Phosphorus Characteristics of Dairy Feces Affected by Diets

Zhengxia Dou,* Katharine F. Knowlton, Richard A. Kohn, Zhiguo Wu, Larry D. Satter, Gangya Zhang, John D. Toth, and James D. Ferguson

ABSTRACT

Phosphorus (P) surplus on dairy farms, especially confined operations, contributes to P buildup in soils with increased potential for P loss to waters. One approach to reduce P surplus and improve water quality is to optimize P feeding and improve P balance on farms. Here we report how varying P concentrations in lactating cow diets affects the amount as well as the chemical forms and fraction distribution of P in fecal excretion, and the environmental implications of this effect. Analysis of fecal samples collected from three independent feeding trials indicates that increasing dietary P levels through the use of P minerals not only led to a higher concentration of acid digest total phosphorus (TP) in feces, but more importantly increased the amount and *proportion* of P that is water soluble and thus most susceptible to loss in the environment. For instance, with diets containing 3.4, 5.1, or 6.7 g P kg^{-1} feed dry matter (DM), the water-soluble fraction of fecal P was 2.91, 7.13, and 10.46 g kg^{-1} fecal DM, respectively, accounting for 56, 77, and 83% of acid digest TP. The other fecal P fractions (those soluble in dilute alkaline and acid extractants) remained small and were unaffected by dietary P concentration. Excess P in the P supplemented diets was excreted in feces as water-soluble forms. A simple measure of inorganic phosphorus (P_i) in a single water extract is highly responsive to changes in diet P concentrations and hence can be indicative of dietary P status. A fecal P indicator concept is proposed and discussed.

In the past few decades, dairy farms in USA have experienced substantial growth in the number of animals per operation. For example, between 1980 and 2000, the mean number of milk cows per operation increased steadily from 32 to 87 (USDA National Agricultural Statistics Service, 2001) while estimated crop acreage per farm increased little. This intensification trend is associated with a higher dependence on purchased feeds to meet animal needs. The consequence is nutrient surpluses on farms and P buildup in soils, which, in turn, contribute to accelerated nutrient losses to waters. In response to impaired water resources, many states are now developing and adopting nutrient management strategies. Several states such as Delaware, Maryland, and Virginia have passed laws requiring P-based management practices for manure and fertilizers when soils exceed state-defined upper limits of soil test P (Sims, 2000).

Adopting P-based nutrient management plans will almost always translate into restrictions on manure applications and limited expansion of operations for dairy farms. Given this increased regulatory focus on P application, there is a need to develop and implement management strategies to improve P balances on farms and sustain animal productivity while minimizing the effect of manure P on water quality. Balancing dairy rations for adequate supply of P to meet animal requirements while reducing excess P in diets is one cost-effective approach to achieving these goals.

More precise formulation of dairy rations can lead to substantial reduction in fecal P excretion without impairing animal productivity. Wu et al. (2000) recorded no differences over a complete lactation in milk yield or other animal performance parameters between cows fed diets containing 4.0 g P kg^{-1} and 4.9 g P kg^{-1}, whereas fecal P excretion was reduced by 23% with the 4.0 g P kg^{-1} diet. Data from several other studies suggest that even lower dietary P levels, about 3.3 to 3.5 g P kg^{-1}, may be adequate for satisfactory milk yields while reducing P excretion in feces (Brintrup et al., 1993; Knowlton and Herbein, 2002; Kohn, unpublished data, 2001).

In areas where soil P buildup is severe and P-based manure management plans are required, reducing fecal P excretion through more precise ration formulation is a sensible and viable option. Powell et al. (2001) estimated that crop acreage required for recycling manure P was decreased by 39% when dietary P was reduced from 4.8 to 3.8 g P kg^{-1}. The 3.8 g P kg^{-1} diet was adequate for lactating cows in a feeding trial (Powell et al., 2001), but diets containing 4.8 g P kg^{-1} or even higher are fairly common on farms, as revealed by several surveys (Wu and Satter, 2000; Sink et al., 2000; Shaver and Howard, 1995).

Potential P loss on animal farms may be related not only to how much P is excreted in manure and applied to fields but also how easily the manure P is dissolved in rainwater and subject to potential runoff loss. That is, the chemical forms of P and their relative proportions in manure play an important role. This was illustrated by Sharpley and Moyer (2000) who, using manure-packed columns in a simulated rainfall study, reported a linear relationship between P loss in leaching and the concentration of water-soluble P in the manures. Water-soluble P was shown to be highly correlated with TP of feces and daily P intake (Powell et al., 2001), and appeared to be the largest single fraction in various manures when tested with sequential fractionation procedures (Dou et

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Abbreviations: DM, dry matter; P_i, inorganic phosphorus; P_o, organic phosphorus; P_t, total phosphorus (in extracts); TP, total phosphorus in acid digest.

al., 2000a,b; Sharpley and Moyer, 2000). However, to date, data are scarce on how varying diet P concentrations affects the chemical forms and fraction distributions of P in manures.

The objective of this study was to investigate the effect of varying diet P concentration in lactating cow diets on the characteristics of P in fecal excreta. Fecal samples collected from three independent feeding trials were analyzed for P concentrations through acid digestion, water extraction, and sequential extractions. Combining diet P and fecal P data with animal performance information, we propose a fecal P indicator concept and discuss its potential use as a management tool for assessing or monitoring P feeding status.

MATERIALS AND METHODS

Feeding Trials and Fecal Sample Collection

Fecal samples were collected from individual cows in three independent feeding trials each employing diets with varying P concentrations. Trial A was conducted to investigate P partitioning during early lactation (Knowlton and Herbein, 2002). The cows were fed a common total mixed ration (TMR) containing 2.8 g P kg^{-1} pre-calving, followed by a common TMR containing 5.1 g P kg^{-1} for 7 d post-calving, then randomly assigned to one of three diets that contained 3.4 (n = 5), 5.1 (n = 4), or 6.7 g P kg^{-1} (n = 4) through Week 11 of the lactation. Total collection of feed and feces was conducted during three-day periods in Weeks 3, 5, 7, 9, and 11 post-calving. Fecal samples were kept individually for each cow per sampling week. Trial B included cows fed TMR diets containing 3.1 (n = 10), 3.9 (n = 14), or 4.7 g P kg^{-1} (n = 13) (Wu et al., 2001). Fecal samples were collected from the rectum during seven sampling periods in the lactation; the samples were composited across sampling times for each cow. Trial C had cows fed TMR diets containing 3.7 (n = 6) or 4.8 g P kg^{-1} (n = 6) for two years (Kohn, unpublished data, 2001). Grab fecal samples used in Trial C were from the first lactation, collected during early, peak, and mid- and late-lactation and kept individually for each cow per sampling time.

In all three feeding trials, the base diets consisted of forages (44 to 50%), grains (31 to 35%), and concentrate mix (14 to 26% of ration DM), plus salt, trace mineral, vitamin, and other additives balanced according to recommendations (National Research Council, 1989) with no mineral P supplementation. For the higher-P diets, dicalcium phosphate (Trial A), monosodium phosphate (Trial B), or monocalcium phosphate (Trial C) was added to achieve the desired P levels. Calcium content for the three trials was in the range of 6.5 to 7.5 g kg^{-1} feed DM. Although dietary ingredients varied between the trials, differences within trials were kept minimal except P concentrations.

Laboratory Analysis

Fecal samples were oven-dried at 55 to 65°C and ground to pass a 2-mm screen prior to laboratory analyses. Concentrations of TP were determined for all samples by microwave-assisted acid digestion (Walter et al., 1997). The two-stage process consisted of preliminary digestion of 0.25-g subsamples of dried, ground fecal material in 10 mL concentrated H_2SO_4 followed by addition of 7.5 mL 30% H_2O_2 and a second digestion. Diluted digest aliquots were analyzed by the Murphy and Riley method (Murphy and Riley, 1962) on a spectrophotometer at 882 nm. Selected fecal samples, including those collected in Week 7 from Trial A, three random samples for each group from Trial B, and mid-lactation samples from Trial C, were tested for P fraction distributions using a sequential extraction procedure adapted by Dou et al. (2000a) from a soil P fractionation scheme developed by Hedley et al. (1982). Briefly, this procedure involves extracting the dried, ground fecal sample with deionized water, 0.5 M $NaHCO_3$, 0.1 M NaOH, and 1.0 M HCl solutions, in that order. Repeated 1-h shaking and filtering is performed with each extractant until the P in the last filtrate is negligible before proceeding to the next extractant. The sums of P in the relevant extracting solutions are referred to as the water-soluble fraction, bicarbonate, hydroxide, and acid-soluble fractions, respectively. Additionally, all fecal samples were tested for readily soluble P by extracting approximately 0.3 g of sample in 30 mL deionized water with 1 h of shaking (this is the same as the first of the sequential extractions).

All extractions were performed at room temperature with a reciprocal shaker at a speed of 150 min^{-1}, centrifuged at 3000 rpm for 10 min, and filtered through a 0.45-μm nitrocellulose membrane with vacuum. Aliquots of filtrates were analyzed for inorganic phosphorus (P_i) by the Murphy and Riley (1962) method and total extractable phosphorus (P_t) by inductively coupled plasma (ICP) spectrometry (Dahlquist and Knoll, 1978). Organic phosphorus (P_o) was estimated by subtracting P_i from P_t.

Data Analysis

Analyses of variance and mean separation by Duncan's multiple range test at a significance level of 5% were performed with the general linear models procedure in SAS (SAS Institute, 1999). Where appropriate, standard errors were reported to illustrate variability about the means. All treatment means of fecal P concentrations are expressed on a dry matter basis (g P kg^{-1} of fecal DM).

RESULTS AND DISCUSSION

Total Phosphorus Concentration

Across all three experiments, concentrations of TP in fecal samples increased with increasing diet P, either averaged across different sampling times (Table 1) or

Table 1. Phosphorus in dairy cow feces as affected by dietary P concentration, measured as total P in acid digest (TP) and readily soluble P in water extract with 1 h of shaking and filtering.†

		Fecal P			
			Readily soluble		
Feeding trial	Diet P	Total	P_t‡	P_i§	P_o¶
	g kg^{-1}	g kg^{-1} fecal dry matter			
A	3.4	5.21 (0.21)	2.32 (0.23)	1.82 (0.15)	0.50
	5.1	9.31 (0.09)	5.32 (0.18)	4.40 (0.19)	0.92
	6.7	12.65 (0.15)	7.39 (0.31)	6.28 (0.27)	1.11
B	3.1	4.88 (0.08)	1.95 (0.04)	1.48 (0.04)	0.47
	3.9	7.48 (0.20)	3.32 (0.10)	2.82 (0.09)	0.50
	4.7	9.05 (0.30)	5.04 (0.10)	4.33 (0.09)	0.71
C	3.7	6.07 (0.18)	2.29 (0.30)	1.85 (0.23)	0.44
	4.8	9.44 (0.35)	3.85 (0.58)	3.36 (0.48)	0.49

† Data are treatment means across sampling times with the standard errors of the mean in parentheses.
‡ Total P in extracts.
§ Inorganic P.
¶ Organic P; calculated as $P_t - P_i$.

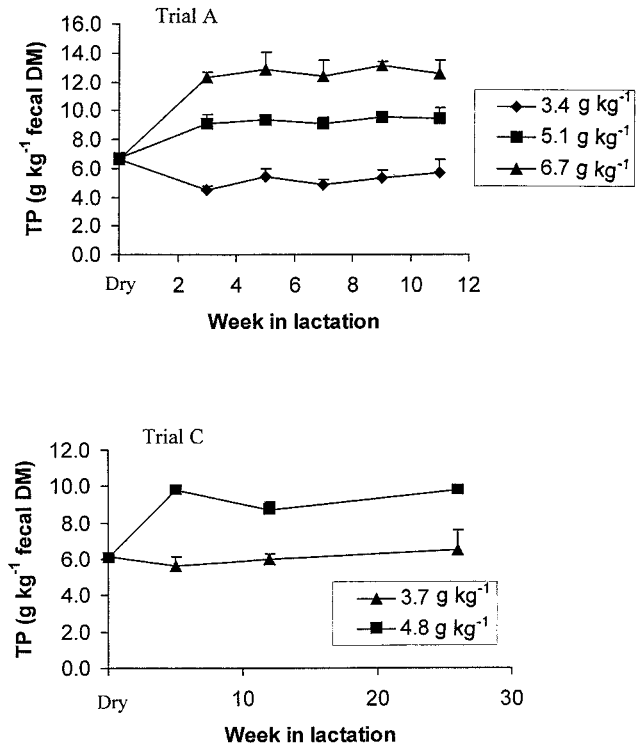

Fig. 1. Acid digest total P in fecal samples affected by diets in feeding Trial A over first 11 wk in lactation and Trial C over 26 wk in lactation. Vertical bars are means + one standard error.

at individual sampling times (Fig. 1). This relationship between fecal P and dietary P in concentration (g P kg^{-1} DM) is consistent with earlier reports of a similar mass-based (g P cow^{-1} d^{-1}) relationship between fecal P excretion and feed P intake (Morse et al., 1992; Wu et al., 2000). These observations are not surprising given the law of mass conservation and the principle of P partition by the animal. In mature lactating cows, P intake is partitioned into milk, urine, and feces. Milk P is nearly constant (about 1 g P kg^{-1} of milk). Urinary P is relatively small, no more than a few grams per cow per day even in high-P diets (Morse et al., 1992; Wu et al., 2001). Fecal P excretion, typically accounting for 60 to 70% of total P intake, is the major route of excretion for unutilized P. In the three feeding trials, the base diets appeared to provide adequate amounts of P (more discussion below), hence the excess P contained in the higher-P diets was excreted in feces, resulting in higher TP concentrations as measured.

Fecal Phosphorus Fractions

Results of the sequential extraction showed that increasing dietary P concentrations resulted in a greater amount of P in the water-soluble fraction whereas the other fecal P fractions remained small with little change. Figure 2 illustrates the relative magnitude of P in the four fractions and their distribution using samples taken during Week 7 in Trial A. For Trials B and C, only the water-soluble P, the most significant fraction, was presented (Fig. 2).

When the concentrations of the water-soluble fraction were plotted against the nonsoluble P (difference between TP and cumulative water-soluble P), it is obvious that the increased fecal TP observed with the mineral P–supplemented diets was almost entirely in the water-soluble fraction (Fig. 3). This is true for all three independent feeding trials. Upon further examining the mass-based total collection data available from Trial A (Table 2), we found that nearly all the extra P intake above the base diet (44.8 and 73.7 g P cow^{-1} d^{-1}) was excreted in feces (55.0 and 71.2 g TP cow^{-1} d^{-1}); and the extra P in feces was almost entirely in the water-soluble fraction (52.2 and 70.2 g P_i cow^{-1} d^{-1}).

The environmental implications of these observations are significant. Water-soluble P is associated, more closely than the other fractions, with potential P loss to waters once manure is field-applied (Sharpley and Moyer, 2000). For agricultural systems that rely upon surface applications of manures to pastures or no-till crops, or where bypass flow pathways exist in soils that can accelerate P leaching, manure containing high levels of water-soluble P can be a particular concern (Sims et al., 1998). Clearly, lowering dietary P concentrations by minimiz-

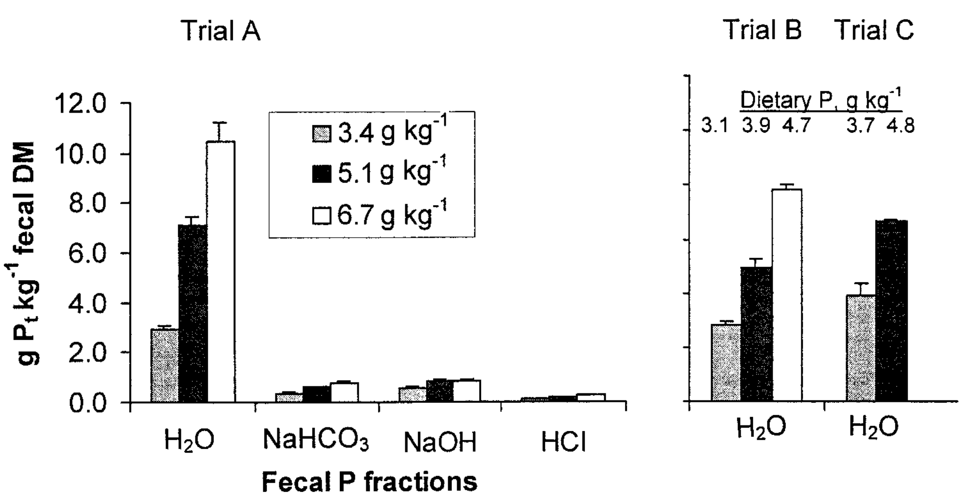

Fig. 2. Phosphorus fraction affected by diets through sequential extraction procedures: a complete fraction distribution with samples collected in Week 7 of lactation (Trial A), and the water fractions for selected samples in Trials B and C. Vertical bars are means + one standard error.

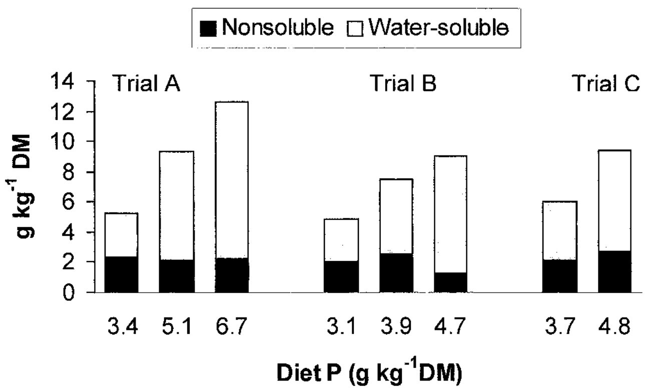

Fig. 3. Water-soluble vs. nonsoluble P concentrations in dairy feces from three independent feeding trials with varying dietary P concentration.

ing unnecessary mineral P supplementation will reduce the excretion of not only total P in feces but more importantly the most environmentally vulnerable P fraction.

Also noteworthy is that even with the base diets that consisted solely of organic feed components, the water-soluble P fraction still dominates the fecal TP. For the three base diets in Trials A, B, and C, the water-soluble P fraction totaled 2.91, 2.83, and 3.91 g P_t kg^{-1}, accounting for 56, 58, and 64% of the TP in the fecal samples. Furthermore, much of the water-soluble P is inorganic (2.32, 2.38, and 3.60 g P_i kg^{-1} for the corresponding base diets). These observations suggest that P contained in the organic feeds was either largely water soluble to begin with or readily digestible by the animal. Either case indicates a high availability of the P in the base diets.

Readily Soluble Phosphorus

Concentrations of readily soluble P in all samples (in contrast to selected samples with the sequential extractions) increased as the dietary P level was raised through mineral P supplementation in all three trials (Table 1). Treatment differences are distinctive, and consistent across sampling times covering the early lactation in Trial A or throughout the lactation in Trial C (Fig. 4).

The amount of P measured in a single water extract, that is, readily soluble P, illustrates several important points. First, readily soluble P accounts for a substantial portion of fecal TP, as can be derived from Table 1.

Table 2. Phosphorus intake, excretion, and water-soluble P in fecal samples affected by dietary P concentration. Samples were collected in Week 7 post-calving from feeding Trial A. Data presented are means of four cows per treatment diet.

Diet P	P intake	Fecal P excretion: Total P	Fecal P excretion: Water-soluble P†
g kg^{-1}	g d^{-1} cow^{-1}		
3.4	97.3	41.8	24.2
5.1	142.1	96.8	76.4
6.7	171.0	113.0	94.4

† Calculated by multiplying the amount of total P in fecal excreta, g d^{-1} cow^{-1} (Column 3), by the ratio of water-soluble P concentration to total P concentration in fecal samples. Water-soluble P is the sum of total P in water extracts through repeated extractions.

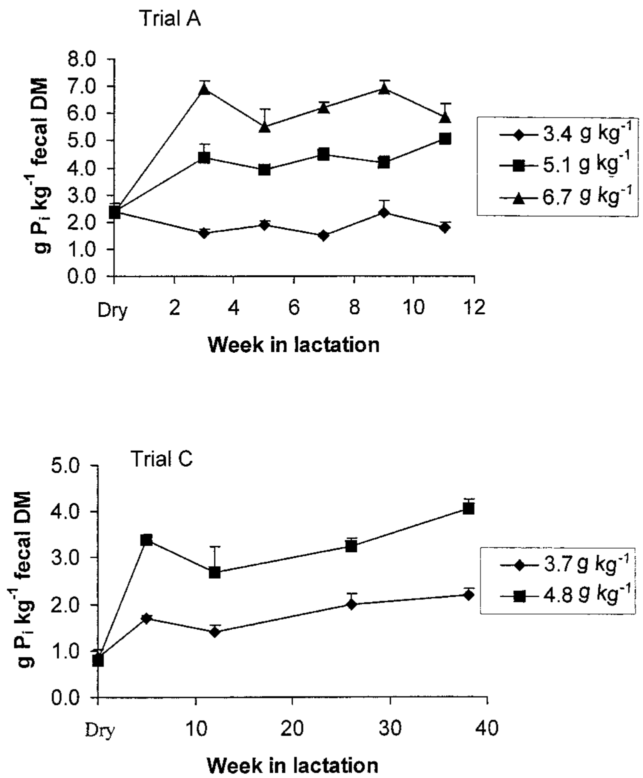

Fig. 4. Inorganic P concentrations determined in water extracts of fecal samples (1-h shaking and filtering) collected from feeding trials featuring early lactation (Trial A), or throughout a complete lactation (Trial C). Vertical bars are means + one standard error.

Second, readily soluble P accounts for most of the water-soluble P determined through repeated water extractions. As illustrated in Fig. 5, the amount of P release dropped dramatically between the first and the second extraction, followed by gradual and steady decreases thereafter as the number of repetitions increased. Note that P determined in the first of the serial water extracts is equivalent to readily soluble P. The P release pattern exhibited in Fig. 5 is consistent for the selected samples from Trials B and C (data not presented) and earlier reports with various manure samples (Dou et al., 2000a,b). It is apparent that readily soluble P measurements can reflect the relative magnitude of fecal P that is most susceptible to potential loss once the manure is land-applied, especially if surface-applied.

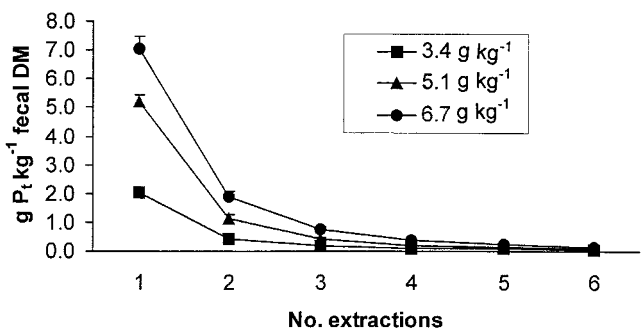

Fig. 5. Phosphorus release pattern through repeated water extraction. Samples were collected in Week 7 post-calving from grouped cows fed three diets containing different P concentrations (Trial A). Vertical bars are means + one standard error.

The third point is that the laboratory procedure for determining readily soluble P is simpler than those for determining TP (requiring acid digestion) or cumulative water-soluble P (requiring repeated extractions). This procedure may be further simplified by analyzing only P_i on a spectrophotometer instead of P_t. The latter requires either an expensive inductively coupled plasma instrument for direct measurements or acid digestion of the extracts if the Murphy and Riley method is to be used with a spectrophotometer. The simplification is possible because concentrations of P_i in water extracts are several times greater than that of P_o (Table 1; also see Dou et al., 2000a,b).

Although both TP and readily soluble P are affected by dietary P concentrations, readily soluble P_i (and P_t as well) measurements are apparently more responsive to changes in dietary P than fecal TP measurements. For example, with dietary P increased from 3.4 to 5.1 g P kg^{-1} in Trial A, readily soluble P_i increased by a factor of 2.4 while TP increased by 1.8. In Trial B, raising dietary P from 3.9 to 4.7 g P kg^{-1} increased readily soluble P_i by a factor of 1.9 while TP increased by 1.5. The important implication is that a simple measure of readily soluble P_i can be indicative of dietary P status, considering that urine P loss is relatively small and negligible even at high-P diets (Wu et al., 2001; Morse et al., 1992). If we can identify the adequate diet P levels satisfying animal needs with minimal excess, the readily soluble P_i of the corresponding fecal samples would serve as a benchmark for P adequacy. Then, measuring readily soluble P_i of fecal materials and comparing the value with the benchmark range would help us "diagnose" if dietary P is excessive or near adequate. With this reasoning, we propose the *fecal P indicator* concept, discussed next.

Fecal Phosphorus Indicator

First, we need to identify the adequate dietary P level that meets lactating cow requirements for P with minimal excess. For the three feeding trials, the base diets containing 3.1 to 3.7 g P kg^{-1} appeared to be adequate or near adequate for milk production (Table 3). Other observed parameters, such as dry matter intake and body weight change, did not differ between the base diets and P-supplemented diets (Knowlton and Herbein, 2002; Wu et al., 2001; Kohn, unpublished data, 2001). However, in a different trial, Wu et al. (2000) recorded a negative P balance and a small decrease in milk yield during late lactation with a base diet containing 3.1 g P kg^{-1} compared with a 4.0 g P kg^{-1} diet. Integrating multiple research findings (summarized in Table 3), we believe that a dietary P concentration of 3.3 to 3.5 g P kg^{-1} represents the apparent adequate range. This range is comparable with the lower end of the recommendations provided by the National Research Council (National Research Council, 2001).

The regression equation below, derived from combined data of all three trials, defines the quantitative relationship between readily soluble P_i (Y, g kg^{-1} fecal DM) and dietary P concentration (X, g P kg^{-1} feed DM) for the trials:

$$Y = -2.80 + 1.37X \ (R^2 = 0.95, \text{standard error} = 0.39) \quad [1]$$

Using this equation, the empirical P benchmark as readily soluble P_i would be 1.73 to 2.00 g kg^{-1} for the apparent adequate diet P range (3.3 to 3.5 g P kg^{-1}). For each dietary P increment of 0.5 g P kg^{-1} unit (from 3.5 to 4.0 g P kg^{-1}, for instance), readily soluble P_i in feces would increase by 0.69 g kg^{-1}. In Trials A and C, the P concentration in the base diets is within the apparent adequate P range and the corresponding readily soluble P_i measured is 1.82 and 1.85 g kg^{-1}, respectively. For Trial B, readily soluble P_i may embrace a similar value, judging from the measurements of 1.48 g P_i kg^{-1} with the 3.1 g P kg^{-1} diet and 2.82 g P_i kg^{-1} with the 3.9 g P kg^{-1} diet (Table 1).

There is some theoretical basis supporting the fecal P indicator concept and the notion of "diagnosing" dietary P status based on readily soluble fecal P_i measurements. According to Spiekers et al. (1993), fecal P can be categorized into three components: (i) unavailable dietary P, referring to dietary P that cannot be absorbed

Table 3. Milk production responses to diet P concentrations, a summary of three feeding trials included in the present study and literature data.

Trial features	Dietary P A	Dietary P B	Dietary P C	Milk† A	Milk† B	Milk† C	Reference
	g P kg^{-1}			kg d^{-1}			
4 cows per treatment, 11 wk early lactation	3.4	5.1	6.7	49.5a	47.8a	45.8a	Trial A (Knowlton and Herbein, 2002)
10 cows per treatment, 2–3 yr	3.1	3.9	4.7	42.3a	38.7b	39.4ab	Trial B (Wu et al., 2001)
6 cows per treatment, one complete lactation	3.7	4.8		34.9a	34.8a		Trial C (Kohn, unpublished data, 2001)
8 cows per treatment, one complete lactation	3.1	4.0	4.9	35.0a	36.5a	36.2a	Wu et al., 2000
20 cows per treatment, 10 mo	3.0	5.4		27.3a	30.4b		Kincaid et al., 1981
26 cows per treatment, two lactations	3.3	3.9		25.4	24.5		Brintrup et al., 1993
23 cows per treatment, 12 wk mid-lactation	3.9	6.5		23.9	24.4		Satter and Wu, 1999
6 cows per treatment, 21 mo‡	2.4	2.8	3.3	29.9a	37.5b	37.1b	Valk and Sebek, 1999

† Different letters within trials indicate significant differences ($\alpha = 0.05$).
‡ Data cited here are for one of several sampling periods. For the study details, refer to original publication.

under any conditions; (ii) inevitable P loss, consisting of microbial residue P and metabolic P; and (iii) regulated P, a component that varies according to P intake relative to cow requirement. The regulated P fraction is of primary interest concerning dietary P status. If dietary P is deficient, the animal will utilize as much feed P as possible, and regulated P will be negligible. If dietary P is marginal, some small amount of regulated P is likely, but if dietary P exceeds animal needs, much of the surplus P will be excreted in feces as regulated P (Wu et al., 2000). Therefore, dietary P status (i.e., deficient, near adequate, or excessive) may be assessed through the measurement of regulated P against a range of benchmark values.

We reason that the unavailable dietary P is largely organic and water-insoluble plant cell wall residues. The inevitable P loss includes P in microbial residues, sloughed gut tissue, and digestive secretions (Wu et al., 2000). Most of the P in this fraction would be organic and relatively insoluble, although the smaller portion of P in digestive secretions would be water soluble. In contrast, regulated P would be largely, if not completely, water soluble because it is a reflection of the portion of the P that was consumed in excess of the animal's needs but reentered the digestive tract in saliva from the circulation (Scott et al., 1985; Ternouth, 1989; Ternouth and Coates, 1997). Salivary P is in inorganic forms (Valk et al., 2000). Based on this reasoning, the readily soluble P_i measured in a single water extract of fecal material would provide a *relative measure* of the regulated P component. The degree of the relevance will depend on the amount of P fed relative to the requirement. If P is fed at the requirement level, readily soluble P_i will reflect the soluble part of the inevitable P plus some small amount of regulated P; as more P is fed in excess of the requirement, it will reflect more of the regulated P. According to this relationship, readily soluble P_i in feces will increase as more P is fed, and the increase should account for most of the increased fecal P concentration.

Applying Spiekers' theory, Wu et al. (2000) constructed an example distribution of the three fecal P components affected by dietary P concentrations. We expanded the calculation to a wider dietary P range and converted the mass-based (g d^{-1}) data into concentration-based (g kg^{-1} fecal DM) values. These were then graphed to illustrate the change of the three P components as a function of diet P concentrations (Fig. 6). While inevitable P loss remains constant and unavailable dietary P as a fixed percentage of total P intake increases slightly, regulated P responds dramatically to changes in dietary P (Fig. 6). We then superimposed the readily soluble P_i measured for the three feeding trials onto Fig. 6 (stars). Clearly, readily soluble P_i as measured reflects the trend as well as the relative magnitude of regulated P.

Certainly, P metabolism in lactating cows is complex and the bioavailability of P in diets and its absorption by animals are affected by numerous factors, detailed discussion of which is beyond the scope of the current study. An advantage of the fecal P indicator approach

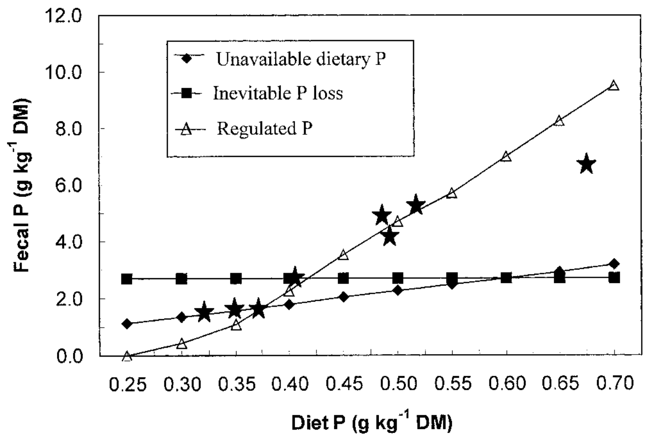

Fig. 6. Fecal P components (unavailable dietary P, inevitable P loss, and regulated P) as a function of dietary P concentrations (Spiekers et al., 1993). Superimposed stars represent inorganic P values measured in water extracts of fecal samples from three independent feeding trials, illustrating a similar trend and relative magnitude of the regulated P fraction.

is that we can "bypass" the complexity of P metabolism processes and influencing factors and focus on the outcome, that is, the P excreted and its characteristics, with a rapid and simple test. This is analogous to the PSNT approach (Magdoff et al., 1984) for estimating soil available nitrogen, which "bypasses" the complexity of soil N transformation processes and affecting factors and focuses on the end result, that is, nitrate concentrations in the soil profile under empirically defined conditions (e.g., sampling time, depth, field history).

Obviously, the fecal P indicator concept and related quantitative parameters need to be rigorously tested with large-scale and preferably field-originated datasets. Once adequately tested and proved successful, this fecal P indicator has the potential to serve as a useful tool for "diagnosing" excessive P feeding on dairy farms, particularly where P minerals are used as diet supplements. Adding P minerals to dairy rations is a common practice on many U.S. dairy farms, as indicated by recent surveys showing dietary P levels of 30% or even more above the recommended range (Wu and Satter, 2000; Sink et al., 2000; Shaver and Howard, 1995). Reducing the unnecessary mineral P supplementation would lower feed costs for farmers, help conserve P minerals as nonrenewable resources, and reduce potential environmental losses.

The fecal P indicator we propose has several advantages over relying solely on feed analysis and diet formulation to reduce excess P excretion. Indeed, routine forage testing is highly recommended and practiced on many farms and P content is measured along with many other nutritional parameters. The problem is that these standard analyses provide little information on the availability of P. In fact, to date there is no rapid, inexpensive, noninvasive, and reliable method for routine determination of P availability in feeds. Additionally, P contents of forages and other feed ingredients can vary considerably with coefficient of variation exceeding 20% (Adams, 1974; Kertz, 1998). Thus, in practice, P minerals are added to provide a margin of safety against the variation of P contents in feeds and the uncertainties associated with P availability in mixed diets (Shaver and Howard, 1995).

Some farms, by our observation, have lowered dietary P concentrations recently, due to a combination of education, increasing regulatory pressure, and a flurry of research findings evidencing no negative effect of reduced dietary P on milk production. However, the practice of P overfeeding and mineral P supplementation is likely to continue on many farms unless management tools are developed to address the concerns and uncertainties. We believe that measurements of readily soluble P_i at the "rear-end" as a reflection of P consumption and utilization by the animals in comparison with benchmark values can provide feedback, and the peace of mind, for lowering dietary P at the "front-end."

Inorganic versus Organic Phosphorus

There have been concerns over the potential influence of dietary manipulation on dissolved organic P in excreted manure. Dissolved organic P, not readily adsorbed on soil particles, may be more mobile than inorganic or orthophosphate, thereby serving as a greater potential threat to waters (Chardon et al., 1997). In the present study, organic P concentrations in the filtrates of a single water extraction (i.e., readily soluble P_o) generally tended to increase as more mineral P was added to the base diets (Table 1, last column). In other words, eliminating or decreasing the amount of mineral P supplementation is likely to provide the benefit of decreasing soluble organic P in feces as well.

CONCLUSIONS

Varying P concentrations in lactating cow diets has a dramatic effect on P excretion in feces, with much of the effect being on the water-soluble fraction. Unnecessary mineral P supplementation leads to diets with P in excess of animal requirements; the excess dietary P is excreted in feces as water-soluble forms, increasing susceptibility to environmental losses when the manure is land applied. A simple measure of inorganic P in 1-h water extracts of fecal material may provide an indication if dietary P is excessive or near adequate. Data from three independent research feeding trials suggest a measure of approximately 2 g kg^{-1} fecal DM, as inorganic P in a 1-h water extract, to be a reference value indicating adequate diet P status. The higher the fecal inorganic P concentration (1-h water extract), the more excessive the dietary P concentration. Further research and testing with field data are needed to evaluate this fecal P indicator of overfeeding. A verified and refined fecal P indicator would provide a practical management tool for dairy producers and farm service personnel to enhance P balance and reduce P surplus on farms.

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REFERENCES

Adams, R.S. 1974. Variability in mineral and trace element content of dairy cattle feeds. J. Dairy Sci. 58:1538–1560.

Brintrup, R., T. Mooren, U. Meyer, H. Spiekers, and E. Pfeffer. 1993. J. Anim. Physiol. Anim. Nutr. 69:29–36.

Chardon, W.J., O. Oenema, P. del Castilho, R. Vriesma, J. Japenga, and D. Blaauw. 1997. Organic phosphorus in solutions and leachates from soils treated with animal slurries. J. Environ. Qual. 26:372–378.

Dahlquist, R.L., and J.W. Knoll. 1978. Inductively coupled plasma–atomic emission spectrometry: Analysis of biological materials and soils for major, trace, and ultra-trace elements. Appl. Spectrosc. 32:1–29.

Dou, Z., J.D. Toth, D.T. Galligan, C.F. Ramberg, Jr., and J.D. Ferguson. 2000a. Laboratory procedures for characterizing manure phosphorus. J. Environ. Qual. 29:508–514.

Dou, Z., J.D. Toth, C.F. Ramberg, Jr., and J.D. Ferguson. 2000b. Phosphorus fraction distributions in animal manures. p. 1–9. *In* Proc. 8th Int. Symp. on Animal, Agricultural and Food Processing Wastes, Des Moines, IA. 9–11 Oct. 2000. ASAE, St. Joseph, MI.

Hedley, M.J., R.E. White, and P.H. Nye. 1982. Plant induced changes in the rhizosphere of rape seedlings: III. Changes in L value, soil phosphate fractions and phosphate activity. New Phytol. 91:45–56.

Kertz, A. 1998. Variability in delivery of nutrients to lactating dairy cows. J. Dairy Sci. 81:3075–3084.

Kincaid, R.L., J.K. Hillers, and J.D. Cronrath. 1981. Calcium and phosphorus supplementation of rations for lactating cows. J. Dairy Sci. 64:754–758.

Knowlton, K.F., and J.H. Herbein. 2002. Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. J. Dairy Sci. 85:, in press.

Magdoff, F.R., D. Ross, and J. Amadon. 1984. A soil test for nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:1301–1304.

Morse, D., H.H. Head, C.J. Wilcox, H.H. Van Horn, C.D. Hissem, and B. Harris, Jr. 1992. Effect of concentration of dietary phosphorus on amount and route of excretion. J. Dairy Sci. 75:3039–3049.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36.

National Research Council. 1989. Nutrient requirements of dairy cattle. 6th rev. ed. Natl. Acad. Sci., Washington, DC.

National Research Council. 2001. Nutrient requirements of dairy cattle. 7th rev. ed. Natl. Acad. Sci., Washington, DC.

Powell, J.M., Z. Wu, and L.D. Satter. 2001. Dairy diet effects on phosphorus cycles of cropland. J. Soil Water Conserv. 56:22–26.

SAS Institute. 1999. SAS for Windows. Version 8. SAS Inst., Cary, NC.

Satter, L.D., and Z. Wu. 1999. Phosphorus requirement in dairy cattle. p. 140–154. *In* Proc. 46th Maryland Nutrition Conf. for Feed Manufacturers, Baltimore. 10–12 Mar. 1999. Univ. of Maryland, College Park.

Scott, D.F., G. Whitelaw, W. Buchan, and L.A. Bruce. 1985. The effect of variation in P intake on salivary P secretion, net intestinal P absorption and fecal P excretion in sheep. J. Agric. Sci. 105:271–277.

Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29:1462–1469.

Shaver, R., and W.T. Howard. 1995. Are we feeding too much phosphorus? Hoard's Dairyman 140:280–281.

Sims, J.T. 2000. The role of soil testing in environmental risk assessment for phosphorus. p. 57–81. *In* A.N. Sharpley (ed.) Agriculture and phosphorus management. Lewis Publ., Boca Raton, FL.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293.

Sink, S.E., K.F. Knowlton, and J.H. Herbein. 2000. Economic and environmental implications of overfeeding phosphorus on Virginia dairy farms. J. Dairy Sci. (Suppl. 1) 83:143.

Spiekers, H., R. Brintrup, M. Balmelli, and E. Pfeffer. 1993. Influence of dry matter intake on faecal phosphorus losses in dairy cows fed rations low in phosphorus. J. Anim. Physiol. Anim. Nutr. 69:37–43.

Ternouth, J.H. 1989. Endogenous losses of P by sheep. J. Agric. Sci. 113:291–297.

Ternouth, J.H., and D.B. Coates. 1997. Phosphorus homeostasis in grazing breeder cattle. J. Agric. Sci. 128:331–337.

USDA National Agricultural Statistics Service. 2001. USDA-NASS home page. Available online at http://www.usda.gov/nass (verified 25 July 2002). USDA-NASS, Washington, DC.

Valk, H., J.A. Metcalf, and P.J.A. Withers. 2000. Prospects for minimizing phosphorus excretion in ruminants by dietary manipulation. J. Environ. Qual. 29:28–36.

Valk, H., and L.B.J. Sebek. 1999. Influence of prolonged feeding of limited amounts of phosphorus on dry matter intake, milk production, reproduction and body weight of dairy cows. J. Dairy Sci. 82:2157–2163.

Walter, P.J., S. Chalk, and H.M. Kingston. 1997. Overview of microwave-assisted sample preparation. p. 55–222. *In* H.M. Kingston and S.J. Haswell (ed.) Microwave enhanced chemistry: Fundamentals, sample preparation and applications. Am. Chem. Soc., Washington, DC.

Wu, Z., and L.D. Satter. 2000. Milk production and reproductive performance of dairy cows fed two concentrations of phosphorus for two years. J. Dairy Sci. 83:1052–1063.

Wu, Z., L.D. Satter, A.J. Blohowiak, R.H. Stauffacher, and J.H. Wilson. 2001. Milk production, phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. J. Dairy Sci. 84:1738–1748.

Wu, Z., L.D. Satter, and R. Sojo. 2000. Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. J. Dairy Sci. 83:1028–1041.