Animal management to reduce phosphorus losses to the environment[1]

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ABSTRACT: Water quality in the United States is threatened by contamination with nutrients, primarily nitrogen and phosphorus. Animal manure can be a valuable resource for farmers, providing nutrients, improving soil structure, and increasing vegetative cover to decrease erosion potential. At the same time, application of manure nutrients in excess of crop requirements can result in environmental contamination. Environmental concerns with P are primarily associated with pollution of surface water (streams, lakes, rivers). This pollution may be caused by runoff of P when application to land is in excess of crop requirements. Increased specialization and concentration of livestock and crop production has led to the net export of nutrients from major crop-producing areas of the country to areas with a high concentration of animal agriculture. Concentrated animal agriculture has been identified as a significant source of P contamination of surface water. Areas facing the dilemma of an economically important livestock industry concentrated in an environmentally sensitive area have few options. If agricultural practices continue as they have in the past, continued damage to water resources and a loss of fishing and recreational activity are inevitable. If agricultural productivity is decreased, however, the maintenance of a stable farm economy, a viable rural economy, and a reliable domestic food supply are seriously threatened. Decreasing the P content of manure through nutrition is a powerful, cost-effective approach to reducing P losses from livestock farms and will help farmers meet increasingly stringent environmental regulations. This paper reviews opportunities available to reduce the P content of livestock manure, including more accurate interpretation of the published P requirements of animals, improved diet formulation and group-feeding strategies to more precisely meet requirements, and approaches to improve availability of feed P for monogastric and ruminant species.

Key Words: Cattle, Phosphorus Excretion, Phytase, Poultry, Swine

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Introduction

Increased specialization and concentration of livestock and crop production has led to the net export of nutrients from major crop-producing areas of the country to areas with a high concentration of animal agriculture. Livestock utilize P inefficiently, excreting 60 to 80% of that consumed. Therefore, the majority of P brought on to the farm in feed stays on the farm, rather than being exported in meat or milk.

Animal manure is typically land-applied to supply nutrients for crop growth, but N and P are in imbalance in manure relative to crop needs. Land application of manure to meet the N needs of the crop results in the overapplication and accumulation of P in soils. Historically, P contamination of surface water was thought to be associated primarily with erosion. As application of P in excess of crop requirements continues, however, soil becomes saturated and runoff of P can occur independently of erosion (Daniel et al., 1992).

Areas facing the dilemma of an economically important livestock industry concentrated in an environmentally sensitive area have few options. If agricultural practices continue as they have in the past, continued damage to water resources and a loss of fishing and recreational activity are almost inevitable. If agricultural productivity is reduced, however, the maintenance of a stable farm economy, a viable rural economy, and a reliable domestic food supply are seriously threatened. Practices that reduce P losses from farms without

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impairing profitability must be developed and implemented.

Improved understanding of P digestion and metabolism in livestock will improve efficiency of P utilization, reducing P excretion and minimizing the imbalance of N and P in manure. This paper will review the requirements of dairy cattle, beef cattle, swine, and poultry species for dietary P, four nutritional approaches to reducing the P content of manure, and the economic impact of reducing P excretion and losses from the farm system.

Role of Animal Agriculture

Concentrated animal agriculture has been identified as a significant source of P contamination of surface water (median contribution = 7 to 48% of total P loads, depending on watershed; Smith and Alexander, 2000). These losses were calculated with a model using measured stream water quality data and spatial data on sources, landscape characteristics, and stream properties. The relative importance of different nutrient sources varies greatly in different regions of the United States. Animal agriculture is a minor source of nutrient pollution in the populous Northeast and Great Lakes, for instance. In contrast, the Shenandoah Valley of Virginia is an example of an area of intensive animal agriculture associated with increased contamination of surface water. The Shenandoah Valley has the highest population of both dairy cattle and poultry in the state, and as many as 20% of the dairy farms also have at least one poultry house. Estimated manure nutrient production in the Shenandoah Valley exceeds crop requirements on a yearly basis. Manure phosphate per acre of cropland increased by 90% between 1978 and 1992, and an analysis of soil tests in 1993 and 1994 indicated that nearly 90% of samples were ranked “high” or “very high” in P (Pease et al., 1998). Although there is controversy as to the threshold level of soil test P that leads to P runoff, these soils clearly need no additional P.

The link between animal numbers, manure application to a limited land area, and P contamination of surface water was also demonstrated in the Lake Okeechobee watershed in Florida. From 1973 to 1988, P concentration in the water of Lake Okeechobee in Florida increased by 250% (Negahban et al., 1993). During this same time period, dairy cow numbers in the three counties surrounding the lake increased by more than 900 cows/yr (Boggess et al., 1997), and dairies were identified as the source of 40% of the P load to the lake (Negahban et al., 1993). The appearance of lake-wide algae blooms led to the imposition of stringent regulations designed to reduce agricultural runoff.

Increasing Regulatory Pressure

Increasing public concern with water quality and increased awareness of the effects of concentrated livestock production have led to the development and implementation of increasingly stringent environmental regulations. Greater pressure on states from the federal government in the last decade to enforce federal clean water regulations has significantly increased the level of regulatory pressure felt by farmers.

One key change in water quality regulations in the past 5 yr is the shift from a primary focus on N to an increasing focus on P contamination of surface water. Limiting manure application to the P needs of the crop is one way to avoid continued accumulation of P in soil, and to minimize potential P runoff and contamination of surface water. Regulations limiting manure application to the P needs of the crop are in place for all farms in Maryland (Water Quality Improvement Act, 1998) and for poultry farms in Virginia (Virginia Poultry Waste Management Program, 1999). The recently finalized federal Concentrated Animal Feeding Operation regulations to address water pollution call for site-specific decisions on whether N- or P-based manure application limits are needed to protect water quality (EPA, 2001). Also, some federal cost-share funding is now being linked to the development and implementation of P-based nutrient management plans. Phosphorus-based nutrient management regulations dramatically increase the amount of land required to dispose of manure, and will have a severe, detrimental effect on the agricultural economy in areas of intensive animal agriculture.

Phosphorus Requirements

Dairy Cattle

Phosphorus is required by lactating cows for bone mineralization or growth, milk secretion, energy metabolism, fatty acid transport, phospholipid synthesis, amino acid metabolism, and protein synthesis. Phosphorus is also a component of nucleic acids involved in cellular metabolism, enzyme systems, and buffer systems. Regulation of P balance involves absorption from the small intestine, mobilization from bone, and secretion in saliva. Phosphorus (phosphate) absorption in the small intestine increases on an absolute basis with increasing P intake despite a reduction in apparent digestibility of P in response to increasing dietary P content.

The National Research Council periodically reviews and summarizes the nutrient requirements of various species and issues publications listing these requirements. In the current dairy NRC, the P requirement is described using a factorial approach (NRC, 2001). The absorbed P requirement to support maintenance, growth, pregnancy, and lactation are calculated and summed, and then adjusted for availability of P in feedstuffs to calculate the amount of P that must be fed. Table 1 describes the total absorbed P requirement for nonpregnant, mature lactating Holstein cows of varying milk yield and DMI, and the dietary P concentration

Table 1. Phosphorus requirements for Holstein cows (600 kg BW) with varying DMI and milk yield (NRC, 2001)

	Milk yield, kg/d						Milk yield, kg/d					
DMI, kg/d	30	32	34	36	38	40	30	32	34	36	38	40
	Absorbed P requirement, g/d						Dietary P requirement, % of diet DM[a]					
21.8	49	51	52	54	56	58	**0.35**	0.36	0.37	0.39	0.40	0.41
22.5	49	51	53	55	57	58	0.33	**0.34**	0.35	0.37	0.38	0.39
23.2	50	52	54	56	57	59	0.32	0.34	**0.35**	0.36	0.37	0.38
23.9	51	53	54	56	58	60	0.32	0.33	0.34	**0.35**	0.36	0.38
24.6	52	53	55	57	59	61	0.31	0.32	0.34	0.35	**0.36**	0.37
25.3	52	54	56	58	60	61	0.31	0.32	0.33	0.34	0.35	**0.36**

[a] Boldface data indicate dietary P concentrations based on NRC-predicted DMI for the specified level of milk yield.

required for these nonpregnant mature cows. The P availability used to calculate this dietary requirement is from the sample lactating cow diet included in the software distributed with the publication.

An important point to emphasize is that, like other nutrients, the requirement of the animal for P is for absorbed quantities of P, not dietary concentrations. For convenience in balancing rations, P requirements are commonly expressed as a percentage of DM. The actual dietary concentration required to yield the required quantity of P, however, varies with dry matter intake and feed source. For instance, the current NRC requirement for a 600-kg dairy cow producing 36 kg/d of milk is ~56 g of absorbed P per day (Table 1). The dietary P concentration required in the dietary DM for this cow is 0.37 to 0.33%, as DMI varies from 20 to 25 kg/d.

Phosphorus Requirements for Beef Cattle

The P requirements for beef cattle in the latest NRC (1996) are calculated using the factorial method and are based on current body weight and rate of protein gain, milk production, and fetal weight in the last 3 mo of pregnancy for cows and heifers. The maintenance requirement is considered to be 16 mg of P per kilogram of body weight, reflecting endogenous fecal P loss. Phosphorus requirements for growth are calculated as 3.9 g of P per 100 g of protein gain, based on data published in 1950. Phosphorus needs for milk are similar to those in the dairy NRC, at 0.95 g/kg milk, and fetal P requirements are 7.6 g/kg fetal weight during the last 3 mo of gestation. Availability of feed P is assumed to be 68% from all sources. As an example, the dietary P requirements (grams/day) for growing and finishing Angus steers are presented in Table 2. The dietary P concentration needed to meet these requirements varies widely with DMI, breed, BW, growth rate, and physiological state.

These published requirements may overestimate the actual P requirements for growing and finishing cattle. Erickson et al. (1999) fed 66 crossbred finishing steers diets containing 0.14, 0.19, 0.24, 0.29, or 0.34% P for 105 d. The measured P intakes ranged from 15.9 to 36.4 g/d; the calculated P requirement for these steers was 22.5 g/d. Although the two low-P diets were deficient in P according to the NRC (1996), these authors observed no effect of dietary P on DMI, ADG, feed:gain ratio, carcass weight, bone strength, meat tenderness, or marbling. They concluded that corn-based diets contain adequate P to meet the requirements of growing and finishing steers without any supplemental P.

Phosphorus Requirements for Swine

The P requirements for swine as reported in the latest swine NRC (1998) can be found in Table 3. Although the requirements listed in the NRC are the best available estimation of the requirement, it is important to realize that the accuracy of these requirements is limited by

Table 2. Phosphorus requirements for growing and finishing Angus cattle of varying body weight and average daily gain (NRC, 1996)

	Body weight, kg					
ADG, kg/d	200	250	300	350	400	450
	Dietary P requirement, g/d					
0.5	11	11	12	12	14	15
1.0	16	16	16	16	18	18
1.5	21	21	20	20	21	21
2.0	26	25	25	24	25	24
2.5	31	30	29	27	27	26

Table 3. Dietary P requirements (% of dietary DM) of swine of varying body weight (NRC, 1998)

	Body weight, kg			
Item	10–20	20–50	50–80	80–120
Total P	0.60	0.50	0.45	0.40
Available P	0.32	0.23	0.19	0.15

available data. In the latest swine NRC (1998), there were 151 references cited with regards to P requirements. Of those, only 37 were from the 1990s, and only 5 of those 37 addressed P requirements. Perhaps more importantly, only 1 of the 37 addressed the bioavailability of P from feed ingredients. Therefore, the majority of data used to support current estimations of P requirements is 15 yr old or older. As a result, the accuracy of these estimations may need to be questioned. Certainly the genetics and production characteristics of the U.S. pig population have changed drastically during that period of time. In addition, the genetics and production characteristics of grain sources used in swine diets have also changed.

Historically, P requirements for pigs were reported as total P (P_{total}). In recent years, awareness has increased that the bioavailability of P differs among feedstuffs. For this reason, the swine industry has moved to defining the P requirement on a digestible or available P ($P_{available}$) basis. The P requirements listed in the most recent swine NRC (1998) are expressed both as the amount of P required per kilogram of diet and as the amount of P required per day. Obviously, feed intake affects the amount of P consumed per day. Therefore, in diets with increased energy content, it may be necessary to raise the concentration of P as feed intake is reduced. Ultimately, P requirements for market animals should probably be based on the amount of P required per kilogram of gain or per kilogram of lean tissue accretion. Data needed to estimate requirements on this basis are limited.

Another consideration in formulating swine diets to meet P requirements is the available Ca ($Ca_{available}$) content of the diet. Ideally, diets should be formulated on an $P_{available}$:$Ca_{available}$ basis, but data on the availability of Ca from feed sources for swine is almost nonexistent. The use of enzymes such as phytase alters the availability of P and Ca, further complicating the issue. These interactions will be discussed in more detail later in the paper. In the end, P nutrition for swine is an exercise in risk management, with the nutritionist trying to decide how low to reduce dietary P without affecting performance or carcass characteristics.

Phosphorus Requirements for Poultry

The most recent NRC publication addressing the nutrient requirements of poultry (NRC, 1994) has established a nonphytate P requirement of 0.45% for broilers from 0 to 21 d of age, declining to 0.30% during the finishing period. Higher requirements, particularly early in life, have been established for meat-type turkeys although controlled research regarding the requirements are even more limiting than for broilers. These recommendations are based on research published between 1952 and 1983 measuring growth rate, feed efficiency, and bone ash as response criteria. There has been very limited research regarding P requirements of broiler chickens in the last decade. Studies by Huyghebaert (1996, 1997), Beltran-Lopez et al. (2000) and Godoy et al. (2002) all confirm the NRC recommendation. However, a recent study also suggests that available P levels can be reduced by up to 30% with no negative impact on broiler production performance resulting in a significant reduction of P excretion (Fritts and Waldroup, 2003). A similar reduction in P excretion has been observed when feeding lower concentrations of dietary P to egg layers although the impact on egg production and quality has been inconsistent and compromised egg production and shell quality are sometimes observed (Summers, 1995; Keshavarz, 2000).

Skinner and Waldroup (1992) and Skinner et al. (1992) recently examined the influence of complete removal of inorganic P from broiler finisher diets on growth, bone strength, and the incidence of skeletal abnormalities. There were no negative effects of P removal on growth rate, feed conversion, tibia length or width, or the incidence of leg abnormalities in either of these studies. There was a reduction in bone breaking strength that could be largely eliminated through higher levels of Ca supplementation. More recently, Chen and Moran (1995) observed an increased incidence of skeletal defects following processing as a result of P withdrawal. However, the environmental potential of this P withdrawal justifies further research to identify more precise parameters that might allow significant reduction of P concentrations in broiler finisher diets. Although finisher diets are generally only fed in the last week before market, finisher feed typically represents approximately 40% of the total feed consumed by a commercial broiler.

The research cited above and used to establish the NRC requirements has focused on defining absolute requirements for nonphytate P. Many of these studies involved genetic stocks not common in the industry. This is of concern as animal genetics can influence requirements for P and responses to dietary additives such as phytase. Punna and Roland (2001) provided evidence that there may be variability in the response of different genetic strains to increasing available P in the diet. These researchers found a greater response to P and phytase supplementation in a low-susceptibility strain than in a high-susceptibility strain as indicated by the incidence of severe tibial dyschondroplasia lesions. This is an important observation because of the commercial and welfare importance of tibial dyschondroplasia. Several studies also suggest that the P requirement for maximal bone mineralization is higher than for growth (Huyghebaert 1996, 1997; Beltran-Lopez et al., 2000). These considerations become more important under industry conditions where nutrient availability is often limited due to feed quality, inconsistency of feed manufacture, management challenges, and compromised bird health including enteric health.

Studies regarding the impact of dietary phosphorus supplementation on bone mineralization and skeletal abnormalities also suggest that a holistic approach, which accounts not only for simple growth measures, but also health and metabolic end points and perhaps excretion should be adopted in establishing phosphorus requirements.

Reduced Overfeeding to Decrease P Content of Excreta

In all species of livestock, P fed in excess of animal requirements is excreted, making reduced overfeeding a powerful tool to reduce the P content of manure.

Overfeeding and P Excretion—Dairy and Beef Cattle

In dairy cows, several studies indicate a direct link between P intake and P excretion (Morse et al., 1992b; Wu et al., 2000, 2001; Knowlton et al., 2001; Knowlton and Herbein, 2002). A Florida study was among the first to show this link (Morse et al., 1992b). Twelve cows were fed diets containing one of three concentrations of P (0.3, 0.41, 0.56% of dietary DM). Excretion increased linearly with increasing intake, and nearly all of the difference in P intake with the high-P diet compared to the low-P diet was excreted.

Overfeeding of dietary P is common in the field. Phosphorus is often fed to dairy cattle 20 to 40% in excess of published requirements (Shaver and Howard, 1995; Sink et al., 2000). A survey conducted by Wu (2003) in Pennsylvania indicates that the extent of overfeeding is less now than was indicated in these earlier surveys. In growing beef cattle, Erickson et al. (1999) reported an industry average dietary P content of 0.35 to 0.39% of DM, compared to published requirements for growing steers of about 0.20% P.

Why Overfeed? In dairy cows, the most common explanation for overfeeding of dietary P is the perception that high-P diets improve reproductive performance. This perception likely originates from the observation that severe P deficiency impairs reproductive performance in cattle. The original studies that established this belief were primarily with range cattle (Eckles et al., 1932; Beeson et al., 1941), and the dietary P concentrations necessary to induce this impaired reproductive performance were below 0.20% of the dietary DM for lactating cows. This dietary concentration is far below the concentration found in most feedstuffs in modern lactating cow rations even without supplementation, and in all of these studies, P intake was seriously confounded with intake of energy and other minerals.

Although severe P deficiency may impair reproductive performance, there is no research data to suggest a benefit from feeding P to dairy cows in excess of NRC requirements (Brodison et al., 1989; Brintrup et al., 1993; Wu et al., 2000). A review by researchers in Wisconsin outlines 13 studies with 785 lactating cows fed diets low in P (0.32 to 0.40% P) or high in P (0.39 to 0.61% P; Satter and Wu, 1999). Dietary P had no effect on days to first estrus, days open, services per conception, days to first AI, or pregnancy rate (Table 4).

Table 4. Reproductive performance of lactating cows fed diets low or high in P (summary of 13 trials; Satter and Wu, 1999)

Item	Low P (n = 393)	High P (n = 392)
Dietary P, % of dietary DM	0.32–0.40	0.39–0.61
	mean ± SD[a]	
Days to 1st estrus	46.8 ± 10.9	51.6 ± 13.8
Days to 1st AI	71.7 ± 16.2	74.3 ± 10.6
Days open	103.5 ± 21.4	102.1 ± 13.0
Services per conception	2.2 ± 0.9	2.0 ± 0.5
Pregnancy rate	92% ± 6%	85% ± 5%

[a] Differences between means were not statistically significant for any measured variable.

Two other factors that have led farmers to overfeed P are undetected variation in the P content of feeds and inconsistencies between NRC requirements and the advice farmers receive. Undetected variation in the P content of feeds leads to imprecise ration formulation. Phosphorus content of forages analyzed by the Northeast DHI Forage laboratory from May 1994 through April 1995 was highly variable (Kertz, 1998). The coefficient of variation in P content of forages was 20 to 25% for most forage types, and P content was more variable for grasses than for legumes. Despite this variation, wet chemistry analysis of forages for P content is not routinely requested.

Field recommendations influence P intakes in the field. Inconsistent recommendations from nutritionists, veterinarians, and extension personnel have led many farmers to feed P in excess of the NRC recommendations. Until the environmental consequences became obvious, overfeeding P was viewed as cheap reproductive insurance. Revisiting the literature makes clear that there is no documented benefit to overfeeding P.

One final reason P is overfed is the inclusion of feeds in the diet that are naturally high in P. Many byproduct feeds are high in P, most notably the byproducts of corn processing and ethanol production. These are increasingly popular feed supplements for beef and dairy cattle because of the protein and energy they supply. However, inclusion of these feeds in higher amounts often increases the dietary P content beyond the animal's requirement. Koelsch and Lesoing (1999) constructed nutrient balances for Nebraska livestock farms and found that producers who used these byproducts had greater imbalances between P inputs and outputs than producers who did not. In their study, the seven cattle operations who fed these products imported twice as much P onto their farms as they exported in meat, crops, and manure (input:output ratio of 2.0:1). In contrast, the nine farms that did not feed these products exported nearly as much P as they imported (input:output ratio of 1.1:1).

The popularity of these high-P byproducts will likely continue, and there is no easy solution to the problem of the resulting elevated dietary P. In the short term, producers using these feeds should at least remove unneeded supplemental inorganic P from diets. In the long run, however, the true cost of the use of these high-P feeds should be carefully considered. If the inclusion of these byproducts will cause significant nutrient imbalance in the livestock operation and lead to difficulty meeting environmental regulations, then these feeds may not be as inexpensive as they appear.

Overfeeding P and P Runoff. Analysis of fecal samples from cows fed diets varying in P content indicates that increasing dietary P not only increases total fecal P, but also increases the amount and proportion of fecal P that is water soluble (Dou et al., 2002). Water-soluble P is the form of P that is most susceptible to loss in the environment. In cows fed diets containing 0.34, 0.52, or 0.67% P, the water-soluble fraction of fecal P was 2.9, 7.1, and 10.5 g/kg fecal dry matter, respectively. This increase in the proportion of water-soluble fecal P in cows fed high-P diets is likely because excess dietary P ends up in feces after being digested and absorbed from the small intestine. Absorbed P in excess of the animal's requirements is re-secreted from the bloodstream into saliva (Ternouth, 1990) and then excreted in feces. By definition, this excess P is primarily in the water-soluble form.

Research in Wisconsin showed even more directly that addition of excess P to diets increases the potential for P losses from land-applied manure, even at similar manure P application rates (Ebeling et al., 2002). Manure from cows fed diets containing two different dietary P concentrations (0.31 vs. 0.49% P) were applied to silt loam soils and subjected to simulated rainfall just before corn planting and again after harvest. The manure from cows fed the high-P diet contained 2.7 times more P than the low-P manure. When applied at equivalent manure application rates, runoff of P from soils receiving high-P manure was 10 times higher than from soils receiving low-P manure. When manure application was adjusted for constant manure P application, P concentrations in runoff were four times higher from soils receiving high-P manure than from those receiving low-P manure despite equivalent P application rates.

Overfeeding and P Excretion—Swine

Swine manure contains high levels of P, the result of poor digestibility of phytate P and feeding above the P requirement. In pigs as in cows, overfeeding P increases P excretion directly. Bridges et al. (1995) fed 24 crossbred barrows diets containing 0.50, 0.40, or 0.30% P plus phytase at 1,000 units/kg. Twelve pigs were lightweight, averaging 61.8 kg at the start of the study, and 12 were of heavyweight, averaging 101.2 kg at the start. The high-P diet was typical of that fed to finishing pigs at the time of the study, whereas the 0.40% P diet reflected requirements according to the 1988 NRC. In the lightweight pigs fed the low P–phytase diet, the intake of P was reduced by 4.08 g/d per pig (–37.3%) compared to high-P control, and P excretion was reduced by 2.94 g/d (–40%). In the heavyweight pigs, the reduction in P intake per pig was 4.53 g/d (–34%) and the reduction in P excretion was 3.66 g/d (–37.8%) with the low P–phytase diet compared to the high-P diet. In both studies, the apparent digestibility of P and P retention were not affected by dietary P content ($P > 0.10$).

Kornegay and Verstegen (2001) presented data from several surveys conducted in the late 1980s through the mid-1990s, indicating that P was being fed at 110 to 155% of its requirement as listed in the most recent NRC (1998). The result of this overfeeding is a diet that is more expensive and results in a larger concentration of P in manure. As in dairy cattle diets, overformulation of P in swine diets results from uncertainty of the actual P requirement, lack of homogeneity of the group of pigs being fed, and misinterpretation of published requirements.

Advances in research are improving this situation, in swine as in other species. Jongbloed et al. (1997) estimated that P excretion per growing pig in the Netherlands was reduced by 50% between 1973 and 1995 because of improvements in the understanding of P availability and P requirements and the implementation of exogenous phytase in pig diets. This reduction in excretion was due to the reduction in dietary P content of growing-finishing pigs in the Netherlands by more than 2.5 g/kg and a simultaneous increase in the efficiency of feed conversion.

Overfeeding and P Excretion—Poultry

As in swine and cattle, intake and excretion of P are tightly linked in broilers, layers, and turkeys. Summers (1995) fed White Leghorn hens diets varying in $P_{available}$ content from 18 to 64 wk of age. The low-P diet (0.2% $P_{available}$) was below NRC requirements, the medium-P diet (0.3% $P_{available}$) was similar to required, and the 0.4% $P_{available}$ diet was considered a "conventional" control diet. Phosphorus excretion was reduced by 20 and 40% in birds fed diets containing 0.3% $P_{available}$ and 0.2% $P_{available}$, respectively, compared to birds fed the control diet. Egg production was reduced in birds fed the low-P diet, but egg production, egg weight, and shell quality were similar in birds fed 0.3% and 0.4% $P_{available}$. The reduction in P excretion with the 0.3% $P_{available}$ diet was identical to the reduction in the total P content of the diet.

The published dietary P requirements appear to be recognized as acceptable based on a lack of recent publi-

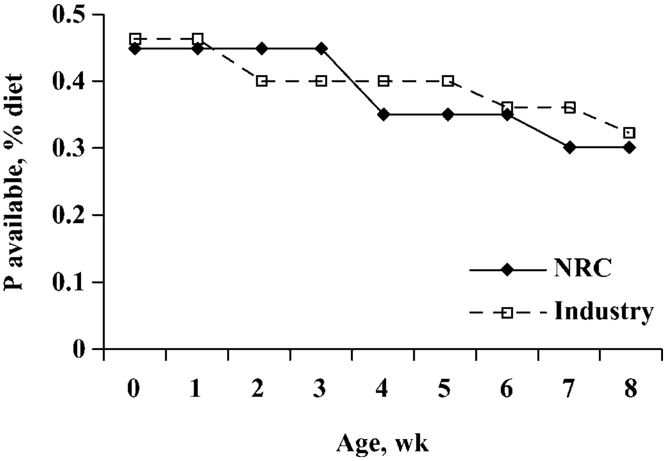

Figure 1. Comparison of current industry practice with NRC (1994) recommendation for available P ($P_{available}$) in broiler diets.

cations on the subject and the fact that industry feeding practice is broadly consistent with these standards (Figure 1). Thus, efforts to improve P availability and utilize more highly available P sources would appear to have greater potential to reduce P excretion than focusing on overfeeding itself.

As in other species, though, some overformulation of dietary P occurs in poultry production for a number of reasons. Phosphorus is an essential mineral for growing broilers, growing turkeys, and layers for adequate skeletal development and production of shells. The importance of this mineral has led nutritionists to build in a significant margin of safety to reduce the likelihood of problems due to inadequate P. Also, dietary P is oversupplied to poultry because of the variability in the P content in the various sources of P, and in the ability of the chick or poult to utilize different sources of P (its bioavailability). Within each P source, the P content can vary greatly (Tables 5 and 6; Jones and Ward, 1979; Shutze and Benoff, 1981). Similarly, Van der Klis and Versteegh (1996) reported that each source of P has a different total P content and available P content (Table 7). This observation was not novel, but the authors highlight the need for accurate data on P availability for formulation of precision diets for poultry.

To minimize excessive P excretion, an effective quality control program must be in place for incoming feedstuffs. Selection of P sources with the highest biological value and most consistent P content, the use of exogenous phytase, and careful selection of dietary P content to match animal needs are techniques poultry nutritionists can use to decrease P excretion and, ultimately, decrease P contamination of surface water.

Table 5. Phosphorus content of meat and bone meal (P, % as fed) from various suppliers (adapted from Shutze and Benoff, 1981)

Source	n	Mean	Low	High
All suppliers	2,277	3.93	1.8	7.0
Supplier 1	983	3.72	1.9	5.9
Supplier 2	680	3.94	1.8	6.3
Supplier 3	101	4.42	2.4	6.5

Feeding According to Physiological State

In all species, nutrient requirements vary with physiological state, including changes in growth rate, productivity, pregnancy, gender, and age. Formulating diets to meet the P requirements of a more homogenous group of animals reduces overfeeding, reducing the P content of manure.

Crediting Bone P Resorption in Early Lactation Cows

In lactating ruminants, opportunity exists to reduce P excretion by accounting for the P released through the normal catabolism of bone that occurs in early lactation. When sheep were fed diets varying in Ca and P content throughout pregnancy and lactation (Braithwaite, 1983b), body P reserves were mobilized in late pregnancy and early lactation. This mobilization was in response to Ca requirements and was not affected by dietary P content.

Bone consists of Ca and P deposited within an organic collagen matrix. The highly porous nature of this matrix provides bone with an extensive surface area, making bone a highly labile source of both Ca and P. Bone mineral content is the result of the balance between rates of bone accretion and bone resorption. Bone accretion remains relatively constant within animals of a given age (Braithwaite, 1976; Braithwaite, 1983a), so changes in bone mineral retention are due primarily to changes in rate of resorption.

Net bone resorption is likely a normal consequence in early lactation due to the rapid increase in demand for Ca to support milk yield. The postpartum ruminant is typically in negative Ca balance (Braithwaite, 1976), and parathyroid hormone is secreted in response to this hypocalcemia (Shappell et al., 1987). Parathyroid hormone stimulates the conversion of 25-hydroxycholecalciferol to dihydrocholecalciferol. Together, parathyroid hormone and dihydrocholecalciferol stimulate bone resorption (Braithwaite, 1976; Ternouth, 1990).

Phosphorus release from bone during early lactation provides a readily available source of P to meet the needs for maintenance and milk yield. Ternouth (1990) suggested that beef steers fed P-deficient diets could mobilize up to 30% of bone mineral, or 6 g/d of P, meeting about half of their dietary requirement. Satter (2002) extended this estimate to a 600-kg lactating cow, and estimated that as much as 600 to 1,000 g of P could be mobilized in early lactation. Supporting this, Knowlton and Herbein (2002) observed that mobilization of P from body reserves may meet a significant proportion of the dairy cow's net need for P during early

Table 6. Assay values for meat and bone meal (% as fed) received in North Carolina feed mills (adapted from Jones and Ward, 1979)

Nutrient	n	Mean	SD	Low	High
Moisture	114	9.19	2.10	4.48	21.89
Crude fat	208	10.47	1.17	7.24	14.6
Crude protein	314	50.55	2.18	42.44	60.78
Calcium	181	8.61	1.76	3.96	15.0
Phosphorus	186	4.09	0.69	1.08	7.25

lactation. Assuming P balance reflects P resorption from bone, cows mobilized up to 25 g/d of P from bone in the first 3 to 5 wk of lactation. The requirement for absorbed P in early lactation totals 45 to 70 g/d, depending on milk yield (NRC, 2001). Although Knowlton and Herbein (2002) reported no effect of diet on P retention, they observed an interaction between week of lactation and dietary P content, suggesting that dietary P affected the duration of net bone P resorption. Cows in all treatment groups mobilized P from body reserves at wk 3 of lactation, but only cows fed the low-P diet remained in negative P balance during wk 5. Reserves of P mobilized in early lactation must obviously be replenished in later lactation, and questions remain about the timing and rate of replenishment of bone P stores, as well as the duration and ultimate extent of mobilization of those reserves.

Phase Feeding—Swine

The P requirement of the pig changes with age. With increasing age, the quantity of P required increases, but, due to increased feed intake, the required P content of the diet decreases (NRC, 1998). The more frequently the diet is reformulated, the more accurately the nutrient needs of the animal can be met, and increased efficiency of nutrient utilization will result in decreased excretion.

Phase feeding is a management tool for reducing nutrient excretion, and it is commonly practiced in the industry today. However, very little if any recent research has focused on the reduction in P excretion as a result of phase feeding. Several studies have documented substantial reductions in N excretion as a result of phase feeding (Henry and Dourmad, 1993; Chauvel and Granier, 1996; Vander Peet-Schwering et al., 1996). Using estimates of P requirements during the growing and finishing periods (NRC, 1998) and estimates of feed efficiency (Dritz et al., 1997), the reduction in P consumption per pig as a result of phase feeding can be calculated. The P consumption over the entire grow-finish period can be estimated by summing the P intakes for each phase, which can be estimated by dividing the BW gain for each phase by the gain:feed ratio and multiplying by the P content of the diet ([BW gain/gain:feed] × dietary P). Assuming one dietary phase was used, and P was held constant at 0.50% of the diet to meet the requirements of the youngest group, P intake would be estimated as

$$[(30\ \mathrm{kg\ BW}/0.424) \times 0.0050] + [(30\ \mathrm{kg\ BW}/0.341) \times 0.0050] + [(40\ \mathrm{kg}/0.274) \times 0.0050] = 1.52\ \mathrm{kg\ P}.$$

If, instead, a three-phase feeding system was implemented, the reduction in P intake and excretion can be calculated. Assuming total P requirements of 0.50, 0.45, and 0.40% and gain:feed estimates of 0.424, 0.341, and 0.274 for pigs weighing 20 to 50, 50 to 80, and 80 to 120 kg, respectively, P consumption can be estimated as

$$[(30\ \mathrm{kg\ BW}/0.424) \times 0.0050] + [(30\ \mathrm{kg\ BW}/0.341) \times 0.0045] + [(40\ \mathrm{kg\ BW}/0.274) \times 0.40] = 1.33\ \mathrm{kg\ P}.$$

This represents a 12.5% decrease in P consumption and a corresponding reduction in P excretion.

Similar to phase feeding, diets can be formulated to more precisely meet the needs of animals for P if animals are grouped and fed by gender, as well as by age. Gilts consume less feed and are leaner at the same BW compared to barrows (Cromwell et al., 1993). Therefore, the dietary concentration of P and other nutrients can be reduced in diets for barrows compared to equal-BW gilts. An overall improvement in feed efficiency will be observed because barrows are not being overfed in order to meet the nutrient requirements of gilts. Calculations similar to those made above for phase feeding can be made for split-sex feeding. Ultimately, phase feeding and split-sex feeding will result in decreased total con-

Table 7. The phosphorus content of some animal feedstuffs and phosphorus supplements and their bioavailability measured in 3-wk-old broilers (adapted from Van de Klis and Versteegh, 1996)

Source	Total P, % as fed	Available P, % of total
Bone meal	7.6	59
Fish meal	2.2	74
Meat meal	2.9	65
Meat and bone meal	6.0	66
Calcium sodium phosphate	18.0	59
Dicalcium phosphate (anhydrous)	19.7	55
Dicalcium phosphate (hydrous)	18.1	77
Monocalcium phosphate	22.6	84
Mono-dicalcium phosphate (hydrous)	21.3	79
Monosodium phosphate	22.4	92

sumption of P, increased efficiency of dietary P utilization, and decreased P excretion.

Phase Feeding—Poultry

Recent research regarding phase feeding for poultry has primarily focused on amino acid nutrition. However, Huyghegaert (1996, 1997) reported comprehensive research regarding phase feeding for P nutrition. These studies provided response surfaces for Ca, P, and phytase supplementation for both growth and bone mineralization and then demonstrated that higher Ca-to-P ratios were beneficial for maximizing bone mineralization and reducing the incidence of tibial dyschondroplasia. The author also suggested that dietary Ca and P could be reduced significantly by feeding a two-feed program to broilers. This concept is reflected in both the NRC recommendation and current industry feeding practice (Figure 1). The situation is even more extreme in turkey production, where dietary P concentration is reduced by more than 250% over the 20-wk growing period. Current poultry industry feeding practice includes the phase feeding concept where broilers are fed as many as five diets to 40 d of age and turkeys consume up to nine different diets to 20 wk of age.

Techniques to Improve Availability of Feed Phosphorus

The availability of P in feedstuffs affects total P requirements in all species, but our assumptions of the availability of feed P are based on relatively few studies. Questions remain in all species about appropriate methods and response variables to determine the availability of feed P. Improved P availability from feed allows the tissue-level needs of the animal to be met with reduced P intake, reducing the P content of excreta.

Approximately 65 to 70% of the total P in cereal grains is organically bound in phytate P (Nelson et al., 1968; Morse et al., 1992b). This form of P is relatively unavailable to monogastric animals as they lack the enzyme phytase (Cromwell, 1992; Ravindran et al., 1994, 1995). Phytase catalyzes the release of phosphate groups from the inositol ring of phytate, making the P more available for absorption in the small intestine (Jongbloed et al., 1992; Cromwell et al., 1993; Lei et al., 1993b; Kornegay, 1995, 1996; Jongbloed et al., 1996; Radcliffe and Kornegay, 1998; Skaggs, 1999; Rice et al., 1999; Zhang, 1999; Rice et al., 2000; Robbins et al., 2000). Phytate P is more available to ruminants than to nonruminants because ruminal microorganisms possess phytase (Clark et al., 1986; Morse et al., 1992b; Yanke et al., 1998).

Improved Availability of Feed Phosphorus in Swine Diets

In the swine industry, there is a great deal of interest in lowering the dietary concentration of phytate P, making more of the plant P available to the pig for absorption. There have been two primary strategies employed to accomplish this: the addition of exogenous phytase to the diet and the development of plants with reduced phytate P content. Both methods result in an increased efficiency of P utilization and decreased P excretion. This section will focus on the use of exogenous phytase in swine diets because this method is commercially available at the present time. However, low-phytic acid grains do have the potential for wide-scale use in the future if agronomic issues such as reduced crop yields can be overcome. In addition, the combination of low-phytic acid grains and phytase may ultimately provide the producer with the greatest ability to lower dietary P content.

Site of Phytase Activity. To assess the site of activity of exogenous phytase within the digestive tract, Jongbloed et al. (1992) studied pigs fitted with simple T-cannulas in the duodenum (approximately 25 cm posterior to the pylorus) and ileum (approximately 15 cm anterior to the ileocecal junction). The pigs were fed a diet containing exogenous phytase, and 85% of the ingested phytase activity was recovered in duodenal digesta, whereas no phytase activity was recovered in ileal digesta. They concluded that the primary site of action of exogenous phytase was in the stomach and duodenum. Confirming this, in two experiments, Yi and Kornegay (1996) reported that phytase activity in the digesta, measured 3 h after ingestion of a meal, decreased from the stomach to the upper small intestine to the lower small intestine. Phytase activity, as a percentage of the total consumed phytase activity, was found to be 51% in the stomach, 31% in the upper small intestine, and 5% in the lower small intestine in Exp. 1. In Exp. 2, values of 41, 16, and 5% were reported for the stomach, upper small intestine, and lower small intestine, respectively.

Site of activity of exogenous phytase is influenced by the digesta pH. The pH optimum for commercially available phytases varies from 2.5 to 5.5; at pH greater than 6, activity is essentially lost. The acidity of the stomach lumen ranges from pH 1.0 to 4.5 (Chesson, 1987) and the luminal pH of the gastrointestinal tract increases from the duodenum to the terminal ileum. Duodenal pH in the pig averages approximately 4.8 but varies with time postfeeding. Jongbloed et al. (1992) reported that the duodenal pH immediately following a meal was 5.7, after which it gradually decreased to pH 3.3. The jejunum, which represents approximately 90% of the total length of the small intestine, has a mean pH of 5.5 to 6.9, whereas the ileum has a mean pH of 7.0 to 7.4.

Effects of Exogenous Phytase on Phosphorus Digestibility. Nelson et al. (1968) demonstrated the ability of exogenous phytase to release P bound to phytic acid. However, only recently has a commercially available phytase preparation been approved for use in swine diets. Addition of exogenous (microbial) phytase has been shown to catalyze the hydrolysis of the phytate molecule, releasing bound phytate P (Jongbloed et al., 1992; Cromwell et al., 1993; Lei et al., 1993b, Kornegay, 1995, 1996; Jongbloed et al., 1996; Radcliffe and Kornegay, 1998; Skaggs, 1999; Rice et al., 1999; Zhang, 1999; Rice et al., 2000; Robbins et al., 2000).

Microbial phytase has been shown to affect performance of pigs fed low-P diets by increasing average daily gains primarily due to an increased feed intake (Simons et al., 1990; Jongbloed et al., 1992; Kornegay and Qian, 1996; Yi et al., 1996). Increases in bone breaking strength or shear force have also been observed in several studies with pigs (Cromwell et al., 1993; Kornegay and Qian, 1996; Yi et al., 1996; Radcliffe and Kornegay, 1998) when phytase was added to a low-P diet. The addition of microbial phytase also decreases P excretion by 25 to 50% (Simons et al., 1990; Jongbloed et al., 1992; Cromwell et al., 1993a; Lei et al, 1993b; Kornegay and Qian, 1996; Yi et al., 1996) by increasing P digestibility or retention (Hoppe et al., 1992; Lei et al, 1993a,b; Mroz et al., 1994; Kornegay and Qian, 1996; Yi et al., 1996) and by decreasing the need for supplemental inorganic P.

Phosphorus Equivalency Values of Phytase. For swine producers to efficiently use microbial phytase, accurate equivalency values of phytase for P must be developed. Ideally, in studies designed to develop equivalency values, diets varying in dietary P content should be fed without added phytase and multiple levels of phytase should be fed with a low-P diet to develop response equations for both P and phytase. These response equations can then be set equal to one another and solved to determine the P equivalency of phytase. In general, linear ($Y = a + bX$, where Y = response and X = the level of P or phytase) or asymptotic ($Y = a(1 - be^{-kX})$, where Y = response and X = the level of P or phytase) curves have provided the best fits for phytase and P responses in corn/soybean meal-based diets (Kornegay et al., 1998). Jongbloed et al. (1996) reported that a logistic curve provided a better fit to the response of P and phytase in a practical Dutch diet.

Before examining the results of several studies attempting to generate P equivalency values, it is first necessary to distinguish between the amount of phytate P released by phytase and P equivalency values of phytase for inorganic P. Many studies in the literature do not attempt to distinguish between these, but they are quite different. The amount of phytate P released by phytase refers to the amount of P released due to the hydrolysis of phytate P. This value is lower than the P equivalency value because phytase is replacing inorganic P, which is less than 100% available. Therefore, in order to determine the amount of inorganic P that can be replaced in a given diet, it is essential to know the bioavailability of P from the inorganic P source. For example, if 500 U of phytase per kilogram of diet could catalyze the release of 0.76 g of phytate P, then the P equivalency value would be equal to 0.76 g divided by the percentage availability of the inorganic P source. If the P from inorganic P was 75% available, then the P equivalency value of phytase would be 1.01 g of P from inorganic P (0.76/0.75).

The bioavailability of P from inorganic P sources used in swine diets is generally quite high, but there has been a substantial amount of variation reported in the literature. Soares (1995) suggested a relative bioavailability value of 90% for defluorinated phosphate, 95% for dicalcium phosphate, and 100% for monocalcium phosphate when monosodium phosphate was used as the standard and given a value of 100. A relative bioavailability of 87% is suggested for defluorinated phosphate and a value of 100% is suggested for dicalcium phosphate when monocalcium phosphate is given a value of 100 (NRC, 1998). Kornegay and Radcliffe (1997) compared four sources of defluorinated phosphate and one source of dicalcium phosphate against a monocalcium phosphate control. They found no significant differences among any of the phosphate sources, with relative bioavailabilities ranging from 95.1 to 105.3%. These relative bioavailabilities were converted to availability of each P source in this study by dividing the increase in digested P (g/kg; digested P in diet − basal digested P) when P is added by the amount of added inorganic P added and multiplying by 100. With the exception of one of the defluorinated phosphate sources (bioavailability = 58.5%), the estimated bioavailabilities of P from all sources used in the study by Kornegay and Radcliffe (1997) ranged from 71.9 to 79.3%, with an average of 75.1%. This is in good agreement with a review by Kornegay et al. (1998) in which the estimated bioavailability of inorganic P across 52 experiments was 76.7% for swine.

For pigs, the P equivalency value for 500 U of phytase per kilogram of diet reported in the literature ranges from 0.27 to 2.47 g of P (Tables 8 and 9). Factors that may influence these equivalency value estimates include grain types fed, the P and phytate content of the diet, response criteria used and, perhaps most importantly, the ratio of Ca to P. Phosphorus absorption is impaired in pigs if the Ca-to-P ratio is too wide (NRC, 1998). In addition, Qian et al. (1996) reported a detrimental effect of a widening Ca-to-P ratio in excess of 1.2:1 on phytase efficacy in pigs. This observation may be the result of a poorer P absorption due to a wide Ca-to-P ratio rather than a decrease in enzyme effectiveness. Excess Ca may also bind to the phytate molecule, making it insoluble and therefore unavailable for exposure to phytase in the gastrointestinal tract.

In the pig studies of Kornegay and Qian (1996), Jongbloed et al. (1996), and Yi et al. (1996), only two levels of P were fed, and the response of various criteria to P was assumed to be linear. In addition, the Ca-to-P ratio in the studies of Kornegay and Qian (1996) and Yi et al. (1996) was 2:1. In the study by Jongbloed et al. (1996), the Ca:P ratios ranged from 1.94:1 to 2.5:1. In a study with growing-finishing pigs, Harper et al. (1997) utilized three dietary concentrations of P and maintained a Ca:P ratio of approximately 1.2:1 to 1.4:1 in all

Table 8. Phosphorus equivalency equations (growth and digestibility measurements) reported in the literature for pigs

Measurement and diet[a]	Equation[b]	Equivalency, g/kg	Reference
ADG			
SP	$Y = 3.41 - 3.07e^{-0.0003X}$	0.80	Yi et al. (1996)[c]
SP	$Y = 1.68 - 2.17e^{-0.0016X}$	0.70	Yi et al. (1996)[d]
CS	$Y = 4.062 - 3.865e^{-0.00095X}$	1.66	Kornegay and Qian (1996)[e]
CS	$Y = 3.362 - 3.380e^{-0.00266X}$	2.47	Kornegay and Qian (1996)[d]
CS	$Y = 0.0654 - 0.0741e^{-0.00839X}$	0.64	Harper et al. (1997)
CS	$Y = 0.084 + 0.002X$	0.99	Radcliffe and Kornegay (1998)
CS	$Y = 1.19 - 1.25e^{-0.0050X}$	1.08	Radcliffe and Kornegay (1998)
CS	$Y = 0.277 - 0.274e^{-0.000797X}$	0.93	Skaggs (1999)
CS	$Y = 0.0977 - 0.0988e^{-0.0035X}$	0.81	Skaggs (1999)
CS	$Y = 0.176 + 0.00213X$	1.24	Rice et al. (1999)
CS	$Y = 0.033 + 0.0032X$	1.63	Rice et al. (1999)
Digestible P			
CS	$Y = 1.01 - 1.0013 \times 0.9963^{X}$	0.85	Jongbloed et al. (1996)
Dutch	$Y = -0.1786 + 1.31/(1 + e^{(-0.0051 \times (X - 378))})$	0.67	Jongbloed et al. (1996)
CS	$Y = 0.173 - 0.177e^{-0.00102X}$	0.67	Skaggs (1999)
CS	$Y = 0.0657 - 0.0596e^{-0.0019X}$	0.42	Skaggs (1999)
P digestibility, %			
SP	$Y = 1.30 - 1.21e^{-0.0019X}$	0.83	Yi et al. (1996)[c]
SP	$Y = 1.31 - 1.51e^{-0.0036X}$	1.10	Yi et al. (1996)[d]
CS	$Y = 2.631 - 2.965e^{-0.00108X}$	1.19	Kornegay and Qian (1996)[e]
CS	$Y = 1.564 - 1.735e^{-0.00284X}$	1.14	Kornegay and Qian (1996)[d]
CS	$y = -0.087 \ln(-6.718 + 7.713e^{-0.000199X})$	1.16	Harper et al. (1997)
CS	$Y = -0.464 \ln(0.888 - 0.0014X)$	0.78	Radcliffe and Kornegay (1998)
MIX	$Y = 0.7452 - 0.4280$	0.63	Kornegay et al. (1998)
CS	$Y = 0.1552 - 0.1489e^{-0.00198X}$	0.99	Skaggs (1999)
CS	$Y = -0.112 + 0.0037X$	1.76	Rice et al. (1999)
CS	$Y = -0.22 + 0.0038X$	1.67	Rice et al. (1999)

[a] SP = semipurified diet, CS = corn-soybean meal based diet, and Dutch = Dutch practical diet.
[b] Y = digestible P, g/kg, and X = phytase activity, U/kg.
[c] Equations based on a basal diet containing 0.05% available P ($P_{available}$).
[d] Equations based on a basal diet containing 0.16% $P_{available}$.
[e] Equations based on a basal diet containing 0.07% $P_{available}$.

Table 9. Phosphorus equivalency equations (measures of bone mineral and breaking strength) reported in the literature for pigs

Measurement and diet[a]	Equation[b]	Equivalency, g/kg	Reference
10th-rib ash, %			
SP	$Y = 1.03 - 1.00e^{-0.0015X}$	0.56	Yi et al. (1996)[c]
SP	$Y = 1.06 - 1.09e^{-0.0014X}$	0.52	Yi et al. (1996)[d]
CS	$Y = 1.848 - 1.926e^{-0.0045X}$	1.65	Kornegay and Qian (1996)[e]
CS	$Y = 1.629 - 1.806e^{-0.0036X}$	1.33	Kornegay and Qian (1996)[d]
10th-rib ash weight			
CS	$Y = 0.0102 + 0.0015X$	0.76	Radcliffe and Kornegay (1998)
CS	$Y = 0.8699 + 0.9413e^{-0.0036X}$	1.02	Radcliffe and Kornegay (1998)
10th-rib shear force			
CS	$Y = 0.348 - 0.357e^{-0.00082X}$	1.11	Harper et al. (1997)
CS	$Y = -0.0243 + 0.0014X$	0.69	Radcliffe and Kornegay (1998)
Metacarpal ash, %			
CS	$Y = 0.112 - 0.1118e^{-0.0029X}$	0.85	Skaggs (1999)
CS	$Y = 0.1127 - 0.1184e^{-0.00095X}$	0.39	Skaggs (1999)
Metacarpal shear force			
CS	$Y = 0.0057 + 0.000005X$	0.27	Skaggs (1999)
CS	$Y = 0.0862 - 0.0891e^{-0.0014X}$	0.41	Skaggs (1999)
CS	$Y = 0.00097 + 0.00149X$	0.75	Rice et al. (1999)
CS	$Y = -0.0788 + 0.002X$	0.93	Rice et al. (1999)

[a] SP = semipurified diet, CS = corn-soybean meal based diet, and Dutch = Dutch practical diet.
[b] Y = digestible P, g/kg, and X = phytase activity, U/kg.
[c] Equations based on a basal diet containing 0.05% available P ($P_{available}$).
[d] Equations based on a basal diet containing 0.16% $P_{available}$.
[e] Equations based on a basal diet containing 0.07% $P_{available}$.

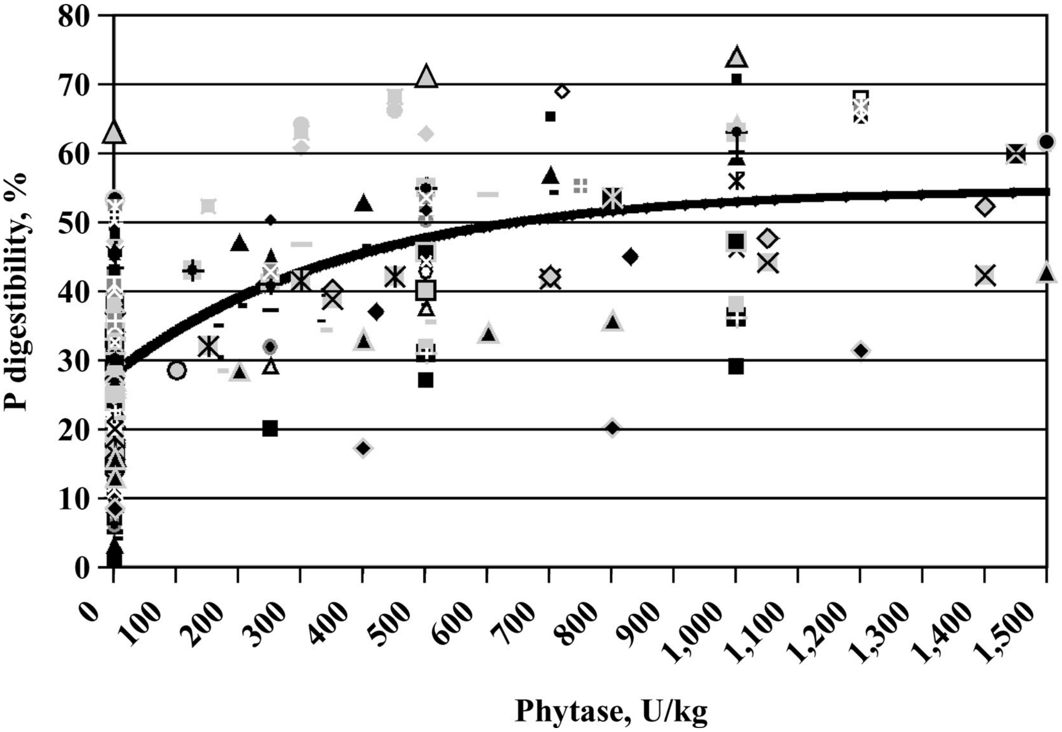

Figure 2. Apparent P digestibility response curve adapted from Kornegay et al. (1998). (Data used to derive the response curve were obtained from Eeckhout and de Paepe, 1991; Nasi, 1991; Beers et al., 1992; Jongbloed et al., 1992, 1996; Lei et al., 1993a,b; Mroz et al., 1993, 1994; Adeola and Sutton, 1995; Cromwell et al., 1995; Kornegay and Qian, 1996; Han et al., 1997; Harper et al., 1997; Liu et al., 1997; Murry et al., 1997; and Kornegay, et al., 1998.)

diets. They reported that, on average, 500 U of microbial phytase released 0.96 g of P/kg of diet.

Radcliffe and Kornegay (1998) fed 96 crossbred weanling pigs a low-P diet (3.5 g/kg) with supplemental inorganic P (0, 0.5, 1.0, or 1.5 g/kg) or microbial phytase (0, 167, 333, or 500) to determine the P equivalency value of microbial phytase. They found that the addition of microbial phytase to a low-P diet improved ADG, rib shear force, shear energy and ash (% and weight), and Ca and P digestibility. The addition of P to the low-P diet improved ADG, rib shear force, energy and ash (% and weight), and Ca and P digestibility. After regressing response criteria against P or phytase level, linear ($Y = mX + b$) P response curves provided good fits for P digestibility and rib shear force. Nonlinear ($Y = a(1 - be^{-kX})$) P response curves provided good fits for ADG and rib ash weight. Phytase addition resulted in linear increases in ADG, rib ash weight, and shear force. Nonlinear increases in P digestibility were observed. By setting the P response equations equal to the phytase response equations and solving for P, phytase equivalency values were derived. In this study, 500 U/kg of phytase was equivalent to 0.84 g of P as inorganic P.

Kornegay et al. (1998) used data from 52 pig experiments to estimate the P equivalency value of phytase. Data from these experiments were used to generate response curves for P digestibility (%), digested P (g/kg), and P excretion as influenced by phytase and P. Figure 2 shows the phytase response curve that was developed for P digestibility. Phytase unquestionably increases P digestibility. However, the magnitude of this response is dependent on diet type, total P content of the diet, phytate P content of the diet, Ca-to-P ratio, and the age and physiological status of the pig. These criteria account for the wide range of P digestibilities reported in the literature. The P digestibility curve described for phytase by Kornegay et al. (1998) was plotted with the actual data used to generate the curve on the same graph in Figure 2. Examining the basal diets, with no added phytase, a range of P digestibility from 8.4 to 63.0% was observed. This wide range is due to the inclusion of plant feedstuffs with intrinsic phytase activity in some studies, differences in the Ca-to-P ratio, differences in the inclusion level of inorganic P, and differences in the phytate P level of the diet. This variation continues as phytase is added to the diet and causes the relatively poor fit ($r^2 = 0.47$) of the response curve calculated in this review.

The variation in these data is decreased; however, if the equation of Kornegay et al. (1998) and the observed values are adjusted by calculating the percentage unit of improvement in P digestibility as phytase is added to the diet (Figure 3). If the improvement in the P digestibility curve extrapolated from the work of Kornegay et al. (1998) is plotted with the improvement in P digestibility curve generated in an early review by Dungelhoef and Rodehutscord (1995), there is very good

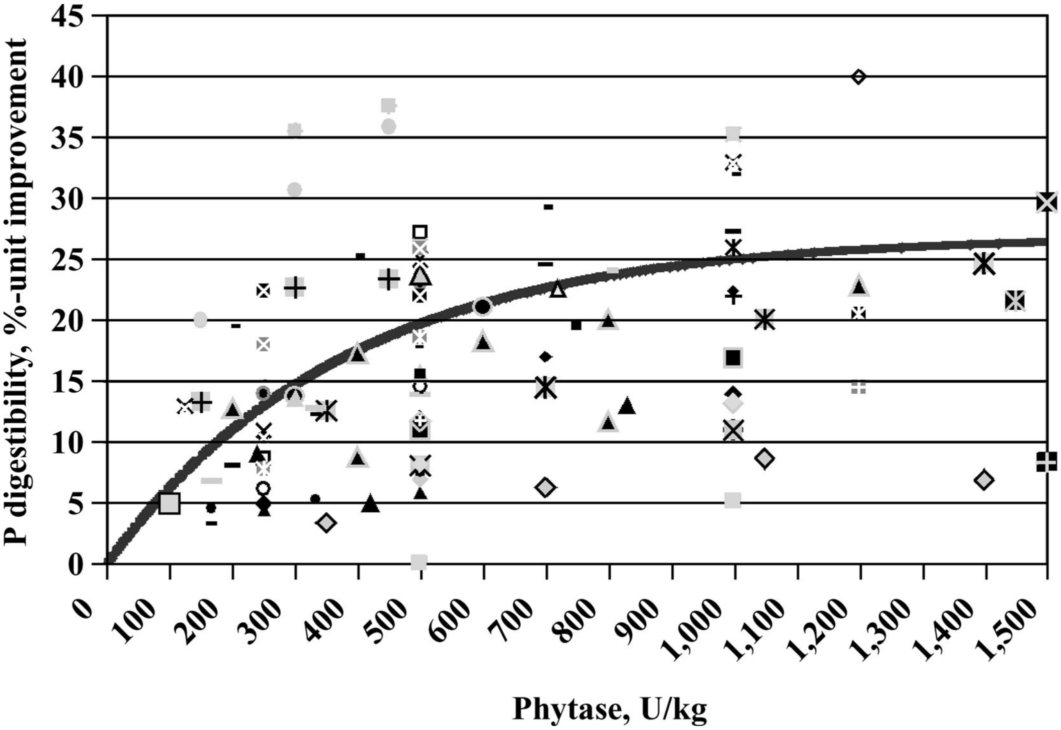

Figure 3. Increase in apparent P digestibility (percentage unit) response curve calculated from Kornegay et al. (1998). (Data used to derive the response curve were obtained from Eeckhout and de Paepe, 1991; Nasi, 1991; Beers et al., 1992; Jongbloed et al., 1992, 1996; Lei et al., 1993a,b; Mroz et al., 1993, 1994; Adeola and Sutton, 1995; Cromwell et al., 1995; Kornegay and Qian, 1996; Han et al., 1997; Harper et al., 1997; Liu et al., 1997; Murry et al., 1997; and Kornegay et al., 1998.)

agreement between the two curves (Figure 4). The curves predict almost identical improvements in P digestibility of up to 800 U of added phytase per kilogram of diet. Jongbloed et al. (1996) took data from an earlier experiment and fit a P digested (g/kg) curve. By taking these numbers, back-calculating digestibility values, and subtracting out the basal digestibility of P (27.5%), it is possible to develop a phytase response curve for the increase in P digestibility. Plotting this against the curves of Kornegay et al. (1998) and Dungelhoef and Rodhutscord (1995) shows a higher estimation of P digestibility improvement with added phytase by Jongbloed (1996).

To adjust for differences in the basal level of dietary P, the phytase response curves for the increase in P digested (g/kg) were plotted (Figure 5). The equations describing the curves of Jongbloed et al. (1996) and Dungelhoef and Rodehutscord (1995) were taken from their respective papers and used to develop response curves. For Kornegay et al. (1998), the increase in digested P (g/kg) was calculated as the increase in P digestibility (%) times the average concentration of P in the diets (3.8 g/kg). The basal level of P was then subtracted from these values to provide values describing the increase in the P digested (g/kg) response curve. As shown in Figure 5, this adjustment improved the agreement between the response curves from the three papers. The equations used to generate the curves for Figures 2 to 5 are shown in Table 10. Based on the review by Kornegay et al. (1998) 500 U of phytase per kilogram of diet will release 0.75 g of P. If this number is divided by the estimated bioavailability of inorganic P (76.7%), then 500 U of phytase per kilogram of diet can replace 0.98 g of P from an inorganic P source. This is in good agreement with the findings of Harper et al. (1997) and Radcliffe and Kornegay (1998).

Improved Availability of Feed Phosphorus in Poultry Diets

In poultry as in swine, one of the most important factors regarding the availability of feed P is the source from which the chicken or turkey must obtain P for growth and other functions affecting performance. Phosphorus in practical poultry diets may come from inorganic P from mineral sources, inorganic P from animal products, or organic (phytate) P from plant sources. In general, P from inorganic sources is believed to be highly available, whereas phytate P is relatively unavailable in poultry diets. Currently, a number of nutritional approaches are being evaluated to increase the availability of phytate P and reduce the potential of P pollution. These include 1) formulating diets to more precisely meet P requirements to avoid excess P excretion, 2) adding microbial phytase or other feed additives to poultry diets to increase phytate P availability, and

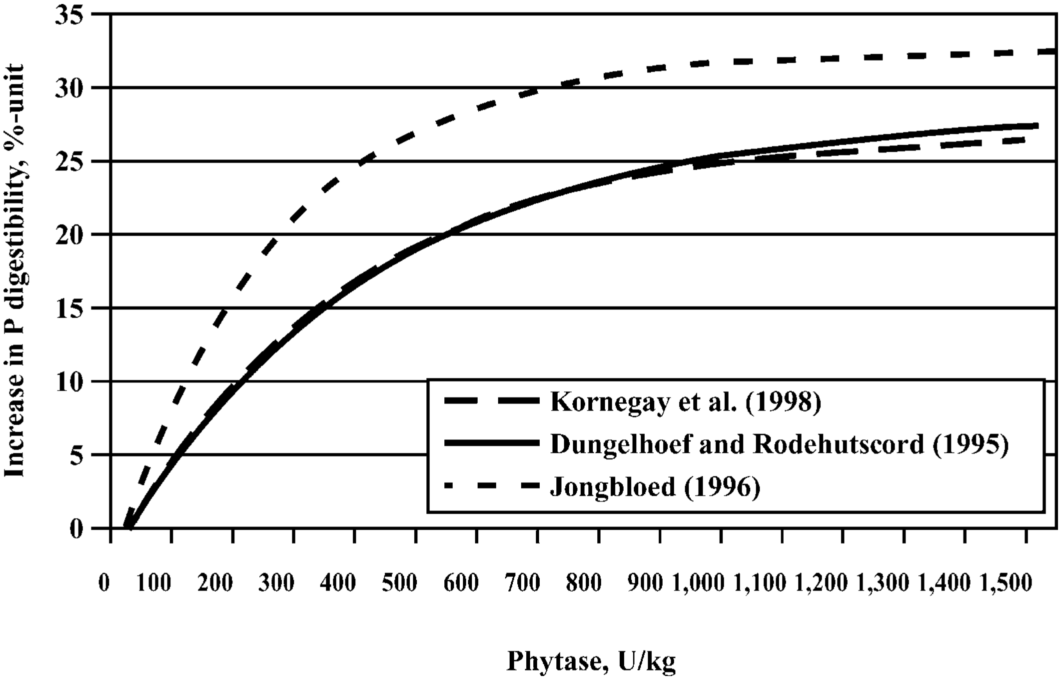

Figure 4. Comparison of phytase response curves for the increase in apparent P digestibility (%). The response curve of Kornegay et al. (1998) was based on the P digestibility response curve presented in that paper. (The response curve of Dungelhoef and Rodehutscord was based on data from Nasi, 1990; Simons et al., 1990; Borggreve et al., 1991; Beers, 1992; Beers et al., 1992; Eeckhout and De Paepe, 1992a,b,c; Jongbloed et al., 1992; Lantzsch and Wjst, 1992; Jongbloed et al., 1993; Kemme and Jongbloed, 1993; Mroz et al., 1993, 1994.) The response curve of Jongbloed (1996) was based on data from Beers et al., 1992.

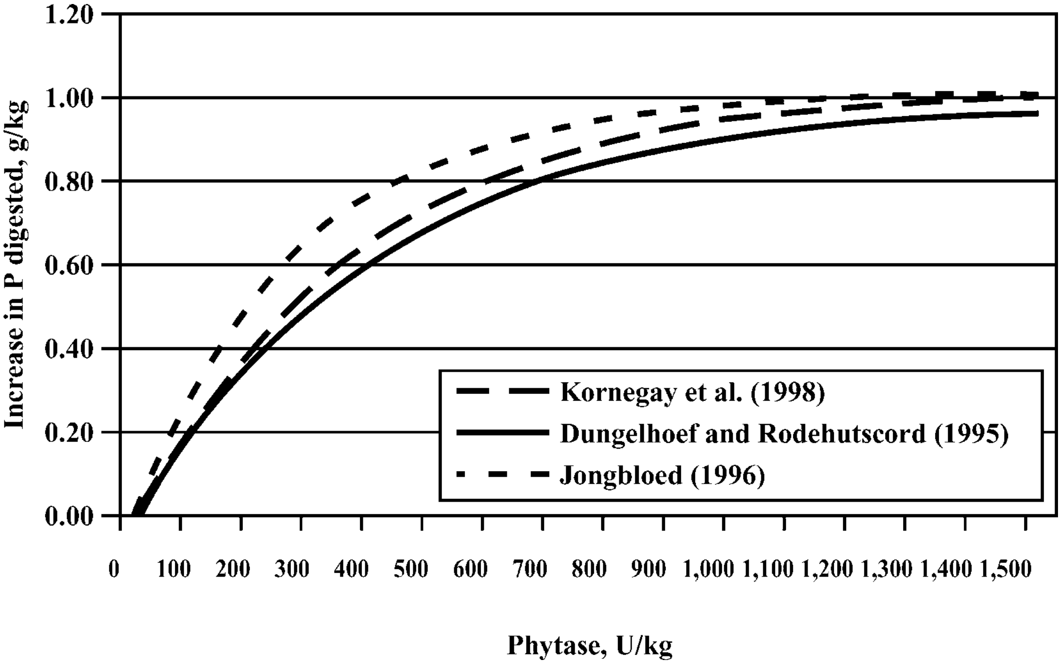

Figure 5. Comparison of phytase response curves for the increase in apparent P digested (g/kg of diet). The response curve of Kornegay et al. (1998) was based on the P digestibility response curve presented in that paper. (The response curve of Dungelhoef and Rodehutscord was based on data from Nasi, 1990; Simons et al., 1990; Borggreve et al., 1991; Beers, 1992; Beers et al., 1992; Eeckhout and De Paepe, 1992a,b,c; Jongbloed et al., 1992; Lantzsch and Wjst, 1992; Jongbloed et al., 1993; Kemme and Jongbloed, 1993; Mroz et al., 1993, 1994.) The response curve of Jongbloed (1996) was based on data from Beers et al. (1992).

Table 10. Equations used to generate phytase response curves in Figures 3 through 5 and response values for 250, 500, and 1,000 U of added phytase activity per kilogram of diet as predicted by the equations used to develop the curves

	Response to phytase, U added/kg of diet		
Equations for measurements	250	500	1,000
Apparent P digestibility, %			
$Y = 54.86(1 - 0.4908e^{-0.00263X})$[a]	40.91	47.63	52.92
Apparent P digestibility, %-unit			
$Y = 26.93(1 - e^{-0.00263X})$[a]	12.98	19.70	24.99
$Y = 28.1(1 - e^{-0.0024X})$[b]	12.68	19.64	25.55
$Y = (59.197 - 32.30 \times 0.9963^{X}) - 27.5$[c]	19.79	27.52	31.79
Increase in apparent digested P, g/kg			
$Y = 1.026(1 - e^{-0.00263X})$[a]	0.494	0.751	0.952
$Y = 0.99(1 - e^{-0.0025X})$[b]	0.460	0.706	0.909
$Y = 1.01 - (1.0013 \times 0.9963^{X})$[c]	0.614	0.853	0.985

[a] Kornegay et al. (1998).
[b] Dungelhoef and Rodehutscord (1995).
[c] Jongbloed (1996).

3) genetically reducing the phytate P content of cereal grains.

Kornegay (1999), in a review of literature, estimated that the average bioavailability of P from multiple inorganic P sources was 46.2% for broilers. For comparative purposes, the relative bioavailability of P in calcium phosphate supplements is generally set at 100%, with the bioavailability of other sources expressed relative to this. The P from rock phosphate sources, for instance, is less available than the P from calcium phosphate (Sullivan et al., 1994; Summers, 1997). The bioavailability of P from commercial dicalcium phosphate products varies considerably, however, and depends on the specific response criteria evaluated (Lima et al., 1997). Phosphorus bioavailability was greater and less variable when evaluated based on growth effects and relative blood P concentrations as compared to bone ash and bone breaking strength criteria. Relative P bioavailability ranged from 79 to 110% for the seven commercial sources of dicalcium phosphate examined (including several of non-U.S. origin). Thus, there is considerable variation in the availability of P for even the most highly available inorganic source of P.

Inorganic P from animal sources has been shown to have a bioavailability similar to that from mineral sources (Waldroup and Adams, 1994). There is a lack of research regarding factors influencing the availability of P from animal sources although the precise chemical form of P and the presence of contaminating (and competing) minerals could be surmised to be important considerations.

Organic sources of P are high in phytate P and are therefore considered to be poor sources of P for poultry. There has been considerable research regarding the use of other dietary ingredients to increase the availability of P from such sources as corn and soybean meal (Qian et al., 1997; Cromwell et al., 1998; Boling et al., 2000; Kasim and Edwards, 2000; Li et al., 2000; Edwards, 2002). Inclusion of dietary ingredients, such as vitamin D, organic acids, phytase, and low-phytate P corn, have been reported to increase P availability from the typical corn/soybean meal diet for poultry. The effect of these feed ingredients on P digestibility and excretion is summarized in Table 11, and the effect of these ingredients on bone mineral content in poultry is summarized in Table 12.

Low-Phytic Acid Grains. Two types of low-phytate corn (**LPC**; *Zea mays* L.) types, *lpa*1-1 and *lpa*2-1, which are phenotypically identical to wild-type corn hybrids, have recently been developed by USDA scientists. These LPC have been reported to have 60% and 50% lower phytic acid P content respectively than their wild-type corn hybrids, with no reduction in total P content. Chick bioavailability studies showed that P from *lpa*1-1 was from 45 to 52% available compared to 10% for normal corn (Cromwell et al., 1998). Li et al. (2000) conducted an in vitro P release study and reported that 23% of total P was released by normal corn compared to 65% from LPC. As in the study of Cromwell et al. (1998), these workers found that the total P content of corn is not affected in LPC, but the level of phytate P is decreased, allowing increased availability to poultry.

Li et al. (2000) conducted a trial replacing normal corn with LPC in the diet of male broilers to evaluate its effect on performance to 21 d of age. Diets contained 0.45% $P_{\text{available}}$ and 1.2% Ca. Replacing normal corn with LPC increased P retention (6.7%) and reduced P excretion by 22%, indicating better utilization of P from a diet containing LPC. Feed efficiency was improved by 6 units, whereas body weight increased slightly when the LPC was substituted for normal corn. No effect of corn type was reported on tibia ash or toe ash. Similarly, Yan et al. (2000) observed that broilers fed LPC had similar body weight, feed conversion, mortality, and tibia ash to birds from normal corn, but that fecal P content was significantly reduced.

Table 11. Effect of various feed ingredients on phytate P utilization and excretion in poultry

Units	Total P, g/kg	$P_{available}$, g/kg[a]	Phytase, U/kg	Vit. D_3, μg/kg	1-OHD_3, μg/kg	25-OHD_3, μg/kg	1,25$(OH)_2D_3$, μg/kg	Citric acid, %	Excreta P, g/kg	Phy-P retention, %[b]	Source[c]
Broilers											
2–5 wk	4.6	2.1	0; 250; 500; 2,500	—	—	—	—	—	2.08; 2.03; 1.9; 1.84	—	1
8–20 d	4.2	1.4	—	—	0; 20	—	—	—	8.9; 5.9	—	2
0–16 d	5.2	2.2	—	27.5; 112; 220	—	—	—	—	—	51; 58; 57	3
0–16 d	5.2	2.2	—	—	—	—	0; 10	—	—	55.3; 72.7	3
0–16 d	4.7	2.1	—	—	5	5	5	—	—	53.3[e]; 76.2; 71.2; 74.4	3
0–21 d	5.1	2.7	0; 300; 600; 900	—	—	—	—	—	—	54.1; 56.4; 58.3; 59.9[d]	4
0–21 d	5.1	2.7	—	66; 660; 6,600	—	—	—	—	—	56; 58.4; 58.2[d]	4
Layers	3.3	1.55	600	—	—	—	0; 5	—	—	62.9; 76.6	5

[a] $P_{available}$ = available P.
[b] Phy-P = phytate P.
[c] Source: 1 = Zhang et al. (2000); 2 = Biehl and Baker (1997); 3 = Edwards (2002); 4 = Qian et al. (1997); 5 = Carlos and Edwards (1998).
[d] Total P.
[e] Control treatment (without supplementation).

Exogenous Phytase. The use of phytase in poultry diets is not new, but the products available are currently being evaluated and refined. Numerous studies have demonstrated that the availability of phytate P can be increased by 20 to 30% through the addition of phytase to complete poultry diets (McKnight, 1996; Kornegay, 1999). Qian et al. (1997) fed low-$P_{available}$ (0.26% $P_{available}$) diets containing 0 to 900 U of phytase/kg of diet to broilers from 0 to 3 wk of age. They reported a linear increase in BW gain, feed intake, toe ash content, and P and Ca retention with phytase addition. These measurements were negatively influenced by widening the dietary Ca:P_{total} ratio from 1.1 to 1.7, and synergistically improved by additions of vitamin D_3 (66 or 660 μg of D_3/kg diet). Increasing Ca:P_{total} ratio decreased all measurements regardless of the presence

Table 12. Effect of various feed ingredients on bone mineral content in poultry

Units	Total P, g/kg	$P_{available}$, g/kg[a]	Phytase, U/kg	Vit. D_3, μg/kg	1-OHD_3, μg/kg	25-OHD_3, μg/kg	1,25$(OH)_2D_3$, μg/kg	Citric acid, %	Tibia ash, %	Toe ash, %	Source[b]
Broilers											
2–5 wk	4.6	2.1	0; 250; 500; 2,500	—	—	—	—	—	—	11.1; 11.3; 11.6; 12.6	1
8–20 d	4.2	1.4	—	—	0; 20	—	—	26.5; 36.5	—	2	
0–16 d	5.2	2.2	—	27.5; 112; 220	—	—	—	—	29.1; 33; 34.2	—	3
0–16 d	5.2	2.2	—	—	—	—	0; 10	—	32.1; 37.2	—	3
0–16 d	4.7	2.1	—	—	5	5	5	—	30.5[d]; 37.3; 35.1; 32.8	—	3
0–21 d	5.1	2.7	0; 300; 600; 900	—	—	—	—	—	—	11.1; 11.7; 11.8; 12.4	4
0–21 d	5.1	2.7	—	66; 660; 6,600	—	—	—	—	—	11.7; 11.8; 12	4
Layers											
24 wk	3.3	1.55	600	—	—	—	0; 5	—	49.8; 50.1	—	6
Turkeys											
7 wk tom	—	5.5; 1.5; 2.6; 3.65	—	—	—	—	—	—	47.7; 37.2; 42.5; 47.1	—	7
7 wk tom	—	—	0; 500	—	—	—	—	—	39.6; 43.4	—	7
7 wk hens	—	5.5; 1.5; 2.6; 3.65	—	—	—	—	—	—	49.3; 38.5; 44.2; 48.6	—	7
7 wk hens	—	—	0; 500	—	—	—	—	—	41.0; 45.4	—	7

[a] $P_{available}$ = available P.
[b] Source: 1 = Zhang et al. (2000); 2 = Biehl and Baker (1997); 3 = Edwards (2002); 4 = Qian et al. (1997); 5 = Boling et al. (2000); 6 = Carlos and Edwards (1998); 7 = Atia et al. (2000).
[c] Control treatment (without supplementation).

or absence of phytase. A Ca:P_{total} ratio of 1.1 to 1.4 was determined to be optimum based on the performance criteria evaluated. Phosphorus retention was also linearly increased with phytase, quadratically affected by increasing the Ca:P_{total} ratio, and increased by feeding 660 μg of D_3/kg diet D_3 compared to 66 μg of D_3/kg diet.

Organic Acids. Boling et al. (2000) reported that sodium citrate and citric acid were equally effective in increasing phytate P utilization when included in a P-deficient (0.60% Ca and 0.1% $P_{available}$) corn/soy-based diet. When graded doses (0 to 6% of diet DM) of citric acid + sodium citrate (1:1, wt:wt) were fed to broiler chickens from 8 to 22 d of age, a linear increase ($P <$ 0.01) in BW gain and tibia ash was observed. Relative to chicks fed no citric acid (negative controls), tibia ash and weight gain were increased by 43 and 22% respectively in chicks fed 6% citric acid. Also the addition of 1,450 U/kg phytase with 6% citrate further enhanced bone ash and weight gain.

Vitamin D. Edwards (2002) reported that differences in phytate utilization are observed when utilizing cholecalciferol and/or its derivatives. Day-old Peterson × Arbor Acres cockerel broilers were supplied experimental diets supplemented with 5 μg/kg of either 1,25-$(OH)_2D_3$, 1α-OHD_3, or 25-OHD_3 to determine their effect on phytate utilization. Supplementation of either 1,25-$(OH)_2D_3$ or 1α-OHD_3 increased performance values, such as BW gain, feed conversion, P and Ca retention, plasma concentration of P and Ca, and tibia ash content. Phosphorus excretion and incidence of rickets were reduced. The inclusion of 1,25-$(OH)_2D_3$ gave the most consistently enhancing effect, whereas 25-OHD_3 showed mixed responses.

Interaction with Dietary Ca. There is an important relationship between Ca and P nutrition and metabolism. Absorption of both dietary Ca and P is influenced by the concentration of dietary P (Summers, 1997), and P absorption is reduced with increasing levels of dietary Ca. A wide Ca-to-P ratio lowers Ca and P absorption, whereas a narrow ratio will increase Ca and P utilization (Li et al., 2000). The NRC (1994) currently recommends a Ca-to-P ratio of 2.2:1 for optimal growth and performance. In addition, the incidence of skeletal abnormalities, such as tibial dyschondroplasia, is increased as P intake increases and is reduced as dietary Ca content is increased. Thus, achieving the proper balance between these two minerals might allow reductions in dietary P and P excretion with limited impact on skeletal development and bone strength.

There is also considerable interest in the influence of source and particle size of maize on nutrient availability and phytate P utilization. Kasim and Edwards (2000) reported small, significant differences in bone ash, plasma Ca, and P and phytate P retention when birds were fed different sources of maize used in a diet deficient in available P (5 g/kg). Kasim and Edwards also determined that when increasing the particle size of maize (geometric mean diameter = 484, 573, or 894 μm), Ca, P, and phytate P retention and bone ash content all increased. The addition of phytase (600 U/kg) enhanced this response. Improvements in BW gain or efficiency were not observed with changes in maize particle size but were observed when phytase was supplemented to the diet.

Variation in Composition of Poultry Litter. By nature, poultry litter is a heterogeneous mixture of bedding material, fecal matter, spilled feed, and other materials. Thus, litter composition can be quite variable depending on both the relative proportion and composition of these components and, consequently, precise values for the nutrient content of poultry litter are not available. However, research by Patterson et al. (1998) provides representative baseline values for litter nutrient content and some indication of the variation in chemical composition that can be expected. The authors measured litter production and nutrient composition for 15 poultry houses representing two poultry companies. Selected facilities represented a range of housing styles, management systems, and production schemes that would typically be encountered in the U.S. poultry industry. Litter samples in this study had higher total nitrogen (N) content (5.52%) and lower P (4.55%), and potassium (K, 3.19%) concentrations on a dry matter basis than were previously reported in the literature. In addition, variation from the highest to the lowest values exceeded 130, 110, and 125% for N, P, and K, respectively. Interestingly, the N, P, and K content of litter was consistently higher for the company that grew broilers to a lighter market weight despite the fact that the two companies studied utilized similar nutritional programs. Clearly, factors other than nutrition can affect nutrient excretion.

Phytase in Ruminants

Few studies have evaluated the effect of diet on ruminal phytase activity. Yanke et al. (1998) observed a linear increase in ruminal phytase activity with decreasing forage:concentrate ratio in steers fed either 100% hay, 55% barley:45% hay, or 90% barley:10% hay (4.3, 8.1, and 17.5 units/mL of ruminal fluid). In a continuous culture fermenter utilizing ruminal fluid from goats, Godoy et al. (2001) observed an increase in phytate P availability with an organic P buffer compared to an inorganic P buffer, regardless of dietary P concentration. Guyton et al. (2003) observed an interaction of starch source and supplementation with purified phytic acid on endogenous ruminal phytase activity. The direction of the response to phytic acid dihydrocholecalciferol supplementation differed with starch source. In cows fed diets containing dried ground corn, ruminal phytase activity was numerically greater in cows fed phytic acid than in cows fed the low-P diet. In contrast, cows fed diets based on steam-flaked corn, phytase activity was similar with and without phytic acid supplementation.

More extensive research is needed on the effect of diet on ruminal phytase activity. If situations in which endogenous ruminal phytase activity is consistently low can be identified, the addition of exogenous phytase may lead to marginal improvements in P availability. Because P intake and excretion are so tightly linked, even small improvements in availability of feed P should yield large dividends. Improving P availability of dairy rations by 5 percentage units (i.e., from 60 to 65%) and reducing P intake accordingly to keep absorbed P constant would reduce P excretion by dairy cows by 15%, thus reducing the potential pollution of surface water significantly. (Calculations assume lactating cows were fed diets to meet the NRC requirement for phosphorus. Phosphorus intakes reduced with increasing digestibility of dietary P. Phosphorus excretion calculated as P intake − (milk P + maintenance P), calculated according to NRC [2001]). With roughly 750,000 dairy cows in the Chesapeake Bay Watershed (Jonker and Kohn, 1998), an increase in P availability of this magnitude and the appropriate reduction in P intake would reduce P excretion by 1,750 t/yr, or the equivalent of 3,500 t of P_2O_5/yr. This example makes clear the need to better define the availability of P in feedstuffs and to seek out technologies that may increase the availability of dietary P in ruminants.

Improved Efficiency of Conversion of Feed to Product

Increased productivity per animal allows the market demand for animal product to be met with fewer animals and reduced total manure nutrient excretion. An example with dairy cows will serve to demonstrate this link between productivity of the individual animal and aggregate nutrient loss from livestock farms.

In the United States, milk production per cow increased from 5,083 kg in 1977 to 8,228 kg in 2001, a 62% increase (National Agricultural Statistics Service, 2002). Further increases in milk production per cow may benefit water quality. Increasing milk yield per animal to dilute the “fixed cost” of maintenance increases the efficiency of nutrient utilization by the animal. The maintenance requirements of an animal are the nutrients required to maintain the animal’s body and must be met before any production (growth, milk, pregnancy) can occur. In dairy cows, for instance, maintenance requirements are essentially the same regardless of milk yield, and these requirements are met before any nutrient is used for milk synthesis. Increased efficiency of nutrient utilization (i.e., increased P in product/P intake) decreases manure nutrient excretion per unit of product (i.e., manure P/milk P). Increased productivity per animal allows the market demand for milk to be met with fewer cows and reduced total manure nutrient excretion (Dunlap et al., 2000). This concept of the dilution of maintenance costs improving the efficiency of conversion on feed to product applies to improved productivity per animal in all species.

Increased animal productivity can be achieved with a variety of management practices. Three strategies used to enhance milk production per cow include the administration of bovine somatotropin, increased length of the daily photoperiod, and thrice daily milking. Injecting lactating cows with exogenous bovine somatotropin triggers a series of coordinated changes in metabolism that increase milk production (Thomas et al., 1991; Bauman, 1992). With the use of bovine somatotropin, a greater proportion of consumed nutrients are used for milk synthesis, allowing increased milk yield. The use of bovine somatotropin typically increases milk yield by 4.9 kg/cow daily, although significant variation is observed among herds and cows (Thomas et al., 1991). Extending the daily photoperiod to 16 h of light and 8 h of dark by using artificial lighting increases milk yield compared to cows exposed to 12 or fewer hours of light per day (Dahl et al., 2000). On average, cows exposed to a long daily photoperiod have increased milk yield of 2.5 kg/d, and milk composition is not affected (Dahl et al., 2000). Increasing the milking frequency also increases milk yield. Milking cows thrice daily increases milk yield by 3.5 kg/d compared to twice daily milking (Erdman and Varner, 1995). Dunlap et al. (2000) evaluated the effects of these three practices on N losses from dairy farms, and they found that, when the use of all three technologies was simulated, N losses to manure were decreased by up to 16%. Although P losses were not evaluated, these practices should affect P losses similarly.

Economic Impact of Reducing Phosphorus Excretion and Losses from the Farm System

Feed Costs

Dairy Diets. The impact on net farm income of reduced overfeeding of P depends on the regulatory conditions affecting the farmer. If the farmer is not under P-based nutrient management, and applies manure without regard to its P content, the only impact of feeding excessive P is on his feed bill. A 100-cow herd increases their feed bill by $800 to $1,050/yr by feeding P at 0.50% of dietary DM compared to feeding at 0.35% P, and with P at 0.55% of dietary DM, the feed bill would be increased by $1,460 to $1,570/yr (Sink et al., 2000).

Swine Diets. Economic and environmental benefits can be realized by minimizing overformulation of P in swine diets as well. Assuming a gain:feed ratio of 0.357 for pigs up to 23 kg and 0.333 for pigs greater than 23 kg, a producer could save approximately $0.09 per hog marketed by reducing P in the diet by 0.1 percentage unit. Additional money would also be saved due to the extra space generated in the ration by the removal of inorganic P. Depending on the level of P in the diet, this 0.1-percentage-unit reduction in P would also result in as much as a 20% reduction in P excretion over the life of the pig. Minimizing overformulation is the easiest and cheapest way to reduce P excretion by pigs.

Another often overlooked approach to reducing the P content of swine manure is to reduce the amount of feed wasted. Any feed spilled from the feeder into the pit represents a monetary loss to the producer and an increased nutrient load that must be land applied. A recent review estimated that feed wastage in the United States ranges from 2 to 12% (Van Heugten and Van Kempen, 1999). Kornegay and Verstegen (2001) estimated that 1 and 7% feed wastage would result in 18 and 117 g of feed P wasted per pig marketed, respectively. These authors calculated that this would result in a loss of income of \$0.36 and \$2.48 per pig for 1 and 7% feed wasted, respectively. The environmental and economic impacts of feed wastage are very real, and improvements made in this area can be quite beneficial.

Phosphorus-Based Nutrient Management

Phosphorus-based nutrient management regulations require that manure application be limited to the P needs of the crop, preventing soil P accumulation. Most livestock farms produce more manure P than their crops require, and these P-based plans will require that the excess manure be exported.

For the farmer under mandatory P-based nutrient management, the costs of excessive P supplementation and P excretion are much greater than just an increased feed bill. These additional costs include the cost of exporting manure in excess of what can be applied to land, and the cost of purchased N fertilizer to meet the remaining N needs of crops (limiting manure application to P removal results in underapplication of N relative to crop needs). A study at Virginia Tech examined dairy and dairy/poultry operations of different sizes, estimated potential P losses, and simulated net farm income under different policy scenarios (Pease et al., 1998). One of the policy scenarios was a restriction on P applications to that taken up by the crop harvested.

In this study, the policy limiting P application was the only policy with any measurable impact on P losses from dairy and dairy/poultry operations. Phosphorus losses were reduced by 28 to 43% by this policy, but net farm income was dramatically affected, falling by 11 to 23%. The reduced net farm income was due primarily to the increased cost of purchased nitrogen fertilizer to meet the N requirements of crops. The impacts on net farm income are likely underestimated in this study, as it was assumed farmers could dispose of excess manure off the farm at no charge. If and as similar P-based policies are actually enacted, saturation of the market for manure will likely mean farmers will have to pay to have manure removed from their farms, reducing net farm income still further. While manure obviously has fertilizer value, it is bulky and expensive to transport, and the cost of trucking the material any distance quickly exceeds its fertilizer value.

Phosphorus-based nutrient management plans will be difficult for many livestock farms to implement, but fine-tuning the nutrition programs can help. The impact of reducing P intake on P losses from the farm system can be estimated in several ways. In dairy cattle, one can predict P excretion simply as the difference between P intake, and P in milk, retained in body weight gain, and fetal development (Van Horn, 1992). Given allocation of manure to crops, and estimated nutrient uptake by those crops, one can calculate acreage required to land-apply manure with changes in P intake. On a dairy farm milking 100 cows with different cropping strategies, P intake has a significant impact on acreage required for disposal of manure on a P basis (Table 13). Acreage required to dispose of manure generated by the herd increases by about 80% as dietary P concentration increases from 0.35 to 0.55%. Alternatively, given a fixed land base and different cropping strategies, we calculated the maximum number of milking cows supported by that land base. As dietary P concentration increases from 0.35 to 0.55%, the herd size that can be accommodated with P-based limitation of manure application decreases by 45%.

On swine and poultry farms, the inclusion of exogenous phytase in the diet reduces the cost of purchased P supplements by improving the availability of phytate P in feedstuffs and reduces the cost of manure disposal. Two studies demonstrate that phytase can be cost-effective for land limited hog and poultry farms under P-based nutrient management regulations. Bosch et al. (1998) estimated potential net returns from the inclusion of phytase on two representative swine farms (high and low animal density). Net returns were the savings in feed cost and manure disposal cost less the cost of the addition of phytase to the diet. On the land-limited farm, net returns to phytase addition were \$0.49 per hog (\$7,334 annually for a 15,000-hog farm), but net returns were negative (–\$0.02 per hog) on the farm with lower animal density (not land limited). The net return with phytase was sensitive to the price of crops grown and the amount of P reduction obtained with phytase. A similar study evaluating net returns to phytase inclusion on a representative turkey farm (Bosch et al., 1997) found that phytase increased the value of litter for fertilizer (by increasing the N:P ratio) and reduced feed costs. Phytase net returns to the farm, assuming land limitation and P-based nutrient management regulations, were \$1,435/yr. The net returns to phytase addition have likely increased since the publication of these two studies, as the cost of the enzyme has decreased.

The economic importance of preventing P losses from livestock farms has been demonstrated clearly in the Florida dairy industry. In the 1980s, several regulatory and incentive programs were implemented in the Lake Okeechobee watershed in Southern Florida to reduce P losses to surface water (Morse, 1996; Boggess et al., 1997). Treatment facilities were required to manage wastewater from parlors and holding areas, waterways were fenced, wells were monitored, and farmers were required to meet rigid standards for P application. Noncompliance fines were steep. At the same time, a voluntary buyout program was implemented. As a result, dairy cow numbers decreased by 26% and milk production decreased by 17% from 1987 (the year of program implementation) to 1993.

Table 13. Effect of dietary P content on manure disposal on dairy farms under P-based nutrient management[a]

	Dietary P content, % of dietary DM				
Item	0.35	0.40	0.45	0.50	0.55
Acres required for a 100-cow herd[b]	107	128	149	170	191
Maximum cow numbers for a given crop area					
80.9 ha, 50% corn 50% alfalfa	188	156	134	118	104
80.9 ha, 50% alfalfa, 50% corn for grain, with stover removed	247	206	177	155	138

[a] Assumes milk yield of 31.8 kg/d, DMI as predicted by the NRC (2001), heifers grown on the farm, and crop nutrient uptakes as in Van Horn (1992).

[b] Assumes cropping strategy of 50% corn silage, 50% alfalfa silage.

Despite cost sharing of 60 to 70%, dairies remaining in the Lake Okeechobee area faced increased costs of production of more than $1 per 45.4 kg of milk to implement mandatory and optional management practices and structures to reduce P loss from their farms. When increased culling, labor requirements, and variable costs during construction were included, the net expense to producers staying in the area was $568 per cow or $600,000 per dairy (Morse, 1996). The total economic impact of these programs in the region between 1987 and 1993 included decreases of 4% in both total income (down $18 million) and job numbers (down almost 500).

Implications

Phosphorus-based nutrient management regulations increase the amount of land required to dispose of manure, and will have a detrimental effect on the economy in areas of intensive animal agriculture. Opportunities available now to decrease the P content of livestock manure include more accurate interpretation of published P requirements, more precise diet formulation, and utilization of exogenous phytase or low-phytic acid grains in monogastric diets. Improved grouping strategies to decrease variation within groups of animals, and reduced feed wastage will also reduce the P content of land-applied waste. Together, these strategies may decrease the P content of manure by 40 to 60% in swine and poultry and by 25 to 40% in ruminants. Additional research is needed to better define the P requirements of livestock and the availability of P from feed. Reducing the P content of manure through nutrition is a powerful, cost-effective approach to reducing P losses from livestock farms.

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