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Animal Diet Modification to Decrease the Potential for Nitrogen and Phosphorus Pollution

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Introduction

In 1996, the Council for Agricultural Science and Technology (CAST) published a report entitled *Integrated Animal Waste Management*. One of the recommendations in that report was to "change animal diets to decrease nutrient outputs" (CAST 1996, 1). Since that time, concentration of animal production units has continued, public concern about the environmental effects of animal manure has increased, and the Environmental Protection Agency (EPA) has proposed more restrictive requirements for concentrated animal feeding operations (CAFO regulations).

Progress has been made since 1996 to decrease nutrient outputs by animals through diet modification and nutrition. The current study describes the existing technological advancements, the decrease in nutrient outputs possible, the degree of acceptance by poultry and livestock producers, and the potential for further technological advancements.

This study focuses on two nutrients and addresses two environmental concerns. The nutrients are nitrogen (N) and phosphorus (P). Nitrogen is a part of amino acids (AAs) that form *proteins*[1] required by all animals; animals consume protein and AAs and then excrete various forms of N. Phosphorus is a mineral nutrient required for bone growth and many important bodily functions. But these nutrients, if directly discharged into surface water in runoff or deposited in water from aerial emissions, can cause significant water pollution.

The first environmental concern is the *volatilization* of N in the form of ammonia (NH_3) from animal manures. Volatilized ammonia returns to the land or water via rainfall, *dry precipitation*, or direct absorption. Volatilized ammonia also can contribute to odor problems. Although ammonia may be beneficial as a fertilizer for agricultural fields, it may not be beneficial in other ecosystems. Manure in the form of a slurry when injected

[1]Italicized terms are defined in the glossary.

into the soil will have minimal losses of ammonia. The higher the N content of the manure, the greater the risk of ammonia loss. For example, most beef cattle are produced in open feedlots. Ammonia losses can represent as much as 70% of the N excreted by those cattle.

The second environmental concern is manure nutrient distribution. Manure is an excellent fertilizer for crop production. If manure nutrients are applied at rates equivalent to plant needs, then environmental impacts are minimal. If manure is applied at higher rates, however, N can leach into groundwater and P can build up in the soil and contaminate the surface water, harming the environment. As livestock and poultry units have increased in size, it has become more expensive to return manure to the cropland where the feed for the animals originated. The manure distribution problem can be local, regional, national, or even international. For example, approximately one-half of the corn grown in Nebraska is exported to other states or to foreign countries. Although there are many cattle feedlots in Nebraska, there is more than enough land on which to spread manure. Conversely, if midwestern corn is exported to Texas for cattle production, to North Carolina for swine production, or to Delaware for broiler production, it is difficult to return the nutrients to the land where the crops originated.

Decreasing the N and P excreted by poultry, swine, or cattle can minimize these two concerns. In the past, there has been little pressure to decrease excretion, so livestock and poultry producers have typically overfed protein (N) and P. Researchers have made key advances in this field during the past decade. Source reduction is the logical starting point to lessen the environmental impact. Significant changes are occurring, but more can be accomplished.

Decreasing Nitrogen and Phosphorus Excretion by Poultry

Nitrogen

The basic approach for decreasing N excretion by poultry is to determine the digestible protein and AA requirements of poultry and then supply digestible protein and AA concentrations in their diet to meet their needs with minimal excesses. To accomplish this objective, several interrelated approaches are involved: (1) develop more accurate requirement values, (2) know the digestibility of the AA in the ingredients being fed, (3) feed the most digestible ingredients economically possible, (4) increase *phase-feeding* (change in diet with increasing age of birds; i.e., decrease the N and AA concentrations more often as the animal ages), (5) feed male and female broilers separately, (6) decrease the margin of safety in the concentrations fed, and, perhaps, (7) feed for optimum animal performance rather than maximum animal performance. Recent development and application of the *ideal protein* concept for poultry has resulted in a new and powerful tool for decreasing N excretion by poultry (Baker and Han 1994). An ideal protein generally is defined as a balance of indispensable AAs that exactly meets the animal's requirements, with no deficiencies and no excesses. This concept incorporates most of the factors mentioned previously.

The ideal protein concept normally uses *lysine* as the reference AA, with the requirements of all other indispensable AAs expressed relative to, or as a percentage of, lysine. Expressing AA requirements as ideal ratios to lysine allows one to predict AA requirements in many different situations (e.g., there are dietary factors such as varying protein and energy concentrations in the diet, environmental factors such as crowding and heat stress, and genetic factors such as capacity for lean versus fat growth, gender, and health status). Use of ideal protein is a powerful tool to improve the estimation of AA requirements for older birds, which excrete the most N in the production cycle and for which the greatest environmental impact can be realized.

Greater knowledge of AA requirements for different genders and at different ages also permits more effective use of phase-feeding (Han and Baker 1993, 1994). For example, Emmert and Baker (1997) showed that the ideal protein concept can be used to predict digestible AA requirements of broiler chicks at any age (even daily) between hatching and 56 days. Consequently, producers could change their AA concentrations as birds age to supply dietary AA concentrations that better match requirements (Pope and Emmert 2001; Warren and Emmert 2000). Another advantage of ideal dietary protein is that it is based on the digestible, rather than the total, AA concentrations in the diet. All of the ideal AA ratios are based on digestible concentrations of dietary AA. There is considerable variation in digestibility of AA among different ingredients and among different AA within ingredients fed to poultry (National Research Council 1994). This variation is especially large for two very important AAs, lysine and *cystine*. Using digestible AA and ratios in diet formulation eliminates the problem of variations in absorption among AAs. This ideal protein approach encourages the use of more highly digestible ingredients and *crystalline AA* to meet the birds' needs more accurately.

Little research has been conducted with poultry to determine directly the effect of using the ideal protein approach on N excretion. Poultry diets are supplemented routinely with *methionine* and/or lysine so that lower concentrations of total protein or AA can be fed (Fernandez et al. 1994; Han et al. 1992). Studies have shown that feeding poultry diets that are 2 to 6 percentage units lower in protein and supplemented with AA can decrease N excretion by as much as 30 to 40% (Ferguson et al. 1998). In addition, ammonia gas emission from the manure also was decreased greatly by feeding these lower-protein diets (Ferguson et al. 1998).

Degree of Acceptance by Producers

Most of the poultry industry routinely adds methionine and, in some cases, lysine to the diet so that lower concentrations of total protein and AA can be fed. Most of the industry also implements phase-feeding, but the number of diet changes may be less than optimum. A substantial part of the industry uses ideal protein to estimate more closely the AA requirements of older birds. The use of these methods, however, is based primarily on simple production economics (i.e., least-cost, most-profitable production of meat and eggs) and is not specifically intended to decrease N excretion. Least-cost diet formulation does not usually include decreasing N excretion because there has been little or no economic incentive.

Potential for Further Decreases

Nitrogen excretion by poultry could be decreased substantially by feeding diets containing more highly digestible ingredients and lower concentrations of total protein with supplements of crystalline AA. New methods for producing more highly digestible ingredients are needed; these methods include improved feed processing, effective enzymes, improved plant breeding or genetic modification, and effective in vitro or chemical assays for rapid laboratory estimation of digestibility. In addition, lower-cost supplements of AA other than methionine and lysine are needed so that total protein can be decreased further. More research on ideal AA ratios for turkeys and laying hens also is needed to increase ideal protein application in these industries.

Phosphorus

Recently, extensive research has been done on decreasing P in poultry manure. Unfortunately, poultry lack sufficient intestinal enzyme (*phytase*) to release P from *phytate*. The emphasis has been on feeding phytase to increase phytate P availability, thus allowing a decrease in the amount of inorganic P that must be added to poultry diets. Yet, several other strategies can be used to decrease P excretion: feed birds closer to requirements and minimize safety margins that traditionally have been high for P; feed according to declining requirements as birds age (i.e., more phases in phase-feeding programs); use a formulation based on the availability of P in ingredients; use a formulation based on results of rapid analyses of organic and total P content of the ingredients at the feed mill; feed birds based on genetic potential (gender and strain); use feed additives (e.g., phytase, vitamin D_3 metabolites, and organic acids); and use novel ingredients from plants genetically bred to contain low-phytate P. These strategies should be used in combinations based on a cost/benefit analysis that includes a realistic cost for excreted P.

Feeding to Requirements

Limited information is available on the P requirements of poultry today. From work published since 1996, it is clear that the National Research Council's (NRC) 1994 recommendations for nonphytate P concentrations no longer apply to today's poultry genotypes. The actual nonphytate P requirements of laying hens, broilers, and turkeys are lower than those published by NRC (1994). Decreases vary with the age of the bird, strain, gender, and type of poultry.

Most research on P requirements has focused on three phases based on age, similar to those cited by NRC (1994). Yet in the case of broilers, the industry is moving away quickly from a three-phase feeding program to a four- or five-phase program. As birds age, the requirements for P decrease, as stated in the NRC (1994) requirements; this lowering of P needs with increasing age still holds true. Thus, increasing the number of age phases will help decrease P in litter. Very little information is available to compare the P requirements of males directly with those of females. But P requirements of males are higher than those of females during specific age phases simply because the growth rate of males is greater than that of females.

In recent years, several researchers have shown that the available P requirement for laying hens during the first cycle is 0.15% (Boling et al. 2000), which requires about 0.32 to 0.35% total P. There has been little research on either the requirement of available P in the second cycle or the impact of the available P concentration in the feed during the first cycle on performance during the second cycle. Boling and colleagues (2000) reported that adding phytase to a diet containing no added inorganic P (0.10% available P) resulted in a performance similar to that of birds fed 0.15% available P and the positive control diet containing 0.45% total P. The poultry industry currently uses 0.4 to 0.6% total P, so sizeable decreases in P feeding and excretion are possible. Under commercial conditions, it is important to keep in mind mixing accuracy, ingredient variability, and field stress situations before acting on these findings.

Phosphorus Availability from Ingredients

Methods for predicting P availability in feed ingredients based on chemical or physical analysis have not been consistently successful, as shown in a study by Sullivan and colleagues (1992). In that study, P soluble in both citric acid and neutral ammonium citrate correlated well with the biological value of dicalcium phosphates and defluorinated phosphates, but not with the biological value of monocalcium phosphates. To date, one or a combination of several analytical methods has been unsuccessful in predicting P availability over a wide range of feed ingredients. Some potential exists for development of inexpensive, reliable analytical procedures in the future (Krzysztof et al. 1995; Liu, Ledaux, and Veum 1998).

The use of *near infrared spectroscopy* for the rapid determination of phytate P and total P in plant ingredients shows promise as a tool for real-time analysis of plant-based ingredients. The potential exists for these determinations to be made on all ingredients, but whether this technology can be used to predict available P has not been determined. Rapid analysis technology at feed mills would allow decreased safety margins and increased formulation precision, resulting in decreased P excretion.

Use of Feed Additives

Extensive research has been conducted recently on the use of phytase to liberate P from the phytate molecule present in plant-based ingredients, making this phytate P potentially available to poultry. Work by Kornegay and colleagues (1996) formed the basis for recommending the use of 939 units of phytase/kilogram (kg) of diet to replace 0.1% of the inorganic P in the diet. These recommendations were based on replacement of a commercial source of dicalcium phosphate of undefined P availability. If phytase is to replace P in commercial production, it is important to determine a realistic *sparing effect*. This replacement can be accomplished by determining the absolute sparing effect of phytase, based on the reduction of inorganic P in the diet that is possible with a known P availability of the inorganic P source. From a commercial standpoint, in circumstances in which the concentrations of P being fed are generally much higher than the requirements, the use of phytase to replace 0.1% of the inorganic P in the diet has been adopted readily.

Other feed additives, such as citric acid and vitamin D_3 metabolites, seem to increase the efficiency and use of P in poultry diets. Unfortunately, the concentrations of citric acid needed for the sparing effect are high (3% or greater) and its use may decrease feed intake and weight gain. Work by Biehl, Baker, and DeLuca (1998) showed that the use of hydroxylated vitamin D_3 metabolites in broiler diets can release phytate P and that different metabolites have different phytate P-releasing activities. Currently, only one vitamin D_3 metabolite (25-hydroxycholecalciferol) is commercially available, and it is not yet used to spare a part of inorganic P in poultry diets.

Novel Feed Ingredients

The development of grains with low-phytate P content (Raboy, Dickinson, and Below 1984) has provided a potential new tool for decreasing P in poultry manure. These new grain sources have lower-phytate P, whereas total P is unchanged; the availability of the P in these low-phytate grains has been shown to be high for poultry. The use of feed additives, such as phytase, together with the high-available-P grains also has been evaluated and shown to be effective in decreasing P in manure. Care must be taken when formulating diets with these low-phytate grains and phytase to ensure that there is enough phytate P in the diet for the phytase to release. Thus, in some cases, lower P sparing would be expected and lower concentrations of phytase should be used. The new low-phytate grains are not yet being used commercially.

Potential for Further Decreases

Several tools are now available to decrease P in poultry waste, and several others are being developed. The authors of the current study suggest that, based on the tools available today (adding phytase, feeding closer to actual requirements, using ingredients with higher P availability, using vitamin D_3 metabolites and “novel” feed ingredients), the amount of P in poultry waste can be decreased by at least 40%. Appropriate implementation of these tools is necessary. When other technologies are available and have been tested commercially, real-time formulation to actual needs of the birds may become a reality and could result in decreases of more than 60% in excreted P.

Decreasing Nitrogen and Phosphorus Excretion by Swine

Nitrogen

Swine must be provided essential AAs in specific amounts and combinations (ratios) to produce lean tissue efficiently. When practical diets are formulated with typical feed ingredients, however, the concentrations and availability of AAs are not optimal. Therefore, to meet the most limiting AA (lysine), excesses of other AAs are consumed, resulting in excess N excretion. Much of the odor from manure is the result of degradation of excreted protein and other forms of N. Improvements in protein efficiency and N use and retention will decrease not only N excretion to the environment but also the potential for odor production (Hobbs et al. 1996).

Both feces and urine contain nitrogenous wastes. The amount of N excreted by pigs is influenced by three factors: the amount of dietary N consumed, the efficiency with which the dietary N is used by the animal for growth and other functions, and the amount of endogenous N (N excreted at maintenance). Little can be done to influence the amount of endogenous N. Thus, to decrease the amount of N excreted by pigs, either the amount of N consumed must be decreased or the efficiency of use of the dietary N must be increased, or both must occur.

Decreasing Excessive Amino Acid Concentrations

Decreasing excessive AA concentrations is one way to influence N excretion. To avoid dietary N excesses, producers should feed diets tailored to meet the AA requirements of pigs (NRC 1998). Feeding excessive protein concentrations should be avoided. Feeding elevated protein or AA concentrations is sometimes needed, however, to achieve maximum performance, such as in genetically lean pigs (especially in lines that have decreased feed intake), in pigs fed β-agonists (feed additives, such as ractopamine), in gilts fed separately from barrows, and in prolific sows nursing large litters. In each case, research data show that swine need higher concentrations of dietary protein to optimize their lean growth rate or lactation performance. Feeding higher concentrations of dietary protein creates a dilemma, however, because feeding the higher protein diets may cause greater N excretion if the correct balance of AAs is not provided.

Using high-quality protein sources with a good balance of AAs meets the requirement of the most limiting AA (lysine) at lower dietary protein concentrations than using low-quality protein sources. Using feed ingredients with highly digestible versus poorly digestible protein also achieves the goal of decreasing dietary protein concentrations. Formulating swine diets on an ideal protein basis is another means of decreasing N excretion. An ideal protein is one in which dietary AAs at specific ratios relative to lysine closely match those needed for lean tissue protein synthesis and maintenance.

Lowering the dietary protein concentration by two percentage points and supplementing the diet with crystalline lysine is one of the most effective means of decreasing N excretion. This popular, cost-effective practice results in a 20 to 25% decrease in N excretion (Pierce et al. 1994). Greater decreases (up to four to five percentage points) in dietary protein are possible, but only if other AAs such as threonine, tryptophan, methionine, and, potentially, valine and isoleucine also are supplemented. Such diets decrease N intake (Prince et al. 2000), maintain animal growth potential (Kerr and Easter 1995), and decrease N excretion by as much as 20 to 50% (Allee et al. 2001; Sutton et al. 1999). Although it is cost-effective to use lysine and methionine, the other supplemental AAs often are too expensive to be used in practical diets. Because of the rapid technological advances in fermentation procedures for synthesizing AAs, however, these crystalline AAs could become more economically feasible in the near future.

Multiphase and Split-gender Feeding

Multiphase and split-gender feeding are other methods for lowering N excretion. Dividing the growth period into more phases with less spread in weight between groups allows producers to meet the pigs' nutrient requirements more closely. Also, because gilts require more protein (AAs) than barrows of similar body weight, separate penning allows feeding of lower protein concentrations to barrows without compromising leanness and performance efficiency in gilts.

Good Feeding Management

Good quality feeding management is another procedure that can decrease N excretion. Any management procedure that improves the overall efficiency of feed use in a swine herd will decrease the total amount of manure produced and should decrease N excretion. Raising genetically lean pigs, using lean-growth promoters such as β-agonists, controlling diseases and parasites, and using feed processing techniques (fine grinding, pelleting, extrusion, micronization, and removal of fiber and germ) are some ways to improve feed conversion efficiency and decrease nutrient excretion. Improved processing methods, genetic modifications, and specialized feed additives all need further refinement through continued research but have the potential to produce major impacts if economically feasible.

Phosphorus

Most of the P in cereal grains and oilseed meals is in the form of phytate (phytic acid). Like poultry, swine lack sufficient intestinal enzyme phytase. As a result, much of the P in practical swine diets is undigested and excreted in the feces; even some of the more highly digestible inorganic P is not totally used and is excreted.

Pigs use P for skeletal formation and a number of physiological and metabolic functions in the muscles, blood, and other soft tissues. Pigs need a certain amount of P daily. If the consumed amount exceeds the requirement, the excess P is excreted. Thus, the amount of P excreted is influenced by the amount of P consumed and the form (digestibility or *bioavailability*) of P in the diet. To decrease P excretion, either the amount of dietary P must be decreased, the efficiency with which dietary P is used must be increased, or both must occur. Several practices are available for swine producers to decrease excreted P.

Avoid Excessive Dietary Phosphorus

Swine should be fed diets that meet the pigs' requirement for available P (NRC 1998). Small overages for safety purposes and to enhance bone development for growing animals kept for breeding purposes may be justified, but excessive fortification of diets with P (a common practice in the past) is not acceptable today.

Use Highly Available Phosphorus Sources

Feed ingredients vary in their bioavailability of P. For example, the bioavailability of P is much higher in wheat than in corn (50% vs. 10 to 20%; Cromwell 1992). Similarly, the bioavailability of P in meat and bone meal is considerably higher than that in soybean meal (90 vs. 25%). Differences also exist among other oilseed meals, by-product feeds, and even inorganic forms of P. Using ingredients with high P availability and formulating diets to an "available P" basis will help decrease P excretion.

Supplement Diets with Microbial Phytase

One of the most effective means of decreasing P excretion is to supplement diets with phytase. This enzyme of microbial origin degrades some of the phytate as it passes through the pig's digestive tract, making the P more available (Cromwell et al. 1993, 1995). As a result, pigs can be fed diets lower in P compared with diets not containing phytase. One study indicated that P excretion is decreased by 30 to 40% in finishing pigs fed diets supplemented with phytase (Pierce et al. 1997).

Use Low-phytate Corn and Low-phytate Soybean Meal

Genetically enhanced, low-phytate corn is now commercially available. This type of corn, which contains the *lpa1* mutant gene that inhibits phytate synthesis (Raboy, Dickinson, and Neuffer 1990), has essentially the same amount of total P, but less than one-half as much in the form of phytate. As a result, the inorganic P is several times greater in low-phytate corn (0.18%) than in normal corn (0.05%) (Cromwell et al. 1998). The P in low-phytate corn is three to four times more bioavailable than that in normal corn (Cromwell et al. 1998; Douglas et al. 2000; Spencer, Allee, and Sauber 2000). Feeding low-phytate corn in diets with decreased P can decrease P excretion by up to 40% (Pierce and Cromwell 1999b; Spencer, Allee, and Sauber 2000). When phytase is added to low-phytate corn diets, P excretion is decreased even further (Pierce and Cromwell 1999a,b).

Genetically enhanced soybeans low in phytate also have been developed recently. Soybean meal prepared from low-phytate soybeans produces results for enhanced bioavailability of P and decreased P excretion that are similar to the results for low-phytate corn (Cromwell et al. 2000a). Combining low-phytate corn and low-phytate soybean meal decreases P excretion by more than 50% (Cromwell et al. 2000b). Low-phytate soybeans are not yet commercially available.

Good Feeding Management

As mentioned previously in the discussion of N, dividing the growth period into more phases with less spread in weight allows feeding diets that meet the pigs' dietary P requirements more closely. Also, penning the genders of pigs separately allows feeding of lower P concentrations to barrows without compromising bone development in replacement gilts. Finally, the use of any good feeding or management practice that improves overall feed efficiency will decrease manure production and decrease P excretion.

Implications for Nitrogen, Phosphorus, and Odor Control

By implementing today's technologies and continuing research and development, it is reasonable to expect a 40 to 50% decrease in N excretion and a 50 to 60% decrease in P excretion in swine operations in the next five years. In addition, there can be a significant decrease in ammonia and hydrogen sulfide emissions (50%) and total odors (30 to 50%). Greater responses may be possible by increasing the digestibility and nutrient profile of grain resources being developed genetically. Practical research trials and demonstrations are needed that will convince producers to implement procedures based on current knowledge, which will decrease N and P excretion while maintaining performance.

Decreasing Nitrogen and Phosphorus Excretion by Dairy Cattle

Nitrogen

Nitrogen on dairy farms can be a threat to air and water quality when more manure nutrients are applied per acre than can be recycled through grain and forage production, as well as when manure nutrients are stored incorrectly or applied to the land improperly (Hutson et al. 1998; Wang et al. 1999). Studies have shown that on the typical dairy farm, N imported in feed, fertilizer, and N fixation in legumes exceeds that exported as protein in milk or meat by 62 to 79%; of this excess N, 62 to 87% comes from imported feed (Klausner 1993). Approximately 70% of the excess N escapes into the off-farm environment through volatilization, *denitrification*, and *leaching* into groundwater (Hutson et al. 1998).

Precision Feeding

Dairy cattle require protein for maintenance and for production (pregnancy, growth, and lactation). In addition, microorganisms are present in the digestive system of cattle that require N for microbial growth during ruminal fermentation of feeds. The N from protein supplied in excess of required amounts is excreted primarily as urea in the urine, and much of the excreted N is volatilized because of urease activity in feces (Hutson et al. 1998; Rotz et al. 1999). Precision feeding is needed to minimize excess N. The first step in precision feeding is to group lactating cows in the herd according to their requirements based on the amount of milk produced. The next step is to determine accurately the requirements of each group to ensure optimum production while minimizing excess N.

Protein imported to meet dairy cattle requirements can be minimized by optimizing the amount of *rumen degraded protein*, which is used to synthesize microbial protein, and *rumen undegraded protein*, which can supply AAs directly to the intestine. The key to optimizing microbial protein production is to supply the rumen with fermentable carbohydrates, which stimulate microbial growth, along with N sources that meet microbial N requirements. Two primary groups of bacteria ferment feed in the rumen: those that ferment sugars and starches and those that ferment fiber. Microbes that ferment sugars and starches prefer peptides and AAs as their N source, and adequate concentrations of ruminally degradable dietary protein act as a growth stimulant to this group. Fiber-fermenting microbes rely solely on NH_3 as their N source; the NH_3 comes primarily from nonprotein N sources in forages and urea, as well as from the degradation of feed protein. An imbalance of protein or feed N sources in the diet can cause excess ruminal NH_3 that is absorbed through the rumen wall and excreted in urine and milk as urea.

Accumulated scientific knowledge about ruminal and animal requirements and available nutrients in feeds has aided in the development of computer models for on-farm precision feeding of dairy cattle (Fox et al. 2000; NRC 2001). These programs use actual farm information to predict animal requirements and diet energy, ruminally available energy and N, and AA available to the animals from the diet in each production situation. To meet the specific AA demands of high-producing cows, the computer model will suggest that certain feeds be included with low protein degradability in the rumen, which will increase the needed AA supply to the small intestine.

In a study reported by Klausner and colleagues (1998), precision feeding decreased N excretion by 34% while improving milk production. Milk production increased 13% and economic returns improved by more than $40,000 per year for a 320-cow dairy herd. Similar results were reported in other studies (Rotz et al. 1999; Tylutki and Fox 2000).

Adoption

There are several reasons why precision feeding and whole-farm nutrient planning have not been adopted on a widespread basis. The emphasis in feeding is on maximizing animal production and profits rather than on minimizing excretion of nutrients. Least-cost ration balancing and the growing use of by-product feeds results in excess N in many diets. In addition, diets typically are formulated to have a margin of safety to minimize production risk due to variation in the composition of the diet delivered to each animal group. Increased knowledge of requirements, coupled with improved analytical methods for feeds and improved accuracy in delivery of the formulated diet to the intended group of animals, should result in producers and nutritionists using smaller safety margins.

Potential for Decreasing Excess Nitrogen

Studies have shown that implementing whole-farm plans that integrate nutrient management across herd, crop, soil, and manure components can decrease nutrient concentrations on dairy farms while increasing economic returns (Rotz et al. 1999; Tylutki and Fox 2000; Wang et al. 2000). Implementation of these changes must not compromise milk production, growth, reproduction, or animal health. These plans focus on two goals: decreasing protein inputs brought on the farm by more accurately formulating diets as described previously and improving the efficiency of nutrient use through improved feed and crop management strategies.

Suggested actions to meet these goals include the following:

1. **Obtain accurate and representative feed assays for feeds used in the dairy operation to allow precision feeding with minimum margins of safety**. Inadequate forage analysis and lack of control of the ingredient dry matter content of feeding were predicted to increase both annual variation in nutrient excretion (110 kg of N excretion and 29 kg of P excretion) and feed inventory required (55,000 kg of corn silage) and to decrease income over feed costs ($21,792) per 100 cows (Tylutki et al. 2000).
2. **Use high-quality forages**. To increase the amount of forages in the diets, forage quality must be high. For example, maximum intake from forages was expected when the neutral detergent fiber (NDF) content was as follows: alfalfa, 40%; grasses, 55%; and corn silage, 40 to 45% (Tylutki and Fox 2000). Many dairy farms do not have an adequate land base to produce their own grains; therefore, farmers should maximize forage quality and then choose purchased concentrates that accurately supplement their forages.
3. **Improve feeding accuracy**. The addition of feeding error was predicted to increase both annual variation in P excretion (8 kg) and corn silage inventory (8,200 kg) and to decrease income over feed costs ($19,148) per 100 cows (Tylutki et al. 2000).
4. **Reformulate rations to improve accuracy as intake changes**. Chase (1999) calculated that by increasing intake 5%, it is possible to decrease diet *crude protein* about one percentage unit to achieve the same pounds of protein intake.
5. **Control the amount of refusals**. On most farms, feed refusals from the lactating herd are fed to replacement heifers, a practice that can result in excess N in the heifers' diet. The amount of refusals should be adjusted to achieve maximum *dry matter intake*; however, extremely high refusals need to be avoided.
6. **Use milk production, milk components, and milk urea N to track the impact of changes in diet formulation and feeding management**. Milk urea N can be used as an indicator of diet protein deficiency or excess (normal range is 12 to 18 milligrams/deciliter).
7. **Obtain manure analysis so land application can account for N and P concentration alterations due to diet modifications**.

Phosphorus

Recent surveys conducted in the United States indicate that producers typically formulate dairy diets to contain 0.45 to 0.50% P (dry basis). This amount is approximately 20 to 25% in excess of the NRC suggested requirement (NRC 2001). This excess P supplementation costs $10 to $15 per cow annually (approximately $100 million annually in the United States) and may contribute to excessive P loading of soils through manure application.

There are several reasons why dairy producers feed more P than is required. Until recently, research information has been lacking on the P requirement of high-producing cows, particularly research that clearly identifies the minimum amount of P required to avoid deficiency symptoms. This lack of information, coupled with inconsistent feeding standards in Europe and North America, contributed to uncertainty about the dietary P requirement. Perhaps the most important factor contributing to excessive P supplementation of dairy cows, however, is the prevailing belief that adding P to the dairy diet will improve the herd's reproductive performance. Aggressive marketing of P supplements also has contributed to unrealistic margins of safety in diet formulation programs.

A number of studies have demonstrated that adding P to diets containing large amounts of low-quality roughage can improve reproductive performance in cattle. A study in England by Hignett and Hignett (1951) is cited widely on this topic. What is often overlooked, however, is that the diets in these studies typically contained 0.10 to 0.25% P before P supplementation. At these low dietary concentrations, P is likely to be deficient for rumen microorganisms (Durand and Kawashima 1980), resulting in decreased diet digestibility and lowered *microbial protein synthesis*. Decreasing both available energy and protein with these low-quality diets could indeed decrease reproductive efficiency. Thus, the P effect on reproductive performance is a secondary one, expressed through a decreased supply of protein and energy. There is no evidence of a direct effect of P on reproductive performance. Modern dairy diets seldom contain less than 0.30 to 0.35% P before the addition of a P supplement. This amount of P is more than adequate for rumen microorganisms. A review of lactation studies using more typical dairy diets shows no relationship between dietary P content and reproductive performance (Satter and Wu 1999).

Requirement for Phosphorus

The recent publication *Nutrient Requirements of Dairy Cattle* (NRC 2001) provides an excellent summary of the literature on P feeding of dairy cows. The recommended P concentration of diets for cows producing 25 or 55 kg of milk daily is 0.32 and 0.38% (dry basis), respectively. A study appeared after the NRC publication (Wu et al. 2001) that measured bone strength and P content of cows fed diets containing approximately 0.31, 0.39, or 0.47% dietary P for two or three consecutive lactations. The study indicated that the 0.31% P diet was borderline deficient for cows producing more than 11,800 kg of milk in a 305-day lactation. Results of this study and a study by Valk and Ebek (1999) establish that high-producing dairy cows will begin to show signs of P deficiency when the diet contains less than 0.30% P. Knowing this amount allows calculation of a reasonable margin of safety rather than guessing, as has been the practice. Although the NRC (2001) described requirements, they used conservative estimates to determine P availability in feedstuffs; so, in fact, a modest safety margin is already included in the NRC requirements.

Decreasing Dietary Phosphorus

Phosphorus fed in excess of a cow's requirement is excreted in the feces, with only small amounts excreted in the urine. Storage of P in the body is limited to the amount present in normal bone mass, but bone P and calcium are mobilized in early lactation to meet the sudden demands of lactation. As much as 500 to 1000 grams (g) of P may be mobilized from bone in early lactation; this P, of course, must be replaced later in lactation. Milk contains approximately 0.09% P (0.9 g/kg milk); so P mobilized from bone can support a significant amount of milk production in early lactation, which avoids the need to have enriched dietary concentrations of P in early lactation when feed intake lags behind milk production.

Implications

High-producing dairy cows consuming diets containing 0.31, 0.39, or 0.47% dietary P excreted 43, 66, and 88 g fecal P/day, respectively (Wu et al. 2001). Essentially all of the P fed in excess of the 0.31 % treatment was excreted in the feces. Feeding high-P diets increases not only the P content of the manure but also the vulnerability of the manure P to surface runoff. When manure collected from cows fed diets containing 0.31 or 0.49% P was surface applied to plots at equal manure application rates, concentrations of dissolved reactive P in water runoff were almost ten times higher with manure from cows fed the higher-P diet (Ebeling et al. 2002). Most P is insoluble and is associated with soil, but the dissolved reactive P is soluble in water and with rainfall or snow melt will be in the water runoff. When manure was applied at equivalent P rates, runoff of dissolved reactive P was approximately four times higher with manure from cows fed the higher-P diet. One might expect, therefore, that decreasing dietary P from an industry average of 0.45 to 0.50% to the NRC requirement of 0.38% P (high-producing cows) could decrease surface runoff from manure by a minimum of 50%. The plots used in this study had recently been harvested for corn grain that had been no-tilled.

Thus, decreasing dietary P has two important effects. First, the amount of P in manure decreases, and, therefore, the amount of cropland required to use the manure decreases proportionately. Second, the risk of runoff of P from surface-applied manure is decreased when lower concentrations of P are fed. Decreased risk of runoff P is relevant for all dairy producers that surface-apply manure, regardless of the amount of land they have available for spreading manure. The majority of dairy diets formulated today contain 0.35 to 0.40% P before addition of a P supplement. Therefore, by eliminating some or all of the supplemental P, most producers will be able to reach appropriate dietary P concentrations. But producers that use large amounts of by-product feeds containing high concentrations of P may be feeding diets that contain 0.42 to 0.46% P without a P supplement. By-product feeds are often priced lower than grains or oilseeds, so their use in dairy diets is increasing, and it is difficult to minimize P feeding. Dairy producers who choose to include large amounts of by-product feeds rich in P will need to consider injecting manure into the soil as well as using a larger land mass to accept the manure.

Future Benefits of Advances

A 20% decrease of dietary P can be achieved without decreasing animal performance, and this decrease will result in a 25 to 30% decrease in the P content of manure and a similar decrease in the amount of land required for manure application. Perhaps more importantly, runoff of dissolved reactive P from surface-applied manure can be decreased by more than 50% if dietary concentrations of P are decreased by 20%. The dairy industry has started to lessen dietary P concentrations, but progress to date may be characterized as simply a good beginning.

Decreasing Nitrogen and Phosphorus Excretion by Beef Cattle

Nitrogen

Environmental concerns for beef production systems generally are limited to confined feedlot production systems. Formulating diets that do not exceed requirements is important because all protein in excess of requirements has no value to the animal and is excreted in the urine as urea-N. After excretion, urea is hydrolyzed by urease to ammonium (NH_4+) and CO_2. Urease is ubiquitous and conversion to NH_4+ is rapid, potentially within a few hours of excretion (Mobley, Island, and Hansinger 1995; Muck and Richards 1980). Ammonium ions are gradually converted to NH_3, which is volatile. Therefore, protein supplied above requirements for beef cattle is correlated positively with ammonia emission from beef cattle production systems.

Precision Feeding

Cattle can use many unique feeds because of the microflora in their rumen. Although this ability is advantageous, the rumen microbial population presents some challenges for diet formulation. The primary challenge for protein nutrition is that rumen microbes vary in their use of different feeds. Once proteins pass through the first two compartments of the cattle stomach, they are digested and absorbed in a manner similar to that of simple-stomached species (e.g., pigs and poultry). The beef or dairy animal has a protein requirement that must be met by AAs absorbed in the small intestine. For beef cattle, the NRC publication *Nutrient Requirements of Beef Cattle* (NRC 1996) uses the term *metabolizable protein* (MP) to describe protein absorbed at the small intestine. Protein that reaches the small intestine is a combination of *bacterial protein* (BCP) originating from the rumen and *undegraded intake protein* (UIP). Microbes synthesize protein in the rumen to produce BCP. The microbes have a protein requirement that must be met to optimize fermentation in the rumen. The protein used by microbes is termed *degraded intake protein* (DIP). Nutritionally, many complex interactions occur that must be predicted in order to assess accurately the protein requirements of microbes (DIP) and of the animal (MP = BCP + UIP). The BCP contribution to MP requirements can change with every diet composition change, and therefore UIP can be adjusted to meet the animal's remaining need for protein. Diet formulation will become more precise as nutritionists adopt new practices and as research provides updates for the MP system.

Nutritionists previously used the crude protein (CP) system that assumes protein from urea, soybean meal, and corn are equivalent. The CP system is inappropriate because urea is 100% DIP, soybean meal protein averages 70% DIP, and corn protein is variable (40 to 60%) in DIP, depending upon the processing method. By defining requirements for the MP system more precisely, nutritionists should be able to formulate diets more accurately and decrease N excretion. As a rule, UIP commonly is provided in excess of requirements for MP because of the relatively large component of UIP in corn protein. Except when used early in the feeding of young cattle, supplemental UIP has little value in meeting the MP requirement of the animal. The majority of the supplemental protein needs of feedlot animals is DIP to promote BCP production.

Meeting Nitrogen Requirements

Another important component of evaluating protein supply in relation to requirements is that requirements for MP decrease during the finishing period. Therefore, if dietary protein is provided to meet and not exceed the requirements, the diet must change over time in the feedlot. Erickson, Klopfenstein, and Milton (2000) compared phase-feeding using the MP system to a conventional CP concentration used in the industry (Galyean 1996) with both yearlings during the summer and calves during the winter-spring months. Erickson and colleagues found that performance was identical between the different CP concentrations and the phase-fed treatments. Nitrogen intakes, however, were decreased by 11.4 and 18.4%, leading to 15 and 32% decreases in N volatilization from manure when comparing conventional protein concentrations with the MP system for calves and yearlings, respectively.

Adoption

Nutritionists and producers are reluctant to lower dietary protein to concentrations of DIP and UIP that just meet requirements. Reasons for their reluctance include concern with the accurate assessment of the protein content of diet ingredients, accuracy of current estimates of the DIP and UIP content of feeds, difficulty with phase-feeding, and continued refinement of DIP requirements for different diets commonly used in feedlots. Also, because urea is relatively cheap, overfortification does not increase diet cost significantly. Furthermore, there has been no incentive to decrease emissions.

Potential for Decreasing Nitrogen Excretion

Beef cattle are rather inefficient in converting dietary protein into lean tissue. The majority of the protein fed (≥80%) is excreted. One method that could lower N excretion is to find growth-promoting techniques or technologies that increase the animal's protein retention and increase the efficiency of dietary protein use. A second method is to optimize bacterial fermentation and protein production with feedlot diets. Research must address how different feed ingredients, processing conditions, and diet formulations influence the DIP requirement. A third method, possible in the future, will be adoption of a metabolizable AA system. Conceptually, this system is similar to an ideal protein diet for swine and poultry. Currently, formulation of diets on the basis of AA supplied at the small intestine is challenging because the BCP supply must be predicted accurately. Once the contribution of BCP is known, both in terms of exact AA profile and total amount of BCP with different diets, then the difference between the supply from microbes and the animal's requirement can be provided by UIP. With corn-based feedlot diets, the UIP supply is greater than the requirements of feedlot cattle in most situations. Corn contains too much UIP, which results in more MP than required. Therefore, another method to lower N excretion would be manipulation of the DIP:UIP ratio of corn protein in favor of DIP, either by genetic changes of the plant or by different processing methods.

Phosphorus

Current Status of Phosphorus Requirements

One approach to minimize P excretion is to lower manure P by decreasing the amount of P offered in diets. As with N, however, the dietary supply must be adequate to meet requirements for optimum performance. In the past, research was conducted on P because P was expensive, and optimum amounts for feedlot diets were based on concentrations that would give maximum performance and least-cost rations. Because feedlot design has advanced to control runoff from beef cattle production systems, the primary concern with P now is not over-spreading manure on adjacent crop acres (Nelson 1999).

Surprisingly, there are few data for P requirements of beef cattle weighing between 300 to 600 kg fed high-grain diets. Maintenance requirements have been documented with calves (Challa, Braithwaite, and Dhanoa 1989; Ternouth et al. 1996) or cows (Call et al. 1986) because of the ease of feeding diets composed primarily of forages fed at maintenance and low in P. In many parts of the world, soil P is low, which correlates to low concentrations of P in forages grown there. The largest concerns for managing P from an environmental perspective, however, are the concentration of P in feedlots and the spreading of the P in manure on croplands at concentrations exceeding crop requirements.

Phosphorus requirements for gain with feedlot cattle are an important consideration because the cattle typically are gaining more than 1.5 kg per day. Ellenberger, Newlander, and Jones (1950) conducted whole-body analysis for P with dairy cattle ranging in age from newborn calves to cows older than six years. Based on the 1996 NRC recommendation, which cites the Ellenberger study, the P requirement for gain is 3.9 g/100 g of retained protein. Typical feedlot performance with cattle in the normal weight ranges results in protein gains of 150 to 200 g per day. The total amount of P required in the diet is the sum of maintenance and gain requirements. Based on the 1996 NRC equations, which assume 68% absorption by cattle weighing 300 to 600 kg in the feedlot, approximately 15 to 26 g of P are required per day. This amount equals 0.2 to 0.3% of the diet as P, using feed intakes of 9 to 11 kg per day. Erickson and colleagues (1999) fed yearlings 71 to 162% and fed calves 76 to 190% (Erickson et al. 2002) of the NRC-predicted requirements for P and observed no differences in feedlot performance or bone characteristics. Call and colleagues (1978) fed developing heifers either 66 or 174% of NRC-predicted requirements for P and observed no differences in gain, body weight, or reproductive performance over a two-year period. Based on current research with beef cattle, the NRC predictions overestimate the P required for optimum performance.

Acceptance

Many nutritionists believe that the 1996 NRC requirements for P are too low (Galyean and Gleghorn 2001). As a result, dicalcium phosphate and other mineral P sources commonly have been supplemented in feedlot diets. Grains generally contain relatively large amounts of P. Corn, the most common grain used in beef finishing systems (Galyean 1996), contains 0.32 ± 0.04% P in its dry matter (NRC 1996). Grains and oilseed meals have a large proportion of total P as phytate P. This organically bound P is thought to be completely available to ruminants because rumen microbes possess the enzyme phytase. When incubated with rumen fluid, all phytate P was released and was not detected in feces of dairy cows (Morse, Head, and Wilcox 1992).

Potential for Decreasing Phosphorus Excretion

If the 1996 NRC requirements for P are correct at 0.2 to 0.3% of dietary dry matter, then grain-based finishing diets should have adequate P without adding supplemental P because of the relatively large amount of P provided by the grain. Beef producers should discontinue supplementation of mineral P in feedlot diets. The beef industry is questioning the supplementation strategies that have been commonly accepted in the past. Some nutritionists are adopting new formulation strategies for P for two reasons: they accept the recent research indicating that fortification of P in diets is unnecessary because requirements may be lower than previously accepted, and they have concerns about the environmental consequences of overfeeding P.

Future Considerations

Three factors affecting dietary requirements need to be considered in further decreasing dietary P concentrations: maintenance requirements, the amount of retained P (i.e., the requirement for gain), and the absorption or bioavailability of P (68% may be too low). Because more work already has been conducted on the first factor (evaluating maintenance requirements), the P requirement for growth and the bioavailability of P are the least well established for finishing beef cattle. These factors need to be addressed to determine if P can be decreased in feedlot diets. Currently, corn grain contains P that may often result in dietary concentrations in excess of requirements for finishing cattle that are fed typical U.S. feedlot diets. Lowering P in beef feedlot diets below the concentration provided in typical grain diets would require changing the P content of grain or using unique, nongrain feed substitutes. The authors of the current study recommend determining the dietary P concentrations being fed, removing all supplemental P from finishing diets, and applying manure P at concentrations that match crop requirements. In some cases, unique feed ingredients commonly fed in feedlots today contain higher concentrations of P than corn grain does. In these cases, manure P typically is elevated, increasing the land requirements for applying the manure nutrients at concentrations that match crop requirements.

Glossary

Bacterial protein (BCP). The crude protein in rumen bacteria, made up of amino acids and nucleic acids.

Bioavailability. The amount of nutrient in the diet that can be absorbed in a form that can be used in the body for metabolic functions of that nutrient.

Crude protein. A measure of dietary protein that is based on the assumption that the “average” amino acid in a protein contains 16% nitrogen.

Thus, total chemically determined nitrogen x 6.25 (100 divided by 16) = crude protein.

Crystalline amino acid. Amino acid provided in its pure chemical form.

Cystine. A sulfur-containing amino acid that can supply up to one-half of the total sulfur amino acid (methionine + cystine) requirement.

Degraded intake protein (DIP). Crude protein that is degraded in the rumen by microorganisms.

Denitrification. The process whereby fixed nitrogen is converted to nitrogen gas (N_2) and nitrous oxide and returned to the atmosphere.

Dry matter intake. The amount of completely dry feed consumed by animals.

Dry precipitation. Chemicals combining in the atmosphere and falling to the earth.

Ideal protein. A protein with a balance of amino acids that exactly meets an animal's amino acid requirements.

Leaching. The process whereby plant nutrients move down through soil into groundwater.

Lysine. A basic amino acid required for tissue maintenance and growth.

Metabolizable protein (MP). Protein (amino acids) absorbed from the small intestine of ruminants. Contains bacterial protein and undegraded intake protein.

Methionine. A sulfur-containing amino acid required for tissue maintenance and growth.

Microbial protein synthesis. The process whereby protein is synthesized in the rumen as microorganisms grow and multiply.

Near infrared spectroscopy. Feed analysis using near infrared lightwave reflectance.

Phase-feeding. Changing the nutrient concentrations in diets as animals age to meet their nutrient requirements more precisely.

Phytase. An enzyme that degrades phytate, making the phosphorus available.

Phytate. A complex, organic form of phosphorus.

Protein. A polymer composed mainly of amino acids, which contain the elements carbon, hydrogen, oxygen, nitrogen, and sulfur.

Rumen degraded protein. See degraded intake protein.

Rumen undegraded protein. See undegraded intake protein.

Sparing effect. The process whereby one chemical or metabolite decreases the need or requirement for another nutrient.

Undegraded intake protein (UIP). Feed protein that is not degraded in the rumen by microorganisms.

Volatilization. The process whereby chemicals evaporate at ambient temperature.

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