important signaling molecules in regulation of energy balance and energy homeostasis. Porcine melanocortin-4 receptor genotypes have been significantly associated with fatness, growth rate and feed intake (Kim et al., 1999)

Transgenic Animals

Transgenic pigs have been generated by pronuclear embryo microinjection that carry a parotid secretory protein promoter linked to the *E. coli appA* phytase gene (PSP/APPA) (Golovan et al., 2001). This gene produces phytase a bacterial enzyme in the salivary glands and excretes it in the saliva. Phytate phosphorus is indigestible to the pig and composes 56 to 81% of the total phosphorus in common swine feeds. The phytase excreted in the saliva of the transgenic pigs releases phytate phosphorus from animal feed, reducing the need for dietary phosphorus supplementation and reducing phosphorus excretion. True phosphorus digestibility using soybean meal as the sole source of phosphorus was approximately 50% in normal pigs and nearly 100% in the transgenic pigs. In addition, up to a 75% reduction in total phosphorus content of fecal matter was observed between normal and transgenic phytase pigs (Golovan et al., 2001). While transgenic technologies that improve nutrient efficiency are possible many technical, ethical, and consumer acceptance issues must still be resolved.

Optimization of Reproduction

Reproductive efficiency is also important for sustainable animal production. Kanis (1993) proposes that given that the number of growing pigs to be produced each yr is fixed, a higher number of piglets weaned per sow per yr would result in a smaller breeding herd and an associated reduction in breeding herd feed and manure production. This could be accomplished through improvements in fertility, longevity and reproductive rates.

Eissen et al. (2000) stated "for sustainable production, the trends of increasing energy requirements and decreasing body fat reserves should be accompanied by a higher feed intake of sows during lactation". This may be accomplished by genetic selection, management programs or nutrition and feeding programs. Selection for voluntary feed intake during lactation may need to be considered in breeding programs (Eissen et al., 2000).

It has been reported that 50% of sows are replaced each yr (Stein et al., 1990). Improved longevity in the sow herd would result in proportionately more higher-parity sows with the potential for larger litters reducing the amount of manure producer per slaughter pig. In addition, Kanis (1993) notes that improved longevity will also contribute to a better public and ethical image of pork production.

Improved Health

Intensive animal production systems suffer from a high incidence of clinical and subclinical disease problems. Disease incidence may be related to high genetic potentials for production. Reduced maintenance requirement levels for energy and protein might reduce the flexibility of animals to respond to infections and metabolic stresses. Chronic stress may result in abnormal behavior, injuries of internal organs, decreased immune response, reproductive disorders and a higher metabolism.

Definition of Breeding Objectives

Economic values for the component traits in breeding objectives are generally derived from the estimated decreases in production costs per unit of improvement (Weller, 1994). When formulating indexes animal breeders do not usually consider environmental costs, distribution and processing of manure, or the public image of animal production (Kanis, 1993). With the current public and legislative awareness of possible environmental risks associated with animal production direct costs associated with manure management and potential societal benefits should be considered in defining breeding goals. Therefore economic weights for feed conversion, reproductive rates and breeding herd longevity should be considered for re-evaluation in light of their contribution to nutrient efficiency.

Expression of Genetic Potential

Improved understanding of how to profitably maximize the expression of genetic potential in commercial production situation can enhance nutrient efficiency. Genetic lines that have been selected for increased leanness and low feed intake have been found to be more sensitive to heat stress (Nienaber et al., 1997) and immune system activation (Stahly, 1994: Leninger et al., 1998). In addition, it has been documented that genetic populations selected strongly for leanness and reduced feed intake are more sensitive to environmental stressors than some populations that can be characterized as high feed intake (Schinckel et al., 1999). Hyun et al. (1998) showed that stressors in animal environments generally have negative, additive effects on growth performance. Declines in average daily gain and average daily feed intake have been observed between pigs reared in a controlled research environment and typical commercial production conditions of 30% and 27%, respectively (our unpublished data). Therefore, management systems that allow for animals to express their genetic potential or at minimum match management and nutrition to commercially expressed genetic potential could improve nutrient efficiency.

Implications

Nutrient efficiency in animal production has been and may be further improved through genetic selection on component traits. However, direct selection for nutrient utilization may be expensive causing continued reliance on component traits. In addition, continued selection for improved efficiency may result in reduced product quality, reduced reproductive performance, reduced health, increased mortality, increased structural problems and increased levels of inbreeding. Nutrient efficiency of animal production may also be enhanced by genetic selection for reproduction and health traits and definition of selection objectives taking into account manure management. Management systems that allow for animals to express their genetic potential or at minimum matching management and nutrition to commercially expressed genetic potential can also improve nutrient efficiency.

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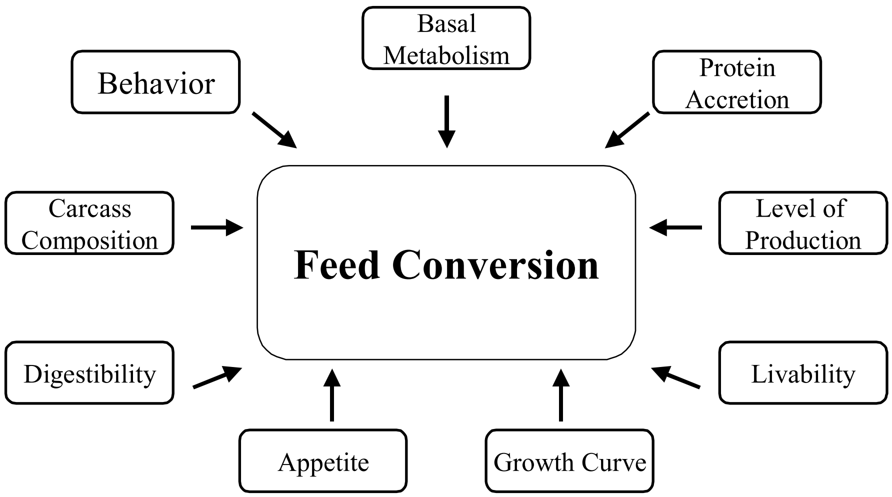
Figure 1. Underlying component traits contributing to feed efficiency.



Modified from: Emmerson, 1997

Table 1. Comparison of a 1957 randombred broiler strain with a 1991 commercial broiler as reported by Havenstein et al. (1994a, b) and Quershi and Havenstein (1994)

	Strain	
Measure	1957	1991
Male body weight at 84 d, g	1,564 [a]	4,770 [b]
Feed conversion at 84 d	3.20 [a]	2.78 [b]
Male carcass yield at 85 d, %	65.8 [a]	73.0 [b]
Total breast meat at 85 d, %	13.5 [a]	16.9 [b]
Tibial dyschondroplasia, %	1.2 [a]	47.5 [b]
Mortality at 42 d, %	2.2 [a]	9.7 [b]
Male total anti-SRBC antibody response at 7 d	0.69 [a]	3.00 [b]

[a,b] Means in the same row with different superscript letters differ $P < 0.05$.