Phosphorus Concentration and Solubility in Dairy Feces: Variability and Affecting Factors

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ABSTRACT

Recent data from phosphorus (P) feeding trials have demonstrated that P concentration in dairy feces is directly affected by P levels in diets and that farm P surpluses as well as potential environmental losses can be reduced through dietary manipulation. The current study was conducted to examine the variability of fecal P under farm conditions and to elucidate factors affecting the concentration and solubility of fecal P. Feed and fecal samples from >30 commercial dairies in the Northeast and Mid-Atlantic regions were analyzed. Dietary P concentrations ranged from 3.45 to 5.78 g/kg of feed DM (DM), and P determined in acid digests (TP) of feces from 5.84 to 12.84 g/kg of fecal DM. On average, 50% of fecal TP was water soluble; of the latter, 83% was inorganic (P_i). Across-farm variability ($n = 33$) had CV averaging 18.9% for fecal TP and >20% for P_i and total P (P_t) in water extracts. Within-farm variability based on multiple samples per herd had the same magnitude as across-farm and was independent of sample numbers from individual farms ($n = 7$ to 30). Of all fecal parameters determined, pH and DM had the lowest variability (CV <10%), water-soluble P_i , P_t , and Ca the highest (CV of 20 to 30%), and total P, Ca, and Mg determined by acid digests were intermediate (CV 10 to 20%). Water-soluble P_i concentrations determined in dried-ground fecal samples were lower than in wet samples. The drying-grinding process changes P_i solubility and the change is not linear. This study confirms that dietary P concentration is the dominating factor affecting fecal P excretion; however, Ca concentration, DIM, and fecal pH also made small, but statistically significant contributions, although some of the mechanisms remain to be thoroughly investigated.

(Key words: dairy farm, phosphorus, dietary management)

Abbreviation key: TP = phosphorus determined in acid digests, P_i = inorganic phosphorus, P_o = organic phosphorus, P_t = total phosphorus (P_i and P_o) in extracts.

INTRODUCTION

In dairy farming, dietary management plays an important role in helping producers balance nutrient supply against animal requirements and in alleviating potential environmental problems. Recent studies have demonstrated that P concentrations in lactating cow diets can be substantially reduced from levels commonly fed on farms without impairing animal performance (Valk et al., 2000; Wu et al., 2001; Knowlton and Herbein, 2002). Reduced dietary P transfers directly to decreased P excretion in feces and consequently reduced potential environmental loss. Dou et al. (2002) demonstrated with data from 3 feeding trials that lower P in diets resulted in lower P determined by acid digests (TP) in feces. More important, the decreases in fecal TP associated with the low-P diets were primarily in the water-soluble P fraction (mostly as inorganic; P_i). Water-soluble P is the most vulnerable P fraction with regard to potential runoff loss (Kleinman et al., 2002a). The finding that water-soluble P_i in feces is highly correlated with dietary P and the fact that water-soluble P_i is relatively easy to measure led to an interesting notion that measurement of water-soluble P_i may serve as an evaluation tool for assessing if excessive P feeding occurs on farms (Dou et al., 2002). However, the amount of water-soluble P_i or total phosphorus in extracts (P_t) determined in manure or fecal samples can vary depending on laboratory procedures such as sample:water ratio or extraction time (Kleinman et al., 2002b). Also, Chapuis-Lardy et al. (2003), using a small number of dairy slurry samples, observed different patterns of P release in sequential water extractions with dried-ground samples compared with wet samples.

While it is indisputable that dietary management should be taken as the first defense against P buildup on farms, conclusions derived from research feeding trials need to be verified under actual farm conditions.

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Research trials are often performed with deliberately controlled experimental settings to isolate and highlight treatment effects while minimizing potential impacts of other factors. In the real world of commercial dairy farms, however, the situation is diverse and many factors interplay simultaneously to affect the dependent variables. Farms vary in resources (e.g., soils, crops, imported feeds, etc.) and management preferences (feeding programs, dietary P levels, etc.). Cows differ in genetic traits and physical or physiological characteristics such as BW or milk yield. These and other intrinsic or managerial differences inevitably add variability to the independent and dependent parameters and may dilute or diminish the numerical relationships between fecal P concentrations and dietary P levels.

The primary objective of the present work was to assess the variability of P concentrations in dairy feces across and within farms and identify factors affecting concentrations of fecal TP as well as water-soluble P, using samples from a diverse group of commercial dairies. A secondary objective was to determine if concentrations of water-soluble P extracted from dried-ground fecal samples differ from extractions using wet samples.

MATERIALS AND METHODS

Source of Samples

33-farm set. Feed and fecal samples along with herd information were obtained from 33 commercial dairies in New York, Pennsylvania, Delaware, and Maryland during the summer of 2002. All herds were Holstein breed, and fed TMR. The number of lactating cows ranged from 37 to 432 with a mean of 114 per farm. Milk yields as herd average for the month during which the samples were collected ranged from 19.6 to 41.7 kg/d, with a mean of 31.5 kg/d per cow.

From each farm, feed and fecal samples were collected on the same day from the lactating cow group only. Feed samples were obtained at the feed bunk at feed delivery, mixed by hand and randomly subsampled, resulting in one composite sample per farm and a total of 33 TMR samples. Fecal samples were rectal grabs from randomly selected healthy lactating cows and were kept individually. Number of cows sampled per farm ranged from 7 to 17 depending on the herd size. The total number of cow fecal samples was 381 in this study.

3-farm set. Separate from the 33-farm set, an intensive fecal sampling scheme was conducted on 3 commercial dairies located in southeast Pennsylvania. The herds were Holstein breed and fed TMR with dietary P concentrations measuring 3.51, 4.75, and 5.09 g/kg of P in feed DM at the time of sampling. Besides collecting

TMR samples (one per farm), rectal grab fecal samples were obtained from all healthy lactating cows in the feeding group, resulting in a total of 29, 27, and 30 fecal samples for the 3 farms, respectively. Analyses from the 3-farm set were used to verify the magnitude of within-farm variability and to further illustrate its independence from sample numbers.

Dried-ground vs. wet samples. Fecal samples from 10 out of the 33-farm set were selected with 4 random samples per farm, totaling 40 samples. In the laboratory, each of the 40 samples was divided: one-half for wet-based extraction (2 g + 98 mL deionized water) and the other one-half was dried at 65°C and ground to pass a 2-mm screen prior to extraction (0.3 g + 100 mL water). The DM of fecal samples averaged 15%, thus the sample:water ratio was essentially the same for the wet vs. dried extractions. Concentrations of P_t , P_i , Ca, and Mg in water extracts were determined following the procedures described below.

Sample Handling and Laboratory Procedures

Feed samples were analyzed at a commercial laboratory for standard feed quality parameters (Table 1) using established procedures. Fecal samples were kept frozen until laboratory analysis, upon which samples were thawed at room temperature, homogenized by hand, and then split into subsamples. The subsamples were used for: (1) DM determination in a convection oven at 65°C, (2) acid digestion with a microwave-assisted digester (Walter et al., 1997); the digests were used for determination of TP, and total Ca and Mg by inductively coupled plasma-atomic emission spectroscopy (ICP-AES), and (3) pH and P_t , P_i , Ca, and Mg in water extracts. The extraction was performed with 2 g of wet fecal sample in 98 mL of deionized water, shaken on a reciprocal shaker for 1 h, and filtered through Whatman 42 paper. After measuring the pH, an aliquot of the water extract was analyzed for P_i by the phosphomolybdate blue method of Murphy and Riley (1962). Another aliquot (0.5 mL) was digested in concentrated nitric acid (1 mL) at 90°C overnight, then determined for water-soluble P_t , Ca, and Mg on ICP-MS (mass spectroscopy). Water-soluble organic P (P_o) was calculated by subtracting P_i from P_t (Dou et al., 2000).

To assess the repeatability of the water extraction procedure, 2 fecal samples, one from the lower end and the other from the higher end in terms of TP concentrations, were run through water extraction with 15 subsamples each (i.e., 15 replications). The water extracts were determined for pH, P_i , P_t , Ca, and Mg (CV = 0.5%, 6.1%, 8.8%, 14.2%, and 3.5%, respectively). Given the general heterogeneous nature of animal manures, we considered the repeatability of the extraction procedure

Table 1. Herd information and selected feed analysis parameters for 33 Holstein dairy herds located in New York, Pennsylvania, Delaware, and Maryland.

	Minimum	Maximum	Mean	SD	CV
Herd size ¹	37	432	114	90	78.66
Milk yield, kg/d per cow	19.6	41.7	31.5	4.8	15.17
Feed DM	0.39	0.60	0.49	0.05	9.54
Feed analysis, g/kg feed DM					
CP	129.9	200.5	174.3	14.6	8.37
NDF	201.0	395.6	315.3	37.9	12.03
ADF	148.1	313.6	220.2	35.4	16.06
P	3.45	5.78	4.50	0.51	11.40
Ca	4.58	11.81	8.08	1.58	19.60
Mg	2.53	4.48	3.37	0.51	15.41
Ca/P	1.09	2.65	1.80	0.34	19.38
Ca + Mg/P	1.77	3.59	2.56	0.40	15.54
Mg/P	0.54	0.97	0.75	0.11	14.96

¹Number of lactating cows.

satisfactory. Thus, all extractions were performed using individual samples without replication. For quality control purposes, a reference sample was included in each extraction or acid digestion set and the relevant parameters were checked against the known values.

Data Analysis

Concentrations of P, Ca, and Mg in feed and fecal samples were reported on a DM basis. Least squares ANOVA and descriptive statistics were performed in SAS (SAS Institute, 1999). A mixed, stepwise regression was performed to identify factors affecting fecal P parameters. Stepwise variable entry and removal in the model examined the variables in the block at each step for entry or removal, taking intercorrelation between variables into consideration. All variables that had a significant impact at the 0.05 level were retained in the model.

RESULTS AND DISCUSSION

Feed Parameters

Nutritional analysis parameters of TMR samples ranged widely among farms (Table 1). The relative variability, calculated as CV across the 33 farms, was lowest for CP (8.4%) and highest for total Ca (19.6%). The large variability is not surprising because farms differ in a variety of ways, such as selection of feed ingredients, sources and processing of feeds, and soil and water conditions under which forages are grown. The magnitudes of the CV in the present study are comparable to those in previous reports. For example, Sniffen et al. (1993) found a 25% CV for Ca concentrations in 25 commonly used ruminant feedstuffs. Also, based on forage samples analyzed over a 12-mo period, Kertz (1998)

reported CV of 14 to 36% for total P, 15 to 30% for CP, and 7.5 to 17.5% for NDF and ADF, respectively.

Phosphorus concentrations in the 33 TMR samples ranged from 3.45 to 5.78 g/kg feed DM; all but one exceeded the relevant recommendations for diet P published by the National Research Council (NRC, 2001). The apparent overfeeding of P on these farms is consistent with recent survey findings that many farms feed excess P to lactating cows (Sink et al., 2000; Powell et al., 2002; Dou et al., 2003). The TMR samples also had a wide range of Ca, from 4.58 to 11.81 g/kg feed DM, comparing to the NRC recommendation of 6.6 g/kg (NRC, 2001). The Ca:P ratio in the feed samples ranged from 1:1 to 2.65:1. Ruminants tolerate a wide range of dietary Ca:P ratio (from 1:1 to 7:1) as long as P supply is adequate (McDowell, 1992).

Concentration and Variability of Fecal P

Fecal TP concentrations differed by more than a factor of 2 among the farms (Table 2; $n = 33$). Individual fecal samples had an even wider range, 3.92 to 16.73

Table 2. Fecal parameters as farm means ($n = 16$ for Mg, $n = 33$ for all other parameters).

Parameter	Minimum	Maximum	Mean	SD	CV
pH	6.65	8.32	7.56	0.46	6.1
	g/kg fecal DM				
DM	130	210	150	10	9.9
In acid digests					
P	5.84	12.84	9.20	1.74	18.9
Ca	15.17	32.20	23.78	4.24	17.8
Mg	7.25	11.65	9.35	1.42	15.2
In water extracts					
Total P (P_t)	2.55	6.79	4.53	1.01	22.2
Inorganic P (P_i)	2.25	6.35	3.79	1.07	28.3
Ca	4.28	13.40	9.50	2.26	23.8
Mg	4.98	8.75	6.80	1.00	14.8

Figure 1. Increasing dietary P led to higher concentrations of acid digest total P (TP) and water-soluble inorganic P (P_i) in feces, whereas water-soluble organic P (P_o) remained unchanged ($n = 33$).

g/kg fecal DM ($n = 381$). From feed to feces, P concentrations became higher and the range wider (3.45 to 5.78 g/kg DM in feed as compared with 5.84 to 12.84 g/kg DM of TP in feces). This concentrating effect is due to a greater disappearance of feed DM than P between the front end (feed intake) and the rear end (fecal excretion). With a digestibility of 65 to 75% for feed DM (NRC, 2001), only 25 to 35% is excreted as undigested feed residues. However, P use efficiency (disappearance) is much lower and fecal excretion higher. For example, the amounts of TP excreted in feces accounted for 55, 67, and 76% of feed P intake when cows were fed diets containing 0.31, 0.39, and 0.47% P (Wu et al., 2001). A concentrating effect is also apparent for Ca and Mg for the same reason (Tables 1 and 2).

Water-soluble P_i and P_t concentrations of by-farm means also exhibited a wide range (Table 2) and accounted for roughly 50% of the fecal TP. On average, 83% of the P_t in water extracts was P_i . Increases in dietary P led to higher TP as well as water-soluble P_i of feces whereas water-soluble P_o remained low and unchanged (Figure 1). Water-soluble P_o is primarily phytate-like P (He et al., 2004), which probably derives from undigested feed residues. Water-soluble P_i may originate from both inorganic P contained in the TMR feeds and P that is released through digestion/hydrolysis within the animal's digestive tract. We do not have detailed information on feed ingredients and compositions for these farms. Nevertheless, the trends displayed in Figure 1 suggest that increasing dietary P, no matter whether the increase is brought about by addition of inorganic P supplements or inclusion of organic feed ingredients that are intrinsically high in P content, is unlikely to change the bioavailability of P. Instead, a higher amount and proportion of P is excreted

Figure 2. Within-farm variability of fecal parameters, selectively displayed for pH and acid digest total P (TP), did not decrease by increasing number of samples per farm.

as water-soluble P_i in feces. It is also interesting to note that only 40% of the total Ca in feces was water-soluble, whereas water-soluble Mg was nearly 73% of the total Mg (Table 2).

Across-farm variability of fecal P and other parameters differed depending on the parameter under consideration ($n = 33$; Table 2). As represented by the calculated CV, pH, and DM had the lowest variability (CV <10%), mainly attributed to the regulating and buffering functions of the animals' digestive physiology (Kohn and Dunlap, 1998; Allen, 2000). The higher variability exhibited by the other parameters, 10 to 20% for acid digest total P, Ca, Mg, and 20 to 30% for water-soluble P_i , P_t , and Ca, perhaps reflects differences in feeds, animals, and management factors. Chemical characteristics of samples might be an additional factor contributing to the highest variability of water-soluble P_i , P_t , and Ca. Considering fecal TP, the magnitude of across-farm variability is equivalent to that reported from another farm-based study (Powell et al., 2002), in which farm means of samples from 98 Wisconsin dairies had an estimated CV of 25%.

Variability of fecal P within farms, calculated as CV based on individual cow feces samples for each farm, exhibited a rather wide range. Fecal TP had CVs as low as 7.6% on one farm but as high as 32% on another; water-soluble P_i had CV as low as 11.6% but as high as 37%. The overall ranking order of the fecal parameter variability within-farm is similar to that across-farms, i.e., pH and DM < acid digest total P, Ca, Mg < water-soluble P_i , P_t , Ca.

The within-farm variability appears to be unrelated to number of samples tested per farm, as illustrated in Figure 2 for selected parameters pH and TP. This is further corroborated by data from the 3-farm set with the intensive sampling scheme ($n = 27, 29$, or 30). On

these farms, within-farm variability had CV ranging from 16.0 to 23.2% for fecal TP and 21.6 to 31.4% for water-soluble P_i , similar to the magnitude for the 33-farm set. Also, when the 33 individual farms were ranked based on the CV for selected parameters (pH, fecal TP, and water-soluble P_i), there was a lack of consistency in the ranking order. In other words, a farm may rank relatively low in variability for one parameter but high in others. This seems to suggest that within-farm variability of fecal P and other parameters is likely to be intrinsic and random in nature. The practical implication is that on-farm sampling and testing must be based on multiple samples, or a composite of multiple samples; yet, large numbers of samples ($n > 10$) are not necessary, as it may not lower the variability.

A large across-farm variability is generally expected because farms can differ in a variety of ways. However, the relatively wide variability within farms obtained in the current study, which in some cases even exceeded that across farms, came as a surprise at first. Within any of the individual farms included in this study, cows were fed the same TMR diet and managed in the same fashion. Hence the main source of within-farm variability was cow differences such as BW, BCS, growth, milk yield, DMI, etc., besides experimental error associated with intrinsic sample heterogeneity and laboratory procedures. Upon further examining literature data, we found that even in rigorously controlled research feeding trials, fecal P variability within treatments appeared to be in the same magnitude as in the current study. For example, in a feeding trial conducted by Wu et al. (2000), fecal TP had CV ranging from 8 to 42% within treatments. In Dou's study (2002), within treatment CV were 2 to 12% for fecal TP and 8 to 35% for water-soluble P_i .

Factors Affecting Fecal P

Factors affecting fecal P concentrations as identified by mixed stepwise regression are shown in Table 3. Clearly, dietary P concentration remains the dominating factor affecting all fecal P parameters (TP, water-soluble P_t and P_i). This is in line with expectations based on existing knowledge. It also confirms the overall trend of higher dietary P leading to higher fecal P observed in P-feeding trials (e.g., Wu et al., 2000; Knowlton and Herbein, 2002; Powell et al., 2002; Dou et al., 2003). However, the relative magnitude of the coefficient of determination (r^2) between dietary P and fecal P was substantially lower in farm-based studies than P-feeding trials. For instance, Wu et al. (2001) reported a coefficient of determination of 0.843 when regressing fecal TP (%) against P intake (g/d), and Dou et al. (2002) obtained a coefficient of determination of

Table 3. Mixed stepwise regression for fecal P concentrations using probability to enter < 0.05 and probability to leave < 0.05 .

Source	df	SS (R^2)	P
Acid digest total P (TP)			
Model	5	902 (0.47)	<0.0001
Partition			
Dietary P	1	433 (0.23)	<0.0001
Acid digest total Ca of feces	1	312 (0.16)	<0.0001
Dietary Ca	1	108 (0.06)	<0.0001
DIM	1	25 (0.01)	0.002
Fecal pH	1	10 (0.005)	0.05
Error	376	1001	
Water soluble total P (P_t)			
Model	6	239 (0.39)	<0.0001
Partition			
Dietary P	1	121 (0.20)	<0.0001
Fecal pH	1	51 (0.08)	<0.0001
Dietary Ca	1	24 (0.04)	<0.0001
DIM	1	8 (0.01)	0.007
Acid digest total Ca of feces	1	6 (0.01)	0.02
Milk yield (kg/day)	1	4 (0.007)	0.04
Error	359	369	
Water soluble inorganic P (P_i)			
Model	4	206 (0.32)	<0.0001
Partition			
Dietary P	1	128 (0.20)	<0.0001
Dietary Ca	1	43 (0.07)	<0.0001
Fecal pH	1	27 (0.04)	<0.0001
DIM	1	5 (0.01)	0.04
Error	377	438	

0.95 regressing fecal TP (g/kg) against dietary P (g/kg) for research trials. For farm-based studies, Powell et al. (2002) observed a coefficient of determination of 0.55 for 47 Wisconsin dairies with single group feeding, and Dou et al. (2003) reported a coefficient of determination of 0.43 for 72 samples from dairy farms in the Northeast and Mid-Atlantic regions. The current study had an r^2 of 0.38 when regressing fecal TP against dietary P alone. Usually, research feeding trials deliberately control major factors to be the same except the treatment, whereas field-based studies like ours, with little intervention except sample collection, typically reflect the impact of all factors potentially affecting the dependent variables.

In addition to dietary P concentrations, fecal pH, Ca, and DIM accounted for small but significant contributions to the fecal P models (Table 3). The DIM effect on fecal P, however minor it appears to be, has not been explicitly noted previously. In an attempt to explore the theoretical basis for DIM effect, we estimated fecal TP concentrations at different DIM stages for a cow fed the same diet throughout a lactation with fixed digestibility, growth rate, and standard milk production curve. The results (detailed data not presented) indicated that fecal TP concentration would increase with increasing DIM because of decreasing milk yield (a sink for P). Perhaps, the lack of notice of a DIM effect in previous studies can be attributed to limited data points coupled with considerable variability, whereas

Figure 3. Relationship between acid digest Ca concentrations and pH of dairy cow feces ($n = 381$).

the large data set in the current study enabled its detection.

The role of pH in affecting water-soluble P is comprehensible from the view of chemistry. Water-soluble P, mostly inorganic P or orthophosphate, exists in dairy feces mainly as Ca-P complexes. As pH decreases, P in these complexes becomes more soluble. In the current study, fecal pH ranged from 5.81 to 8.61; and a linear correlation between water-soluble P_i and fecal pH was statistically significant with a negative slope ($r = -0.37$, $P < 0.0001$). On the other hand, the role of Ca in affecting water-soluble P is not straightforward. Fecal Ca was not a significant factor in the water-soluble P_i model (Table 3), but a separate analysis revealed a strong correlation between fecal pH and acid digest total Ca (Figure 3; $P < 0.0001$). Also, fecal Ca has a major impact on the proportion of water-soluble P_i in TP (Figure 4; $P < 0.0001$). This provides strong evidence of Ca-P com-

plex formation in dairy feces. Apparently, pH and Ca interact and together affect fecal P solubility.

How to explain the role of fecal Ca and pH in the fecal TP model (Table 3) remains a challenge. Because TP is a measure of total P in feces, it should be independent of fecal pH. Yet, the pH effect on TP may not be a mere artifact because regressing TP against pH alone also revealed a trend of increasing TP with pH, i.e., the slope taking a positive value (data not presented). In reference to the Ca effect, it may be argued that dietary P supplementation is usually achieved by adding monocalcium or dicalcium phosphate minerals to diets. The supplementation is unlikely to enhance animal performance. Instead, it leads to increased fecal excretion of P and Ca. This may explain at least partially the contribution of Ca in the TP model. Considering the strong relationship between fecal pH and Ca (Figure 3) plus the common practice of limestone (CaCO_3) being used as an inexpensive Ca supplement, we reason that increasing limestone in diets led to higher Ca and pH in feces, which consequently led to decreases in water-soluble P_i as well as the proportion of P_i :TP in feces. We further hypothesize that increasing limestone in feed may also lead to elevated pH along the digestive tract, which in turn may favor Ca-P complex formation, making P less soluble for absorption and thus leading to a higher excretion of fecal TP. In other words, increases in limestone in diets may produce a "P pulling effect" inside the digestive tract. Of course, this hypothesis, serving as a starting point for further discussion, remains to be thoroughly investigated. A supporting argument is that in monogastric species undergoing chronic kidney failure, calcium carbonate is often used as a phosphate binder to help reduce the absorption of P from the diets (Polzin et al., 2000).

Dried-Ground vs. Wet Samples

The drying-grinding process reduced water-soluble P_i (with little change in P_o) in most cases and the reduction is not linear (Figure 5). The amount of water-soluble Ca also changed nonproportionally, whereas changes in water-soluble Mg were less dramatic and in most cases close to linear (data not presented). Moreover, the relationship between water-soluble P_i and fecal TP was less correlated with data from the dried-ground samples as compared with the wet-based results (Figure 6). At present, we do not know if the change in the amount of P_i associated with the drying-grinding process is chemical or physical in nature, or both. In general, wet-based extraction features minimal alteration of manure properties and thus the results would be more reflective of natural conditions. In addition, wet-based extraction saves time and labor in terms of

Figure 4. Acid digest Ca concentration of feces affects the ratio of water-soluble P_i to acid digest total P (TP) ($n = 381$), suggesting Ca-P complexes as the main P binding forms.

Figure 5. Water soluble P_i determined in dried-ground samples is less than in wet samples ($n = 40$). The drying-grinding process changed the solubility of fecal P and the change is not linear.

sample processing and thus can be easily adopted in laboratories handling large numbers of samples. On the other hand, dried-ground samples offer the convenience of easy storage for repeated use and thus are often preferred for research purposes. Some previously published studies used dried-ground samples (e.g., Dou et al., 2000; 2002), while others used wet samples (e.g., Kleinman et al., 2002b; Dou et al., 2003). The outcome of the direct comparison in the current study emphasizes the need for caution when one compares results from different studies.

CONCLUSIONS

Fecal P and other parameters demonstrate variability, in terms of calculated CV, in the ranking order of

Figure 6. Water-soluble P_i of wet-based extraction better predicts fecal total P than dried-ground samples ($n = 40$).

pH and DM (less than 10%), acid digest total P, Ca, and Mg (10 to 20%), and water-soluble P_i , P_t , and Ca (20 to 30%). The relative magnitude of variability is similar whether measured within individual farms or across the large group of 33 farms. Across-farm variability reflects differences in resources and management among farms, whereas within-farm variability can be attributed to inherent heterogeneity in the herd. Data from this farm-based study confirm the overall trend observed in previous P-feeding studies that higher dietary P leads to increased excretion of P in feces, with much of the increase in fecal P being water soluble. Regardless of dietary ingredients and composition, P concentration in diets remains the dominating factor affecting the excretion and concentrations of fecal TP and water-soluble P_i . Additionally, fecal pH, Ca, and DIM made small but statistically significant contributions to fecal TP and P_i ; the role and implications of some of these additional factors remain unclear and warrant further investigation. Drying and grinding fecal samples changes the concentration of water-soluble P_i and the change is not linear, therefore, caution must be taken when comparing water-soluble P results from different studies using different procedures.

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