Future Direction for Managing N and P on Dairy Farms

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Abstract

Dairy manure contains macro and micronutrients which are valuable nutrients for crop growth when applied to land. However, manure nutrients, especially nitrogen (**N**) and phosphorus (**P**), can become potential pollutants contaminating the environment such as air, soil, and ground and surface water if manure is not properly managed in farms and properly applied to land. Due to growing environmental concerns, efforts to lower N and P excretions from cows and N and P losses during manure storage and after manure application need to be made in dairy operations. Nitrogen and P excretion from dairy cows can be reduced through diet manipulation. Formulating diets meeting or being slightly lower than the N and P requirements for lactating cows (i.e., avoiding excessive dietary N and P) is the most effective strategy. However, N and P-deficient diets must be fed with caution because dairy production can be impaired depending on the degree of N and P deficiency. Substantial N losses occur during manure storage through ammonia volatilization, which causes odor and air pollution. Moreover, N losses during manure storage decrease manure quality as fertilizer (relatively low N and high P), causing potential over-application of P to the field when manure application rate is N-based. Covering lagoons and treating manure with acid (acidification) are effective in suppressing ammonia volatilization from manure. Extracting P from manure by adding chemicals and/or centrifuging can avoid over-application of manure P to land. After manure application, N and P are also lost through volatilization, leaching, and runoff, causing surface water pollution. Selecting proper manure application techniques, crop rotation, and application timing can help not only minimize N and P losses from manured soil but also improve crop production. In conclusions, there are a number of strategies that are effective in lowering N and P losses in dairy operations. When those strategies are applied in combination, the effectiveness in lowering N and P losses would be greater. In addition to these strategies, producers need to monitor their feed, manure, and soil for N and P concentrations, which can identify the opportunities to minimize N and P losses and then environmental impacts in individual farms because dairy farms have various feeding and manure management systems.

Introduction

The amount of fresh manure, excluding bedding and added water, produced by dairy operations is approximately 23 million kg a day in Ohio, making dairy farms the largest manure producers among livestock and poultry operations in Ohio (Figure 1). Dairy manure contains a number of macro and micronutrients, which can be valuable nutrients for crops when manure is used as fertilizer. However, the

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nutrients, especially N and P, are also potential environmental pollutants if manure is not properly managed.

Nitrogen is one of the nutrients excreted in great amounts by dairy cows. A dairy cow producing 40 kg of milk a day excretes about 450 g of N in manure (136,000 kg N daily in Ohio). A considerable amount of N in manure is lost through ammonia volatilization, and the loss occurs on barn floors, during manure storage, and after field application. Depending on various factors (e.g., environmental conditions), the loss of N through ammonia volatilization can be 20 to 80% of total N in fresh manure (OSU Extension, 2006). Livestock animals, including dairy cows, may contribute up to 50% of total anthropogenic ammonia emitted in the US (NRC, 2003). The ammonia emitted from manure contributes to farm odor and affects air quality (US EPA, 2004). Although ammonia emitted to the atmosphere has a short life from hours to days depending on atmospheric conditions, ammonia reacts with combustion sources, such as nitric and sulfuric acids, to form fine particulate matter with a diameter ≤ 2.5 µm (PM2.5; ammonium nitrate and ammonium sulfate; Hristov, 2011), which impairs air visibility and directly affects human health (respiratory diseases; WHO, 2005). Livestock animals in the North Central region may contribute up to 20% of total PM2.5 in cool weather (Hristov, 2011). Nitrogen excreted in manure also directly contributes to surface and ground water pollution through N runoff and nitrate leaching after field application of manure as fertilizer. Nitrogen is also lost through nitrous oxide (**N_2O**) emissions during the process of fecal and soil microbial nitrification and denitrification (more N_2O is emitted from manure-amended soil due to soil nitrifiers and denitrifiers). Nitrous oxide is a powerful greenhouse gas and is 298 times stronger in global warming potential than carbon dioxide. Dairy manure may contribute 33% of total N_2O emitted from animal manure in the US (US EPA, 2015). Moreover, the N losses reduce manure quality as a fertilizer due to the relatively low N concentration, which can negatively affect crop yields when dairy manure is used as a sole fertilizer.

Phosphorus has received attention as a pollutant produced from agriculture since P was identified as the primary nutrient polluting surface water. A dairy cow producing 40 kg of milk excretes about 50 g of P in manure which is about 15,000 kg of P excretion daily from dairy operations in Ohio.The Ohio EPA (2010) estimated that 89% of total P loading into the west basin of Lake Erie is from non-point sources (mostly agriculture), among which animal manure contributed 27% and commercial fertilizers contributed 66% (biosolids contribute 7%). For Grand Lake St. Mary's (OH), livestock animal operations, including dairy farms are responsible for most P loading (Tetra Tech, 2010). Unlike N, manure P is not lost during manure storage at farms but is lost after field application through runoff (Ohio EPA, 2010). Over-applied manure (or manure P) on fields may be the primary source of P in field runoff. High P loading into surface water, primarily originating from agriculture, was identified as the major factor causing eutrophication and harmful algae blooms in lakes (Ohio EPA, 2010).

Therefore, nutrient management, especially of N and P, from dairy feed to manure application is needed to decrease N and P excretion from cows and to lower N and P losses during manure storage and after manure application to fields to minimize environmental impacts.

Dietary Manipulation to Lower N and P Excretion

Nitrogen and P are required nutrients for dairy production and must be provided through diets to meet the requirements for maintenance and lactation. The intake and milk yield of dairy cows can be impaired if dietary N and P supplies are deficient (Lee et al., 2012a; Puggaard et al., 2014). However, if provided in excess, excretion of N and P increases because N and P provided above the requirements are not utilized for maintenance and production in dairy cows but are excreted in urine and feces, i.e., manure (Olmos Colmenero and Broderick, 2006; Alvarez-Fuentes et al., 2016). Once N and P are excreted, these nutrients become potential environmental pollutants that can contaminate air, soil, and water if manure is not properly managed and properly applied to the field (Ohio EPA, 2010; Hristov et al., 2011). One approach for dairy operations is to use dietary manipulation to lower environmental impacts.

A number of strategies have been investigated to improve dietary N utilization, i.e., efficient N utilization to improve production and lower N excretion, such as different types of carbohydrate supplementation, synchronization of ruminal energy and protein, supplementation with ionophores, feeding secondary plant metabolites, and rumen defaunation (Sinclair et al., 2000; Ipharraguerre and Clark, 2003; Makkar, 2003; Hristov et al., 2005). However, these strategies have had minimal effects, or the results have been inconsistent. More recently, supplementary nitrate has been investigated as a feed additive, primarily to lower enteric methane emissions. Encapsulated nitrate (a slow release form of nitrate) fed to beef cattle increased dietary N utilization and decreased urinary N losses compared with supplementary urea. In non-lactating cows, Guyader et al. (2015) observed up to a 12% decrease in urinary N excretion and numerically increased N retention (N utilization efficiency) in cows fed nitrate compared with urea. However, no effects of nitrate vs. urea on dietary N utilization and excretion in dairy cows were also reported (van Zijderveld et al., 2011).

The most powerful and consistently effective strategy among studies on improving dietary N utilization and lowering N excretion is to reduce dietary protein concentrations. Olmos Colmenero and Broderick (2006) compared diets with different dietary crude protein (**CP**) levels (13.5 to 19.4% on a DM basis) in dairy cows. In this study, production was not affected, but urinary N was significantly lowered from 257 to 113 g/day by lowering dietary CP levels. A number of studies have shown that reducing dietary protein concentrations has consistently decreased urinary N excretion (Recktenwald et al., 2014; Lee et al., 2015), and the decreases in urinary N excretion have significantly lowered ammonia emissions from manure during storage (a 2%-unit decrease in dietary CP decreased ammonia emissions up to 40% compared with the control; Lee et al., 2012b). Protein deficiency in diets, however, often impairs milk yield and milk protein yield of dairy cows with depressed dry matter intake (**DMI**). A series of long-term studies indicated that deficient metabolizable protein (**MP**) supplies at about 8 to 13% below the MP requirement (NRC, 2001) decreased DMI, milk yield, and fiber digestibility (Lee et al., 2012b; Giallongo et al., 2015). In these studies, dietary CP concentrations for the low protein diets were about 14% (DM basis), and the control diets were about 16% CP (corn and alfalfa silages-, corn-, and soybean meal-based diets), which met the MP requirement. However, because NRC (2001) under-predicts milk yields when cows are fed a deficient protein diet (Lee et al., 2012b; Figure 2), a slight decrease in dietary protein level below the current requirement (i.e., 15.5 to 16.0% CP) is expected to lower urinary N excretion and ammonia emissions from manure without altering lactating performance.

Phosphorus is also an essential nutrient for lactating dairy cows. If dietary P supply does not meet the requirement for maintenance and lactation, then milk yield can decrease and health problems can occur (Puggaard et al., 2013; Grünberg, 2014). Conversely, if dietary P supply is in excess, then dietary P provided above the requirement is excreted primarily in feces (Alvarez-Fuentes et al., 2016; Figure 3). Therefore, studies have been conducted to find effective strategies to lower P excretion by manipulating diets and rumen environments. However, most strategies have not been effective or had minimal effects. For example, Jarrett et al. (2014) fed a diet with phytase to dairy cows to improve dietary phyate-P availability in the digestive tract. In the study, fecal phytate-P decreased by about 25% with feeding of phytase, but total P excretion increased with phytase supplementation (57.4 vs. 52.6 g/day; $P = 0.02$). Additionally, feeding forage in different sizes was investigated to reduce fecal P excretion. The hypothesis of a study by Puggaard et al. (2013) was that feeding short sizes of forage vs. long forage to cows can lower amounts of saliva P entering the rumen by reducing rumination, which might decrease fecal P excretion because saliva P is the major P source entering the rumen. The hypothesis of another study (Jarrett et al., 2014) was that feeding longer forage can decrease rumen passage rates compared with short forage, which can decrease P excretion in feces. In both studies, short forage significantly increased fecal P excretion by 15 and 6%, respectively, compared with long forage, indicating feeding long forage might be effective in reducing fecal P excretion in dairy cows by lowering rumen passage rates.

Overall, lowering dietary P concentration is the most powerful strategy to reduce fecal P excretion (Figure 3). The next question becomes 'how much can dietary P concentration be reduced?' The requirement model for lactating cows (NRC, 2001) estimates the P requirement to be 0.32 to 0.42% in diets (DM basis; generally 0.40%). However, several studies have shown that slightly lower P concentrations in diets below the requirement did not impair lactating performance and health in long-term feeding studies (Wu et al., 2001; Ekelund et al., 2006; Puggaard et al., 2013). Among those studies, the lowest P concentration in the diets that did not affect production was 0.28% on a DM basis (corn silage-, grass silage-, sugar beet pulp-, and soybean meal-based diet; Puggaard et al., 2013). However, in the same study, a dietary P concentration at 0.26% (DM basis) severely decreased feed intake and milk yield, and feeding at the low level could not be continued in the study. Although this study concluded that 0.28% P in dietary DM was adequate for lactating cows, the study must be repeated to confirm the results with various dietary conditions (a European diet was used in this study). A dietary P concentration of about 0.30 to 0.35% (DM basis) was investigated repeatedly and no detrimental effects on DMI and lactating performance were reported (North American diets were used in those studies; Wu et al., 2001; Knowlton and Herbein, 2002; Odongo et al., 2007).

Therefore, providing dietary N and P in diets that are slightly below or that meet the requirement for lactating cows is the most effective and practical strategy (without extra costs) for producers to decrease N and P excretions from dairy cows.

Strategies to Lower N Losses from Manure During Storage

Manure is stored at dairy farms for days to months with various management systems until field application. The types of manure can be categorized by moisture content, e.g., liquid, slurry, semi solid, and solid, and manure is handled differently depending on types of manure (OSU Extension, 2006). The widely-used manure storage system in large dairy farms is a lagoon and pond to hold liquid manure because the manure is mixed with considerable amounts of water to maintain cleanliness in the milking operation. During manure storage, changes in P concentration are negligible. However, large amounts of N are lost through ammonia volatilization during manure storage. Lee et al. (2011) reported that about 50% of total N in manure was lost through ammonia volatilization within 3 days after feces and urine were mixed in a laboratory incubation system. There are several critical reasons for reducing ammonia emissions from manure during storage: 1) to lower environmental pollutions directly caused by ammonia emitted from manure, 2) to improve manure quality as fertilizer at the time of manure application, and 3) to lower environmental impacts after field application of manure. The potential environmental pollutants resulting in odor, air quality issues, and PM2.5 formation caused by ammonia emitted from manure were addressed earlier (reason 1). The ratio of N and P required for crop growth is quite close to the ratio of N and P in fresh manure (i.e., manure balanced with N and P). Therefore, fresh dairy manure can be a good fertilizer for crops. However, considerable ammonia volatilization during manure storage can create an imbalance between N and P in manure. For example, the ratio of N and P is 7:1 in fresh manure, which changes to 2 to 4:1 at the time of manure application after storage (i.e., manure imbalanced with N and P). Because of the imbalance, dairy manure is not a good sole fertilizer at the time of field application (reason 2). With the imbalanced manure, if manure application is P-based, N provided to crops is less than the requirement, which may affect crop yields. If manure application is N-based, excessive P will be applied to the field, which increases the risk of surface water pollution through P runoff (e.g., eutrophication, harmful algae blooms; reason 3). Therefore, lowering ammonia emissions from manure during storage in dairy operations is critical.

Various strategies have been investigated for decades, and the strategies that have been most effective at mitigating ammonia emissions during manure storage are discussed here. Covering lagoons with impermeable or permeable materials can lower ammonia volatilization up to 20 to 100% compared with manure in uncovered lagoons (Ndegwa et al., 2008). As a result, manure from covered lagoons is expected to be 3 to 4 times greater in N concentration at the time of application compared with manure from lagoons without covering. Another effective strategy is manure acidification. Ammonia volatilization is highly dependent on manure pH, i.e., ammonia formation (NH_3 from $NH4^+$); volatilization is inhibited at low pH (Hristov et al., 2011). In a series of studies, acidification of cattle manure with sulfuric acids considerably lowered ammonia emissions up to 90% during manure storage and up to 67% after field application (Sorensen and Eriksen, 2009; Petersen et al., 2012). The reduction in ammonia emissions during storage resulted in increased manure quality (i.e., readily available N in manure was increased up to 75% with manure acidification; Kai et al., 2008). Moreover, acidified manure may produce up to 70% less methane compared with untreated manure (Petersen et al., 2012). Currently, manure acidification systems in animal operations are commercially available to producers in Denmark. However, potential work hazards with handling strong acids for manure acidification must be addressed.

Extracting P from manure during storage is another potential strategy to decrease environmental impacts. Although this strategy may not affect ammonia volatilization during manure storage (yet to be studied), it could help lower environmental impacts when manure is applied to the field. As described earlier, imbalanced manure is created after manure storage due to considerable ammonia volatilization. Therefore, extracting P from manure will help keep it more balanced in N and P. Phosphorus in manure can be removed through physical, chemical, or thermochemical processes. Because most P is excreted in feces, a physical separation of solid from liquid can extract P from manure. The liquid-solid separation, however, requires specific separation equipment (e.g., screening, centrifuging) for effective particle separation from liquid (Azuara et al., 2013): just gravitational separation was not successful to separate tiny particles from liquid, e.g., 95% of the manure P remains in manure effluent (Powers et al., 1995). Phosphorus-binding chemicals to crystallize and precipitate manure P have been widely investigated, with reports that ferric, calcium, magnesium, and aluminum compounds are effective as P-crystallizing agents (Barrow et al., 1997; Sherman et al., 2000; Cabeza et al., 2011; Antonini et al., 2012). More recently, Azuara et al. (2013) used a pyrolysis process to extract P from manure solid (250 to 600 μm in diameter) after liquid-solid separation. As a result, 90% of total manure P was recovered mostly as a form of ortho-phosphate, and the study reported that the pyrolysis process was cost-effective for swine manure. The P compounds extracted from manure also have been tested as a P fertilizer. In one study, the P extract was as effective as commercial P fertilizers for crop production (Achat et al., 2014). Recently, a large centrifuge was installed at one dairy farm in Ohio to test P removal from manure (Figure 4). The centrifuge precipitated particles and formed a P-rich solid, where the P extraction efficiency after centrifugation was 57% of total P in the manure. The advantage of the centrifuge system is that manure liquid after centrifugation is well balanced with N and P, and the P-rich solid can be transported greater distances at a lower cost. The owner's goal is to remove more than 80% of the P in manure with centrifugation and by adding various P-binding polymers.

Generally, the strategies to lower environmental impacts during manure storage have been pretty effective as demonstrated above. However, the strategies that can decrease ammonia emissions during manure storage may have potential risks of greater ammonia volatilization from the manure after field application, which has not been well investigated. In addition, these strategies usually require extra costs to implement and maintain the systems. Therefore, changing management systems may not be a preferable strategy, especially for medium and small dairy farms.

N and P Losses After Field Application of Manure

The major purpose of fertilization is to increase crop dry matter production and the yield of the harvested parts of crops. Nutrient supply from manure and commercial fertilizers affects not only the size (quantity) but also the nutrient composition (quality) of crops (Heeb et al., 2006). Although crops require various macro and micro nutrients for growth, N and P (with potassium) are usually the most limiting factors in crop production. As indicated previously, however, nutrient supply applied in excess to land potentially increases the risks for environmental pollution. Therefore, fertilization with manure requires careful consideration from both economic and environmental viewpoints.

The sources of N and P required for crop growth are primarily provided from soil organic matter and fertilizer (manure and/or commercial fertilizer). The application rates of nutrients for various crops have been established (MSU Extension, 1995). Therefore, knowing nutrient concentrations in soil and manure is key to appropriate nutrient application to land for maximizing crop yields and minimizing nutrient losses. Producers who do not know the nutrient concentrations in their manure and soil may refer to a guideline available that helps estimate their nutrient concentrations in manure at the time of application (e.g., OSU Extension, 2006). However, the estimated nutrient concentrations (especially N) in guidelines are quite variable. For example, N losses from holding ponds and lagoons were estimated to be 20 to 40% and 70 to 85%, respectively, of total manure N (OSU Extension, 2006). Nitrogen losses from manure are variable depending on factors like surface area, storage length, temperature, and wind (Hristov et al., 2011). Because individual dairy farms are affected by different factors, more studies are needed to examine N losses under various practical conditions to more accurately estimating manure N and P at the time of application. The most efficient strategy is probably to establish a nutrient management plan for individual dairy farms according to their own manure management systems and environmental factors.

Although producers may know the nutrient concentrations in their soil and manure at the time of manure application by lab tests, dairy manure is usually not an ideal sole fertilizer for crops because of its imbalance of nutrients. As described earlier, the imbalance in manure primarily occurs by considerable N losses through ammonia volatilization during manure storage. Therefore, if manure is not managed to decrease ammonia volatilization during storage, such as with acidification and covering lagoons (which is not the case for most farms in the US), addition of a commercial N fertilizer with dairy manure is required at the time of application. Otherwise, dairy manure may limit crop yields when application is P-based (N deficiency) or may increase environmental impacts when application is N-based (over-application of P). However, because adding a commercial N fertilizer to manure requires extra costs to producers, it may not be a favorable strategy in practice. Moreover, manure and soil tests must be conducted to determine the amount of a commercial N fertilizer to be added to the manure.

There are various strategies that can lower N and P losses after manure application to the field. Manure application techniques, rotational cropping, and application timing can significantly affect N and P losses from the field. For example, manure injection into soil significantly lowered ammonia and nitrous oxide emissions from manure compared with surface application (Montes et al., 2013) and N and P losses from runoff (Daverede et al., 2004; Laboski et al., 2013). Crop rotation, e.g., corn and soybean, requires less N addition than consecutive corn cropping because of atmospheric N fixation by legumes, which can be a good strategy for efficient use of an imbalanced manure (relatively low N and high P), such as dairy manure (OSU Extension, 2006). Moreover, manure surface application in winter on frozen ground or snow always needs to be avoided due to considerable losses of N and P through runoff via rainfall and snow melting (Srinivasan et al., 2006). These strategies are not new but are still effective in practice at reducing N and P losses after field application. Therefore, adopting these strategies in combination can significantly lower ammonia volatilization and P losses through runoff from manure-amended soil.

Conclusions

Individual dairy farms have different nutrient feeding and manure management systems depending on size of farm (e.g., herd size) and land for crops. Because herd size is usually maintained at each dairy farm, the amount of manure produced and stored at individual farms does not vary. If feed composition in herd diets is consistent, the amounts of N and P excreted by cows and the N and P concentrations in manure at the time of field application will not vastly vary at individual farms. In addition, nutrient build-up on land is also easily monitored by a soil test before manure application (e.g., once a year). Therefore, it is not difficult for producers to monitor nutrient production, losses, and utilization in their dairy operation systems. Knowing nutrient flows (from feeds to manure as fertilizer) in individual farms will help identify opportunities to improve dairy and crop production and to lower environmental impacts. Formulating dietary protein (i.e., N) and P in dairy diets to meet or be slightly below the requirements is the most important and effective strategy to lower environmental impacts by reducing N and P excretion. After lowering N and P excretion from cows, the key strategy to lowering environmental impacts and maintaining manure quality as a fertilizer is to minimize ammonia volatilization during manure storage. Because individual farms are under different factors affecting N losses during manure storage, a common nutrient management plan across all dairy farms is not ideal. Therefore, establishing a nutrient monitoring plan for individual farms (e.g., N and P excretion, N losses during manure storage, and N and P concentrations at the time of application) is important for appropriate nutrient management.

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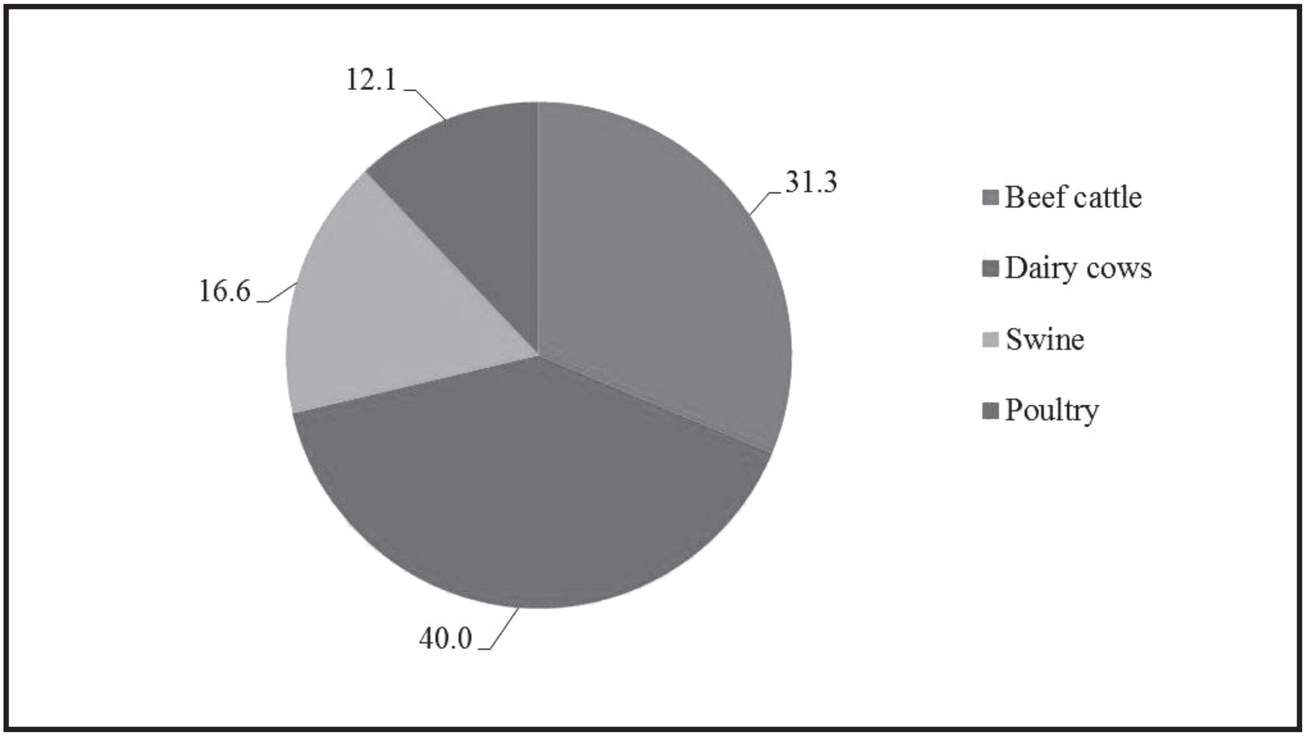

Figure 1. Proportions (%) of daily manure production by livestock in Ohio (calculated based on Ohio livestock populations on January 2014 with typical livestock manure production; ODA, 2015; OSU Bulletin-604, 2006).

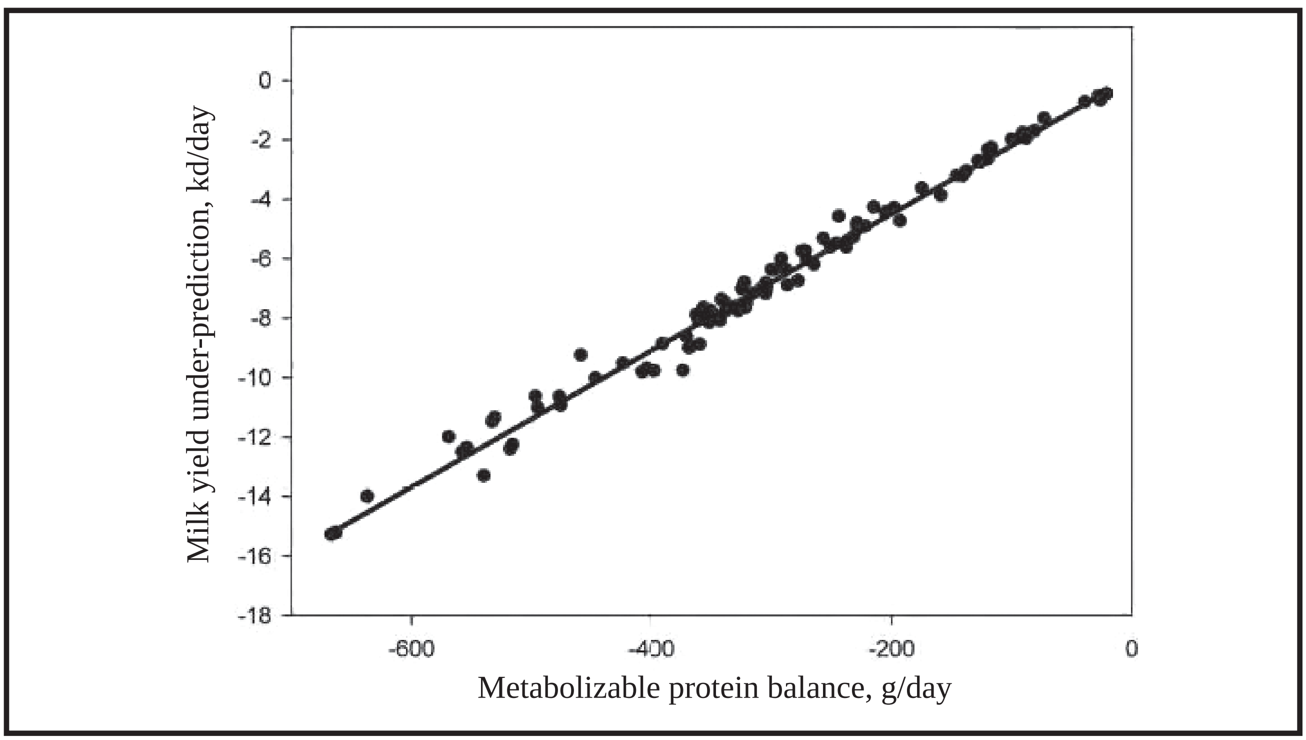

Figure 2. Relationship of metabolizable protein balance (NRC, 2001) and under-prediction of milk yield in dairy cows (Lee et al., 2012b).

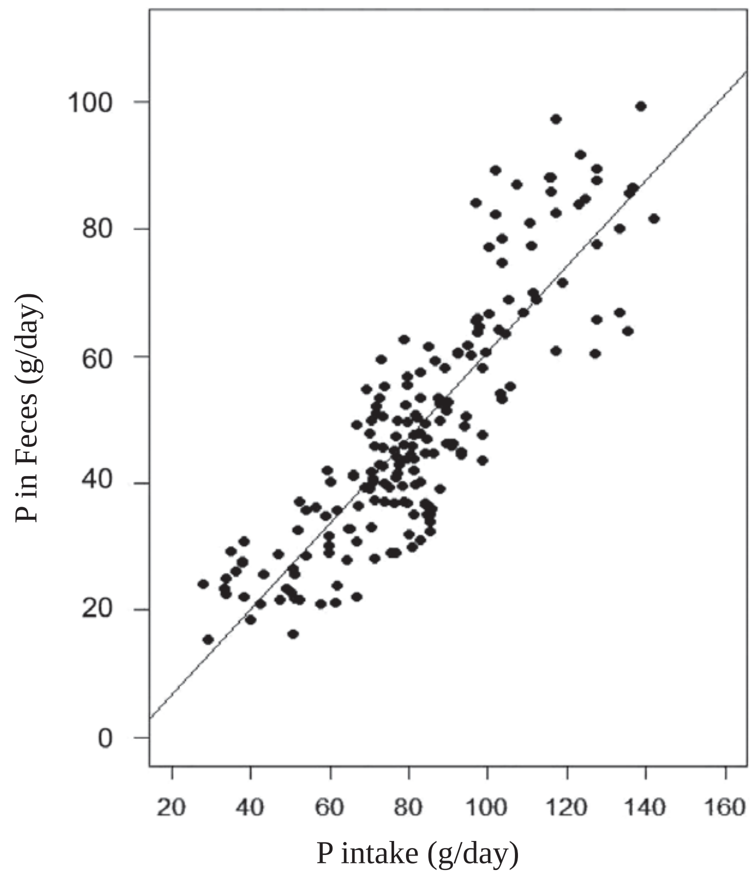

Figure 3. Relationship between P intake and fecal P output (Alvarez-Fuentes et al., 2016).

Figure 4. A centrifuge to precipitate manure solid rich in P (left) and manure solid after centrifuging (right); pictures used with permission.