Published online April 11, 2005

Survey of Water-Extractable Phosphorus in Livestock Manures

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ABSTRACT

Water-extractable P (WEP) in manure is increasingly used as an environmental indicator as it is correlated with P in runoff from soils recently amended with manure. Little information exists on WEP variability across livestock manures. A survey of 140 livestock manures was conducted to assess trends in WEP (dry weight equivalent) related to livestock types and manure storage. Manure WEP ranged widely (0.2–16.8 g kg^{-1}), with swine (*Sus scrofa* domestica L.) having the highest average concentrations (9.2 g kg^{-1}), followed by turkey (*Meleagris gallopavo*) (6.3 g kg^{-1}), layer chickens (*Gallus gallus* domesticus L.) (4.9 g kg^{-1}), dairy cattle (*Bos taurus*) (4.0 g kg^{-1}), broiler chickens (*Gallus gallus* domesticus L.) (3.2 g kg^{-1}), and beef cattle (*Bos taurus*) (2.3 g kg^{-1}). Manure WEP also differed by general storage system; dry manures contained significantly lower WEP concentrations (3.9 g kg^{-1}) than manure from liquid storage systems (5.4 g kg^{-1}). Within liquid storages, no significant differences in WEP were observed between covered and uncovered storages or between bottom-loaded and top-loaded storages. Dry-matter (DM) content of manure was weakly correlated to WEP across all manures ($r = -0.44$), but strongly correlated with WEP in liquid swine manure ($r = -0.87$) and dairy manure ($r = -0.72$), suggesting dissolution of phosphate compounds as manure solids are diluted in storage. Varying positive correlations were observed between WEP in manure and water-extractable Ca, Mg, and Fe, or total P, depending on livestock category. Results of this study show that livestock manure can be categorized by WEP, a key step toward differential weighting of agricultural P sources in P site assessment indices.

Agriculture, particularly livestock agriculture, has been implicated in the growing problem of accelerated eutrophication of surface waters (Carpenter et al., 1998; U.S. Geological Survey, 1999). Land application of manure generated under livestock production can improve soil fertility and tilth, but can also result in elevated concentrations of P in runoff (Sharpley et al., 1994). As P is a primary control of freshwater eutrophication (Thomann and Mueller, 1987), concern over runoff P losses from manured soils has prompted a broad array of guidelines and regulations at federal and local levels (USEPA, 1996; USDA and USEPA, 1999).

Water-extractable P in manure has been linked to dissolved P (<0.45 μm) concentrations in runoff from manure-amended soils. Moore et al. (2000) showed that treating broiler chicken litter with alum (aluminum sulfate) reduced WEP concentrations in the litter relative to untreated chicken litter. Similarly, when alum-treated and untreated litters were broadcast onto pastures, differences in dissolved P concentrations of runoff corresponded with differences in litter WEP. Withers et al. (2001) found that concentrations of dissolved P in runoff from soils amended with mineral fertilizer, cattle manure, and biosolids were proportional to the concentration of WEP in the different amendments.

Water-extractable P in manure can also serve as a quantitative predictor of dissolved P in runoff when expressed as a concentration (e.g., g kg^{-1}) on a dry weight equivalent basis. Kleinman et al. (2002b) applied dairy, chicken, and swine manures at equivalent total P (TP) rates (100 kg ha^{-1}) to three acidic soils with different P concentrations. They found that when manures were broadcast, the WEP concentration of broadcast manure was strongly related to concentration of dissolved reactive P (DRP) in runoff ($r^2 = 0.86$). For all soils, slopes of the regressions between DRP in runoff and WEP in manure were similar. In that study, manure WEP and runoff DRP were greatest in swine slurry, intermediate in layer chicken manure and lowest in dairy manure. Studies by Ebeling et al. (2002), Kleinman and Sharpley (2003), Brandt and Elliott (2003), Vadas et al. (2004b) and Kleinman et al. (2004) have confirmed that WEP concentration in manure and biosolids is a consistent indicator of DRP in runoff when P sources are recently applied to soil. While the fraction of total P that is water extractable (WEP TP^{-1}) is correlated to runoff dissolved P concentrations within certain categories of manures (e.g., dry biosolids as shown by Brandt and Elliott, 2003), expressing manure WEP on this basis does not provide accurate estimation of runoff P concentrations across manures of varying properties. For instance, in Kleinman et al. (2002b, 2004), concentrations of WEP (g kg^{-1}) in dairy manure were lower than in layer chicken manure, corresponding with lower runoff dissolved P concentrations when the two manures were broadcast to soils at the same aerial rate of total P application (kg ha^{-1}). However, because total P concentrations in dairy manure were also low, a higher proportion of total P in dairy manure was water extractable than in layer chicken manure. As a result, WEP TP^{-1} was higher in the dairy manure than in the layer chicken manure, making WEP TP^{-1} a poor predictor of runoff dissolved P concentrations across these manure categories.

Given the strong relationship between manure P and dissolved P in runoff, a number of U.S. states now include P source coefficients, formerly termed P availability coefficients, in site assessment indices (Sharpley et

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Published in Soil Sci. Soc. Am. J. 69:701–708 (2005).
doi:10.2136/sssaj2004.0099

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Abbreviations: DM, dry matter; DRP, dissolved reactive phosphorus; TN, total nitrogen; TP, total phosphorus; WEP, water-extractable phosphorus.

al., 2003; Leytem et al., 2004). These coefficients allow P sources (mineral fertilizers, manures, biosolids) that are applied to agricultural soils to be weighted on the basis of their relative availability to enrich runoff DRP when applied to agricultural soils. For instance, findings from the studies of Kleinman et al. (2002b) and Brandt and Elliott (2003) served as the initial foundation for developing P source coefficients in initial drafts of the Pennsylvania P Index, with the expectation of refining coefficients as more information on WEP in different P sources become available (Weld et al., 2003). Indeed, states in the mid-Atlantic region of the USA are adopting this approach to developing P source coefficients (Coale and Elliot, 2004).

To date, one obstacle to comparing information on WEP in different manures has been the lack of a standard laboratory test for WEP. To be an effective environmental indicator, a WEP test must reflect differences in runoff dissolved P while also meeting reproducibility and other service laboratory analytical criteria. Kleinman et al. (2002a) showed that controlling manure-DM/distilled water ratio and length of shaking period were keys to consistent determination of WEP in manures and estimation of DRP in runoff. As manure DM was diluted with distilled water, P and Ca extracted from manure increased, consistent with increasing dissolution of calcium phosphates. Concentrations of WEP were logarithmically related to shaking time, so that after 1 h of shaking, WEP concentrations were at least 70% of WEP concentrations observed after 24 h of shaking (Kleinman et al., 2002a). Based on these analyses, Wolf et al. (2005) have developed a WEP test for commercial analytical laboratories with a manure DM/solution ratio of 1:200 and a shaking time of 1 h.

Despite analytical differences between studies evaluating WEP of manures and biosolids, existing literature provides a strong indication that WEP varies substantially within and between P sources. In a survey of WEP in biosolids (manure DM/distilled water ratio = 1:250; 1 h shaking), Brandt et al. (2004) found that WEP ranged from <0.1 to 8.9 g kg^{-1}, with systematic differences in WEP based on treatment method (e.g., anaerobic digestion vs. biological P removal). Studies by Dou et al. (2002), Sharpley and Moyer (2000), Kleinman et al. (2002a), Kleinman and Sharpley (2003) employed WEP protocols sufficiently similar to Brandt et al. (2004) to allow comparison. Combined, these studies reported WEP concentrations of 2.7 to 7.4 g kg^{-1} for layer chicken manures, 2.1 to 4.0 g kg^{-1} for untreated broiler chicken litters, 1.9 to 10.5 g kg^{-1} for dairy manures and 6.0 to 9.0 g kg^{-1} for swine slurries.

Although WEP is increasingly used as an environmental indicator, there is a paucity of published information on WEP in manures. This study reports the finding of a survey of WEP in livestock manures submitted to Pennsylvania State University's Agricultural Analytical Services Laboratory over approximately a 2-yr period. Objectives of the study were to determine whether WEP varied systematically across manure categories, and assess trends in manure constituents that provide insight into mechanisms controlling WEP in manure. Results of this study will support the refinement of P Source Coefficients in site assessment indices.

MATERIALS AND METHODS

Manure sampling

A total of 140 manures submitted to the Pennsylvania State University's Agricultural Analytical Services Laboratory between March 2001 and August 2003 were included in the survey. All samples were submitted with information on livestock sources, which included dairy and beef cattle, broiler and layer chicken, swine and turkey. For 90 samples, information on storage and handling was also available.

Laboratory Analyses

Manures were refrigerated at 4°C on receipt and analyzed within 7 d of receipt. Dry matter was determined gravimetrically after drying manure samples at 105°C for up to 14 h. Total P, Al, Fe, Ca, and Mg were analyzed by USEPA Method 3051 using a microwave digestor (USEPA, 1986), with elements determined by inductively coupled plasma atomic emission spectroscopy (ICP).

Water-extractable P was analyzed on fresh samples (i.e., in the condition they were submitted) with DM/solution ratio of 1:200 and a shaking time of 1 h (Wolf et al., 2005). Following centrifugation ($1000 \times g$), extract P was determined by ICP. In addition, water extractable Mg, Ca, and Fe were determined from the same extract on 74 samples. Concentrations of water-extractable elements were calculated on a dry weight equivalent.

Total N was determined by either Elementar Vario Max CN Analyzer (Elementar Americas, Inc., Mt. Laurel, NJ; combustion, chromatographic separation, and thermal conductivity detection of N) or semi-micro Kjeldahl digestion (Bremner, 1996). Watson and Galliher (2001) found Kjeldahl N and N determined by CN Analyzer to be very similar (Kjeldahl $N = 0.56 + 0.94$ CN Analyzer N; $r^2 = 0.95$). This was confirmed by a comparison of both methods on manure and biosolid samples submitted to Pennsylvania State University's Agricultural Analytical Services Laboratory (Kjeldahl N $= -0.02 + 1.00$ CN Analyzer N; $r^2 = 0.91$).

Statistical Analyses

Differences in manure properties were assessed by General Linear Model, with Duncan's pair-wise comparison of means. Differences discussed in the text were significant at $\alpha \leq 0.05$. Data are summarized by box and whisker plots that present (a) first, second (median), and third quartiles as horizontal lines in the box; (b) adjacent upper and lower values as "whiskers" extending from the boxes; (c) means as dashes; and (d) outliers as "*." Associations between manure properties were assessed by Pearson's correlation analysis and modeled by least squares regression (Neter et al., 1996). All analyses were conducted using SAS, Version 8 (SAS Institute Inc., 1999).

RESULTS AND DISCUSSION

General Trends in Manure Properties

Properties of the manures included in the survey ranged widely (Table 1). Dry matter content ranged from 0.5 to 98%. Manure WEP concentrations were from 0.2 to 16.78 g kg^{-1}, equivalent to 4 to 94% of TP. The ratio of TN/TP, which provides insight into excess manure P when manure is applied to meet crop N re-

Table 1. Mean values of chemical properties of manures included in survey with standard deviatons in parentheses.

Livestock	Storage and handling system	N	Dry matter	WEP†	Total P	WEP/TP	TN	TN/TP	Total Al	Total Ca	Total Fe	Total Mg
			%	g kg^{-1}			g kg^{-1}		g kg^{-1}			
Beef												
	All	9	37 (19)	2.3 (1.9)	5.1 (1.82)	0.43 (0.29)	19.5 (6.9)	3.9 (1.0)	5.2 (7.9)	24.9 (29.9)	5.6 (6.7)	5.1 (3.4)
	Bedded pack/litter	3	30 (10)	3.2 (2.0)	5.3 (2.25)	0.57 (0.33)	22.1 (7)	4.3 (0.4)	0.9 (0.64)	8.4 (1.9)	1.24 (0.7)	3.6 (0.7)
	Fresh	2	46 (37)	0.7 (0.6)	4.5 (1.3)	0.17 (0.18)	13.1 (6.2)	3.3 (2.3)	8.0 (0.3)	47.0 (43.2)	13.4 (1.9)	8.8 (7.4)
	Earthen	1	36	0.5	3.2	0.15	13.9	4.3	24.5	6.8	16.2	4.7
	Covered	1	28	4.8	5.1	0.94	21.0	4.1	0.2	5.0	0.4	3.0
	Other	2	46 (25)	2.1 (1.0)	6.7 (2.3)	0.35 (0.27)	24.0 (8.1)	3.6 (0.1)	1.6 (1.2)	46.6 (42.6)	1.6 (0.6)	4.8 (0.2)
Dairy												
	All	68	15 (10)	4.0 (1.8)	6.9 (3.2)	0.60 (0.15)	37.3 (18.5)	5.6 (1.7)	1.8 (1.9)	20.9 (10.7)	2.3 (2.3)	7.9 (5.4)
	Bedded pack/litter	4	31 (6)	2.3 (1.2)	5.5 (2.0)	0.40 (0.14)	21.4 (4.5)	4.2 (1.3)	2.6 (3.2)	16.5 (4.3)	2.4 (2.0)	4.6 (1.5)
	Fresh	7	19 (4)	3.9 (1.2)	5.6 (1.5)	0.70 (0.08)	29.3 (7.4)	5.5 (1.5)	2.3 (2.3)	14.5 (6.4)	3.3 (3.3)	6.3 (2.7)
	Earthen	14	9 (4)	4.3 (1.4)	8.6 (2.7)	0.20 (0.07)	42.8 (17.5)	5.0 (1.4)	2.5 (2.5)	29.8 (10.7)	2.8 (2.6)	11.1 (7.1)
	Aboveground	12	9 (4)	5.1 (1.6)	8.0 (2.8)	0.66 (0.12)	45.1 (16.7)	5.8 (1.2)	1.3 (0.9)	22.2 (8.1)	1.6 (1.0)	8.0 (3.0)
	Covered	7	13 (9)	5.1 (2.6)	7.5 (3.1)	0.66 (0.13)	41.8 (18.4)	5.8 (1.3)	1.3 (1.0)	25.1 (12.8)	1.5 (0.7)	6.5 (2.8)
	Other	24	17 (11)	3.3 (1.8)	6.0 (3.8)	0.53 (0.16)	33.9 (21.3)	5.9 (2.3)	1.6 (1.6)	16.5 (9.7)	2.3 (2.6)	7.5 (6.2)
Broilers												
	All	6	71 (8)	3.2 (1.4)	15.6 (5.7)	0.20 (0.06)	45.5 (10.8)	3.0 (0.8)	2.5 (2.8)	23.7 (8.6)	1.3 (1.0)	6.1 (2.9)
	Bedded pack/litter	1	56	3.0	14.5	0.21	43.1	3.0	0.5	25.9	0.7	6.4
	Fresh	1	66	3.1	15.2	0.20	61.0	4.0	0.4	21.9	0.7	5.5
	Other	4	76 (3)	3.3 (1.9)	15.9 (7.3)	0.20 (0.07)	42.3 (10.0)	2.9 (0.8)	3.5 (3.0)	23.7 (11.0)	1.7 (1.1)	6.2 (3.7)
Layers												
	All	32	58 (22)	4.9 (1.8)	25.6 (6.2)	0.19 (0.05)	49.6 (25.7)	2.2 (1.4)	0.9 (0.5)	133.7 (36.4)	1.3 (0.4)	9.7 (2.8)
	Bedded pack/litter	2	58 (30)	4.8 (1.9)	28.3 (0.6)	0.17 (0.07)	34.7 (8.1)	1.2 (0.3)	1.1 (0.2)	136.8 (41.6)	1.3 (0.1)	8.5 (0.2)
	Fresh	4	68 (24)	2.2 (0.5)	19.9 (4.5)	0.12 (0.04)	87.8 (38.5)	4.3 (1.2)	0.7 (0.1)	103.9 (15.7)	1.1 (0.3)	7.2 (0.3)
	Aboveground	7	47 (15)	5.8 (1.7)	30.1 (5.4)	0.19 (0.05)	43.0 (13.8)	1.5 (0.6)	0.9 (0.3)	132.3 (32.1)	1.3 (0.2)	10.0 (1.2)
	Covered	5	54 (17)	5.4 (1.5)	26.5 (6.5)	0.20 (0.05)	40.1 (10.0)	1.6 (0.6)	1.0 (0.4)	143.5 (18.4)	1.2 (0.3)	8.9 (1.9)
	Other	14	61 (26)	5.0 (1.7)	24.2 (5.9)	0.21 (0.05)	47.5 (23.8)	2.3 (1.5)	0.9 (0.6)	139.0 (45.2)	1.4 (0.5)	10.9 (3.6)
Swine												
	All	20	8 (9)	9.2 (3.7)	28.8 (10.4)	0.37 (0.20)	89.9 (56.9)	3.8 (3.4)	1.2 (0.7)	33.5 (12.6)	2.7 (1.3)	11.4 (6.1)
	Bedded pack/litter	1	34	2.6	5.1	0.52 (0.28)	53.0	10.5	1.4	15.5	1.6	1.8
	Fresh	2	16 (19)	8.6 (0.6)	31.1 (4.0)	0.28 (0.06)	47.8 (13.0)	1.5 (0.2)	1.1 (0.3)	33.8 (3.6)	3.9 (0.8)	14.8 (3.7)
	Earthen	1	1	16.8	18.6	0.90	265.3	14.2	1	18.5	1.1	2.8
	Aboveground	1	5	8.5	42.3	0.20	82.6	2.0	1.5	45.6	4.2	20.5
	Covered	2	10 (2)	9.3 (5.1)	35.2 (9.8)	0.29 (0.22)	46.5 (2.3)	1.4 (0.5)	1.3 (0.1)	39.6 (14.0)	3.2 (1.2)	15.3 (8.5)
	Other	13	5 (3)	9.3 (3.2)	29.1 (9.2)	0.35 (0.17)	92.9 (42.5)	3.4 (1.8)	1.2 (0.9)	34.1 (13.1)	2.5 (1.2)	10.9 (5.2)
Turkey												
	Bedded pack/litter	5	75 (2)	6.3 (1.6)	23.8 (6.7)	0.34 (0.07)	43.9 (13.3)	2.0 (0.7)	2.4 (2.0)	37.6 (19.0)	2.6 (2.2)	6.6 (2.1)

† Concentrations of all analytes except dry matter are presented on a dry weight basis.

quirements, ranged from 1:1 to 14:1. By comparison, an average TN/TP application of 8:1 is required by common grain and hay crops (Sharpley et al., 1998).

Several trends were evident between WEP and other manure properties across the range of manures surveyed. There was a weak, negative correlation between manure WEP and DM that was best described by a power function (Fig. 1). This trend points to the possible dilution effect of manure water on increasing P solubility, hence greater WEP concentrations, in some manures. The correlation was strongest for manures with lower DM content (e.g., DM $< 30\%$), as residuals between observations and the regression model increased with DM. Even though solution/DM ratio was fixed at 200:1 in the water extraction method, differences in P dissolution related to the initial manure water content can influence results of the WEP test, as not all manure P that is potentially extracted with water is recovered within the 1-h extraction period (Kleinman et al., 2002a). This may reflect the kinetics of inorganic P dissolution that can be quite slow (Sample et al., 1980; Nair et al., 1995; Josan et al., 2005). Across all manures, WEP was weakly correlated with water-extractable Ca ($r = 0.28$, $p = 0.02$), and the fraction of TP in manure that was water extractable (WEP TP^{-1}) was well correlated by power model with total Ca in manures (Fig. 2). These correlations support the view of Ca as a significant control of P solubility across livestock manures, as posited by Dou et al. (2000).

There was also a weak, positive correlation between WEP and TP concentrations in manure ($r = 0.57$, $p < 0.001$), suggesting that WEP concentrations in manures are, in part, tied to TP. Several studies have reported concomitant trends in WEP and TP content of manures (e.g., Dou et al., 2002; He et al., 2004). However, management practices that affect manure P solubility without proportional changes in TP, such as application of P sorbing materials to manures (Moore et al., 2000) or

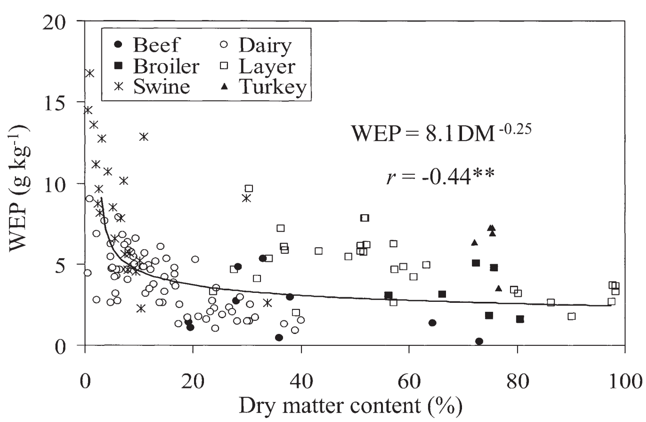

Fig. 1. Relationship of proportion of water-extractable P with dry matter content of manure. * indicates significance at $p < 0.01$.**

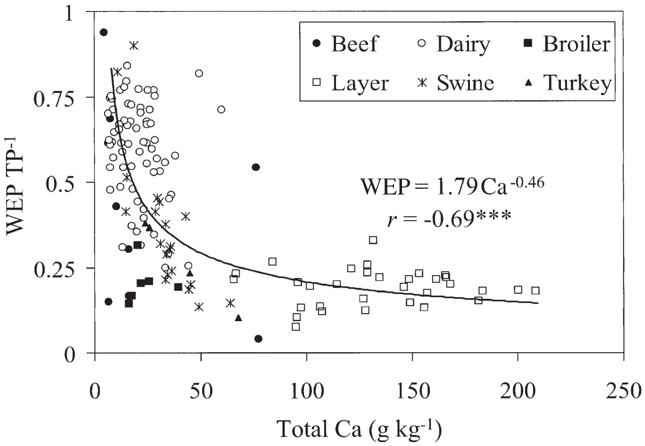

Fig. 2. Relationship of proportion of total P that is water-extractable (WEP TP^{-1}) with total Ca content of manure. * indicates significance at $p < 0.001$.**

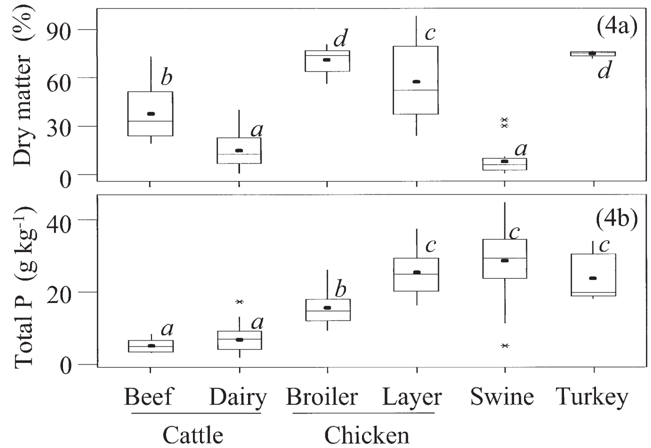

Fig. 4. Box-and-whisker plot of dry matter and total P in livestock manures showing median, upper, and lower quartiles, Duncan mean categories (italic letters), and outliers (*).

addition of phytase to feed (Vadas et al., 2004a), will undoubtedly change the nature of any general association between WEP and TP in manures as they become more established.

Manure Water-Extractable Phosphorus Trends by Livestock Category

Analysis of manure properties within livestock categories highlighted differences in manure properties not apparent across all manures. Significant differences in WEP, WEP TP^{-1}, DM, and TP were clearly evident between livestock categories (Fig. 3 and 4).

Swine and Dairy Manures

As illustrated in Fig. 3a, swine manure, primarily represented by slurries (85% swine samples had DM < 10%), had the greatest mean WEP concentration (9.2 g kg^{-1}), while dairy manure, also represented by a large number of slurry samples (45% of dairy samples had DM < 10%) possessed relatively low mean WEP concentration (4.0 g kg^{-1}). Manure DM was strongly correlated with WEP in both swine slurries ($r = -0.87$, $p <$ 0.01) and dairy manure ($r = -0.72$, $p < 0.01$), consistent with greater dissolution of P compounds with increasing manure water. Swine manure had significantly lower mean DM (8%) than all livestock categories (Fig. 4a), with the exception of dairy cattle manure (mean DM = 15%). Similarities in DM contents of swine and dairy cattle manures reflect common aspects of manure storage and handling in swine and dairy operations, particularly the prevalence of liquid manure systems (Day and Funk, 1998).

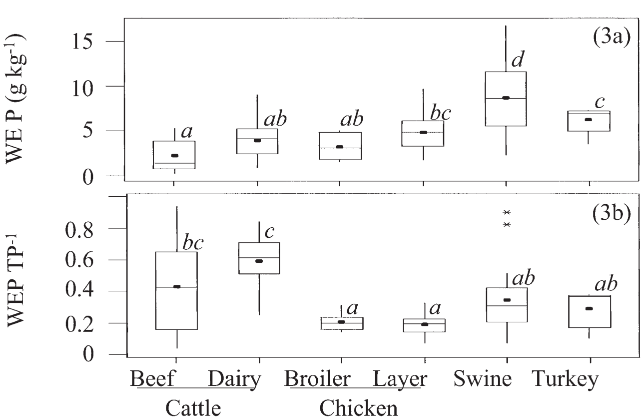

Fig. 3. Box-and-whisker plots of water-extractable P (WEP) and the proportion of total P that is water extractable (WEP TP^{-1}) in livestock manures. Median, upper, and lower quartiles are represented by horizontal box lines and Duncan mean categories by italic letters.

As with WEP, swine and dairy manures contained statistically similar concentrations of water-extractable Ca (mean = 7.4 g kg^{-1} for swine; mean = 4.9 g kg^{-1} for dairy) and Mg (mean = 4.2 g kg^{-1} for swine; mean = 4.9 g kg^{-1} for dairy) that were significantly higher than all other manures. Water-extractable Ca and Mg exhibited negative, albeit variable, correlations with DM in swine manure ($r = -0.87$, $p = 0.005$ for Ca; $r = -0.40$, $p = 0.324$ for Mg) and dairy cattle manure ($r = -0.69$, $p < 0.001$ for Ca; $r = -0.75$, $p < 0.001$ for Mg). General similarities in WEP, water-extractable Ca, and water-extractable Mg relationships with DM support the hypothesis that the dissolution of calcium phosphates in dairy and swine manures and magnesium phosphates in dairy manures is controlled, at least in part, by manure water content. As illustrated in Fig. 5a and 5b, significant positive correlations between WEP and water-extractable Ca were observed in both dairy and swine manure and between WEP and water-extractable Mg in dairy manure. Differences in the strength of the correlations and slopes of regression equations between WEP and water-extractable Ca or Mg indicate that the role Ca and Mg play in P solubility varies between livestock types. The influence of manure water content on the dissolution of calcium phosphate compounds is corroborated by data from Kleinman et al. (2002a) who observed positive relationships with different slopes between WEP and water-extractable Ca in swine slurry and dairy manure when manure DM/distilled water ratios were varied in the laboratory (total Ca was constant in these experiments).

Other factors, in addition to DM, undoubtedly con-

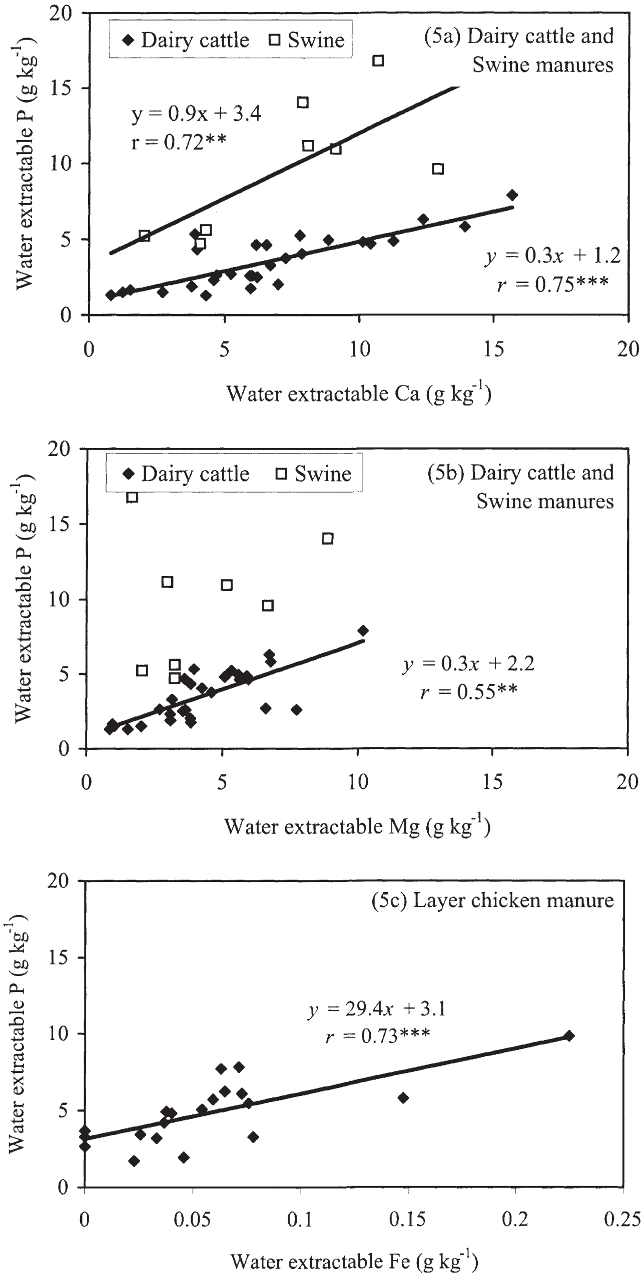

Fig. 5. Relationship of water-extractable P with other water-extractable elements (Ca, Mg., Fe) in dairy, layer chicken and swine manures. ** and * indicate significance at $p < 0.01$ and 0.001 levels, respectively.**

tributed to differences in WEP within and among livestock categories. Dairy and swine diets contain large amounts of Ca, supplemented with Ca-P compounds such as dicalcium phosphate and deflourinated phosphate (Wu and Ishler, 2002; National Research Council, 1998). To a lesser extent, Mg plays an important role in dairy and swine diets, as it may be added as dolomitic limestone and magnesium oxide (National Research Council, 1998, 2001). Although manure pH was not measured in this study, the pH of dairy and swine manures is often reported to be above 7.0 (Chaubey et al., 1994; Sharpley and Moyer, 2000, Kleinman et al., 2002b; Moller et al., 2002), supporting Ca-P and Mg-P stability (Lindsay et al., 1989). In one of the few studies of manure P speciation, Fordham and Shwertmann (1977) identified a variety of calcium phosphates (octacalcium phosphate, dicalcium phosphate) and magnesium phosphates (struvite, trimagnesium phosphate) in liquid cattle manures.

In our survey, total Ca and Mg content of manure (as opposed to water extractable forms of Ca and Mg) were negatively correlated with WEP TP^{-1}, indicating that these elements are strongly associated with solid and solution phases of P in manures. For total Ca, which exhibited the strongest overall correlation, the relationship with WEP TP^{-1} was best described by a power function across all livestock manures (Fig. 2), but was generally linearly correlated when manures were separated by livestock category. In swine manures, WEP TP^{-1} was well correlated with total Ca and Mg ($r = -0.78$, $p < 0.001$ for Ca; $r = -0.69$, $p = 0.012$ for Mg) whereas in dairy manures WEP TP^{-1} was poorly correlated with total Ca and Mg ($r = -0.20$, $p = 0.049$ for Ca; $r = -0.26$, $p = 0.039$ for Mg).

Water-extractable P in swine and dairy cattle manure has also been shown to vary with dietary P intake and animal age (Dou et al., 2002; Ebeling et al., 2002; Knowlton et al., 2002; Baxter et al., 2003). In this survey, the influence of TP in manure on WEP concentration was apparent at the level of livestock category, as trends in manure TP (Fig. 4b) between livestock categories roughly coincided with trends in WEP (Fig. 3a). Within individual livestock categories, TP provided an inconsistent indicator of WEP. A significant positive correlation was observed between WEP and TP in dairy cattle manure ($r = 0.73$, $p < 0.001$), but not in swine manure. Dou et al. (2002) observed concomitant increases in manure TP and WEP from dairy cattle fed diets increasing in TP supplementation. Notably, trends in WEP TP^{-1} between livestock categories (Fig. 3b) were very different from those in WEP concentration (Fig. 3a). Dairy manure possessed the highest WEP TP^{-1} (mean = 59%), as TP concentrations in cattle manure (dairy and beef) were low. In contrast, swine manure had relatively low WEP TP^{-1} (mean = 35%) and was not significantly different from all livestock manures but dairy. As mentioned above, while WEP TP^{-1} provides insight into the fraction of TP that is readily water soluble, it can be a poor indicator of dissolved P in runoff across livestock manure categories, which is controlled by concentration of WEP in manure.

Beef Manure

The lowest mean WEP concentrations of all livestock categories were associated with beef cattle manures, which did not differ significantly from dairy and broiler chicken manures (Fig. 3a). Beef cattle manures included in the study had significantly greater DM than did dairy manures (Fig. 4a), reflecting general differences in storage and/or handling of manures by beef and dairy producers, with a minimum DM content of 19% for beef cattle manures and 1% for dairy manures. Despite large differences in recommended P content of beef and dairy cattle diets, with beef cattle generally consuming less than dairy cattle (National Research Council, 1996, 2001), as well as strong linear correlation ($r = 0.86$) between dietary P intake and fecal TP in dairy cattle (Wu and Ishler, 2002), no significant differences were observed in manure TP concentration between beef and dairy cattle (Fig. 4b). Furthermore, WEP TP^{-1} in manure was not significantly different between these two classes of cattle (Fig. 3b). Associations between WEP and other water-extractable elements as well as between WEP and total Ca and Mg were consistent between dairy and beef cattle.

Poultry (Layer Chicken, Broiler Chicken, Turkey) Manures

Of the three poultry manures, turkey manure, represented by only five samples, had the greatest WEP concentrations, and was second only to swine manure (Fig. 3a). Dry matter content of turkey manure averaged 75%, similar to broiler chicken manure (mean DM = 71%), although WEP of turkey manures was 1.9 times that of broiler chicken manures (Table 1). Given the small sample of turkey manures included in the survey ($N = 5$), representing only three producers, generalizations must be tempered. However, Moore et al. (1995) observed that mean WEP of turkey litter ($N = 30$) was 2.4 times that of broiler chicken manure ($N = 64$), supporting the relative findings of this survey. Even though several studies currently report WEP in turkey manures (Moore et al., 1995; Maguire et al., 2003; Penn et al., 2004), differences in processing of manures and water-extraction procedures preclude direct comparison of WEP concentrations from those studies with this survey. Specifically, Maguire et al. (2003) dried the turkey manures before analysis and all three studies analyzed WEP at a DM/solution ratio that was much narrower than the ratio used in this survey.

As with cattle and swine manures, differences in WEP within and between the two chicken manures were related to manure DM and TP. Dry matter contents of broiler chicken manures were among the highest observed in the survey, while DM in layer chicken manures was intermediate to broiler chicken and beef cattle manures (Fig. 4a). Coincidentally, WEP of broiler chickens was lower, but not statistically so, than that of layer chickens (Fig. 3a). However, while DM helps to explain some of the relative difference in WEP between chicken manures, DM was only weakly correlated with WEP in chicken manures ($r = 0.53$, $p = 0.006$) and was not effective in explaining differences between poultry manures and other species (e.g., layer poultry vs. dairy manures).

The varying correlations between WEP and DM in the manures of different species of livestock suggest that mechanisms of P solubility are somewhat independent between species. For instance, no significant correlations between WEP and water-extractable Ca and Mg were detected in either chicken categories, but a good correlation was observed between WEP and water-extractable Fe in layer chickens (Fig. 5c). Notably, this correlation was strongly weighted by five observations at the lowest and highest water-extractable Fe concentrations. As illustrated in Fig. 2, WEP TP^{-1} was negatively correlated by power model with total Ca content, with the highest total Ca contents in layer poultry manure, consistent with Ca-P as a dominant fraction of TP that is not water extractable. When broiler and layer chicken manures were analyzed separately, no significant correlations were observed between WEP TP^{-1} and total Ca, as the slope of the regressions approached zero in these manures. It is possible, especially for layer poultry manures, which possessed the highest total Ca contents of any manures (Table 1), that the absence of a significant relationship reflects saturation of P with respect to Ca such that total Ca content does not limit P solubility.

Significant correlations between WEP and TP in manure were observed in both broiler chickens ($r = 0.81$, $p = 0.053$) and layer chickens ($r = 0.66$, $p < 0.001$). Elsewhere, Vadas et al. (2004a) found that altering supplemental TP in broiler chicken diets significantly affected concentrations of WEP and TP in manures. Both WEP and TP in layer chicken manure were greater than in broiler manure (Fig. 3a and 4b), although differences were not statistically significant for WEP. Differences in manure P between broiler and layer chickens appear to be a function of bird metabolism, rather than dietary intake of P. Rapidly growing broilers have greater efficiency in metabolizing P, and recommended dietary P intake is higher for broiler chickens than for layer chickens (National Research Council, 1994).

Manure Water-Extractable Phosphorus Trends by Storage and Handling Category

Fewer significant trends in WEP of manure were observed on the basis of storage and handling systems (Table 1). Although fresh manures, bedded pack, and litter had lower mean WEP than earthen, aboveground, and covered systems, differences were not statistically significant (Fig. 6a). Nor were differences observed in

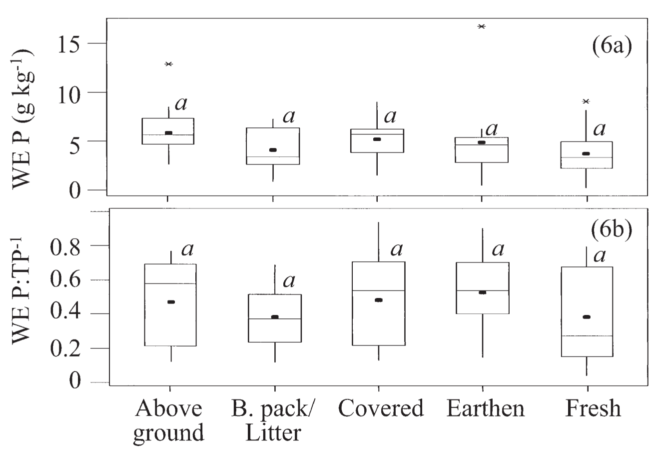

Fig. 6. Box-and-whisker plot of water-extractable P of manure storage and handling system for all manures and dairy manures, showing quartiles (horizontal box lines), Duncan mean categories (italic letters) and outliers (*).

WEP TP^{-1} by storage and handling category (Fig. 6b). Several factors likely contributed to this result.

First, variability in WEP between livestock species increased variances within storage and handling system categories. For instance, poultry manures, including turkey, were combined with cattle manures to form the bedded pack and litter category. When storage and handling systems were segregated by livestock, significant differences became apparent in dairy and layer chicken manures (Fig. 7), which were represented by the largest variety of storage and handling systems. Storage and handling trends in WEP were similar to TP and DM differences in dairy manure, and TP only in layer chicken manure, which did not include slurries prone to DM influences on WEP as discussed above (Table 1). Thus, despite the general lack of WEP trends by storage and handling system across all manures, trends observed in dairy and layer poultry manures point to the potential importance of manure storage and handling on WEP within certain livestock categories.

The second factor explaining the absence of statistical differences in WEP between storage and handling systems is inconsistency in reporting. A total of 41% of all samples did not include information on storage and handling (see "other" category in Table 1), and it is likely that some confusion exists as to how to classify certain systems when submitting samples for testing (especially bedded pack vs. fresh manure). To overcome problems associated with classification, systems were reclassified as dry manure systems (bedded pack, litter, and fresh manures) or liquid manure systems (earthen, aboveground, and covered systems). When systems were classified in this manner, a significant difference was observed in manure WEP (3.9 g kg^{-1} for dry systems, 5.4 g kg^{-1} for liquid systems). Not surprisingly, a significant difference was also observed in manure DM (44% for dry systems, 20% for liquid systems). No significant differences were seen in TP (13.7 g kg^{-1} for dry systems, 14.8 g kg^{-1} for liquid systems) or in WEP TP^{-1} (0.40 for dry systems, 0.49 for liquid systems). Further examination of liquid systems revealed no significant differences in WEP, WEP TP^{-1}, TP, or DM on the basis of manure loading position (top vs. bottom loaded systems) or protective cover (covered vs. uncovered).

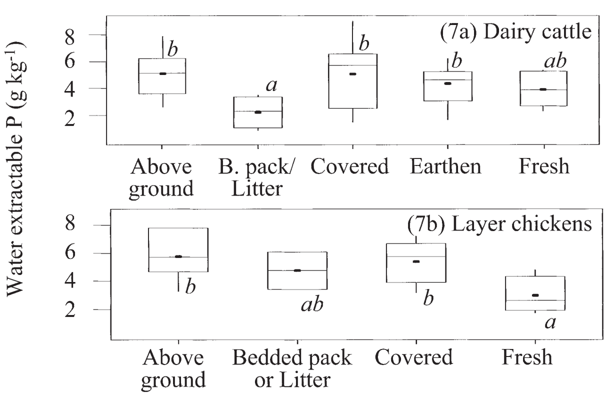

Fig. 7. Box-and-whisker plot of water-extractable P of layer chicken manure storage and handling systems, showing quartiles (horizontal box lines) and Duncan mean categories (italic letters).

Nor were differences observed when loading position and protective cover were evaluated on an individual livestock basis.

CONCLUSIONS

This survey highlights trends in WEP across a broad array of manures. The survey confirms that significant differences in manure WEP exist among livestock types, and, at a very general level, among storage systems. General associations between WEP and DM, particularly pronounced in dairy and swine slurries, and corresponding correlations between WEP and some water-extractable cations (Ca, Mg, Fe) support laboratory findings that increasing water content promotes the dissolution of P compounds in manures. Similarly, associations between WEP and TP point to the role of excess dietary P as a significant factor affecting WEP in dairy and chicken manures.

Results of this survey have implications to P site assessment indices that differentiate P sources on the basis of WEP (Sharpley et al., 2003; Weld et al., 2003). Specifically, this survey shows that distinction of manures within certain livestock categories is needed to accurately reflect WEP. For instance, liquid manure storage systems in dairy and poultry operations have different WEP than dry manure storage systems. Although none of the manures included in this study were reported as having been treated with P sorbing amendments (e.g., alum), application of such amendments would substantially affect the distribution of WEP concentrations found in particular livestock categories. Furthermore, growing efforts to modify livestock diets will also have an effect on WEP in certain livestock systems. Continued monitoring of WEP is needed to improve on the database evaluated in this study and to track changes in manure quality as nutrient management evolves in livestock production.

ACKNOWLEDGMENTS

This research was supported in part by agriculture research funds administered by the Pennsylvania Department of Agriculture.

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