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Distribution of Phosphorus in Manure Slurry and Its Infiltration after Application to Soils

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ABSTRACT

Computer models help identify agricultural areas where P transport potential is high, but commonly used models do not simulate surface application of manures and P transport from manures to runoff. As part of an effort to model such P transport, we conducted manure slurry separation and soil infiltration experiments to determine how much slurry P infiltrates into soil after application but before rain, thus becoming less available to runoff. We applied dairy and swine slurry to soil columns and after both 24 and 96 h analyzed solids remaining on the soil surface for dry matter, total phosphorus (TP), and water-extractable inorganic (WEIP) and organic (WEOP) phosphorus. We analyzed underlying soils for Mehlich-3 and water-extractable P. We also conducted slurry separation experiments by sieving, centrifuging, and suction-filtering to determine which method could easily estimate slurry P infiltration into soils. About 20% of slurry solids and 40 to 65% of slurry TP and WEIP infiltrated into soil after application, rendering this P less available to transport in runoff. Slurry separation by suction-filtering through a screen with 0.75-mm-diameter openings was the best method to estimate this slurry P infiltration. Measured quantities of manure WEOP changed too much during experiments to estimate WEOP infiltration into soil or what separation method can approximate infiltration. Applying slurries to soils always increased soil P in the top 0 to 1 cm of soil, frequently in the 1- to 2-cm depth of soil, but rarely below 2 cm. Future research should use soils with coarser texture or large macropores, and slurry with low dry matter content (1–2%).

FIELD AND WATERSHED SCALE simulation models are used to estimate P transport from agricultural soils to surface waters and to assess the ability of alternative management practices to minimize P transport (Sharpley et al., 2002). However, commonly used models do not simulate the practice of surface application of manures or P transport directly from manures to runoff (Pierson et al., 2001; Sharpley et al., 2002). Vadas et al. (2004, 2005) developed a model to predict P release from surface-applied manures to rainfall and transport in runoff. Their model required knowing the initial water-extractable P content of manure applied to the soil surface. Manure water-extractable P is measured by shaking manure with water at a total liquid to dry matter ratio of 250:1. One model assumption that improved predictions of dissolved P concentrations in runoff for the first rain event after manure application was that the freely draining, liquid fraction of manure slurry, and any P therein, quickly infiltrates after surface application to soils, thereby reducing availability of infiltrated manure P to runoff. This infiltrated slurry P would be subtracted from the total water-extractable manure P applied to the soil to estimate that manure P still available to be leached into soil or moved in runoff during the first rain event after application. Vadas et al. (2004) assumed that 40 to 65% of manure slurry water-extractable P infiltrated into soil after application and before the first runoff event, but these values were model calibration values and not measured estimates.

Several studies have investigated P distribution in the liquid and solid fraction of manure slurry, but mostly from the standpoint of separating slurry for anaerobic digestion, transport, re-feeding, or other utilization systems (Hill and Baier, 2000; Holmberg et al., 1983; Moller et al., 2002; Zhang and Westerman, 1997). Field studies in Arkansas have observed that P in runoff from swine slurry is as much as 85% less than expected, due to the direct infiltration of P from the slurry following land application. Research is now being conducted to account for such P infiltration in the Arkansas P Index, which is a widely used tool in nutrient management planning for animal agriculture (P.A. Moore, Jr., personal communication, 2005). Kleinman et al. (2004) examined P distribution in soil after surface application of manure to soils in 100- × 20-cm boxes and rainfall simulations. They found that high concentrations of P were translocated from the broadcast manures into the upper 1 cm of soil, but only for soils receiving dairy and swine slurries, and not for soils receiving relatively dry poultry manure. They did not observe translocation of manure P beyond the upper 1 cm of soil. The authors did not investigate infiltration of slurry water and P into soil following slurry application but before rainfall. Apparently, there has been no formal investigation of P distribution in manure slurry with regard to its infiltration into soil after application and its subsequent availability to runoff. Therefore, the objectives of this study were to investigate (i) how much and how deep slurry P will infiltrate into soil after surface application and (ii) if laboratory manure slurry separation techniques can accurately and quickly estimate how much slurry P infiltrates into soil.

MATERIALS AND METHODS

We use the term slurry for any manure that has a great enough water content to contain a freely draining liquid that could infiltrate into soil. Some initial experiments showed that manures with a dry matter content of 25% will not have freely draining liquid, but manures with a dry matter content of 15% will. Therefore, our term slurry represents any manure with a dry matter content of less than about 15 to 20%. For our experiments, we collected swine slurry from finishing sows and dairy slurry from lactating Holstein cows to represent typical manure slurry types and dry matter content. Both slurries had been washed into holding tanks and agitated before sampling.

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Abbreviations: TP, total phosphorus; WEIP, water-extractable inorganic phosphorus; WEOP, water-extractable organic phosphorus.

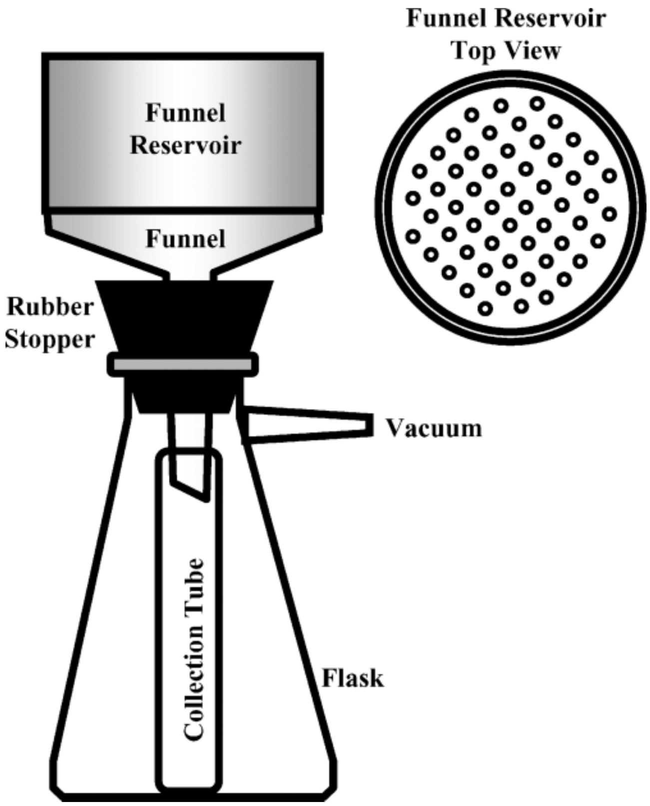

Fig. 1. Schematic of the suction-filtering apparatus used to separate slurry liquids and solids.

We stored all slurries at 4°C when not in use for experiments or analysis. We determined % dry matter gravimetrically after oven-drying at 90°C for 48 h. We analyzed slurries for total phosphorus (TP) by a modified semimicro-Kjeldahl procedure (Bremner, 1996). We estimated water-extractable P by shaking for 60 min 1 g dry-weight equivalent of slurry with enough deionized water to achieve a water to dry matter ratio of 200:1 (Kleinman et al., 2002b). We filtered the mixtures through 0.45-μm filter paper (Pall Corporation, Ann Arbor, MI), and analyzed filtrates for water-extractable inorganic phosphorus (WEIP) by the molybdate blue method of Murphy and Riley (1962). We also digested filtrates by alkaline persulfate digestion and analyzed them colorimetrically for total water-extractable P (Patton and Kryskalla, 2003). We calculated water-extractable organic phosphorus (WEOP) as the difference between total water-extractable P and WEIP.

We collected intact, 30-cm-diameter soil columns to a depth of 15 cm from a grassed Wharton soil (fine-loamy, mixed, active, mesic Aquic Hapludults) in central Pennsylvania. We removed all grass from the soil surface and established uniform soil moisture by immersing columns for 48 h and allowing them to drain for 48 h. Afterward, we covered the soil surface with a single layer of cheesecloth, and evenly applied the dairy and swine slurry in triplicate at a rate of 100 kg total P ha^{-1}. This translated to 300 g of swine slurry and 1200 g of dairy slurry. At 24 and 96 h after slurry application, we removed the cheesecloth and remaining slurry solids. We analyzed slurry solids on the cheesecloth for % dry matter, TP, WEIP, and WEOP as described earlier. After removing cheesecloth, we carefully forced soil upward from the bottom of columns with a piston in 0- to 1-, 1- to 2-, 2- to 3-, 3- to 5-, and 5- to 10-cm increments. For each increment, we scraped off the extruding soil, collected a representative sample, and air-dried and sieved (2-mm) all samples. We analyzed soils for Mehlich-3 P (1:10 soil to solution ratio in 0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.015 *M* NH_4F + 0.013 *M* HNO_3 + 0.001 *M* EDTA; 5 min shake; Mehlich, 1984) and water-extractable P (1:10 soil to solution ratio, 1 h shake). We measured P in extracts by the method of Murphy and Riley (1962).

We separated slurry by sieving, centrifuging, and suction-filtering. Sieving was intended to simulate infiltration of slurry liquid into soil where only the force of gravity is active, suction-filtering to simulate infiltration where a matric potential can also draw water into soil, and centrifuging as an easy, alternate separation method that has been used to estimate soluble P in slurries (Smith et al., 2004). For sieving, we poured a known weight (approximately 150 g) of slurry onto a number 140 (0.106 mm) sieve with a pan underneath. We agitated the slurry gently and allowed it to drain until it had significantly dewatered, which was about 2 h. We weighed the sieve and pan and sampled the material in each to determine % dry matter. For centrifuging, we poured a known weight (approximately 40 g) of slurry into a 30-mL centrifuge tube and centrifuged tubes at 1500 × *g* for 10 min. We then decanted the liquids into a separate tube and sampled the material in each tube to determine % dry matter. For suction-filtering, we poured a known weight (approximately 50 g) of bulk slurry onto the funnel reservoir of a filtering apparatus with 0.75-mm-diameter openings (Fig. 1). We applied vacuum suction, agitated the slurry gently, and allowed it to drain into a collection tube until it had significantly dewatered, which was about 2 min. We weighed the tube and reservoir, and sampled the material in each to determine % dry matter. We analyzed all separated manure materials for % dry matter, TP, WEIP, and WEOP as described earlier.

Using the SAS Version 8 system (SAS Institute, 1999), we conducted an analysis of variance to determine the effect of manure slurry type and time of sampling on the amount of slurry P that infiltrated into soil columns and the subsequent change in soil P. We also conducted an analysis of variance to determine the effect of separation method on the amount of slurry water, dry matter, and P in separated liquids and solids.

RESULTS AND DISCUSSION

Swine slurry contained more P than the dairy slurry (Table 1), with concentrations consistent with those reported for bulk slurries (Kleinman and Sharpley, 2003; Kleinman et al., 2002a, 2002b, 2005; Pote et al., 2001; Sharpley and Moyer, 2000). The WEIP to TP ratio was less for swine (14%) than dairy slurry (36%). The WEOP to TP ratio was 2% for swine and 5% for dairy slurry. In water extracts, WEOP comprised 25% of the total water-extractable P for dairy slurry, and about 12% for swine slurry. These percentages are consistent with those reported by Sharpley and Moyer (2000).

Soil Column Experiments

For swine slurry, there was no difference in dry matter infiltration into soil after 24 or 96 h (Fig. 2a). For dairy,

Table 1. Dry matter and P content of bulk manure slurry used in the study.

Manure slurry	Dry matter	Water-extractable inorganic P	Water-extractable organic P	Total P
	%	mg kg^{-1}		
Dairy	8.0	2714	346	7557
Swine	6.3	6490	907	47374

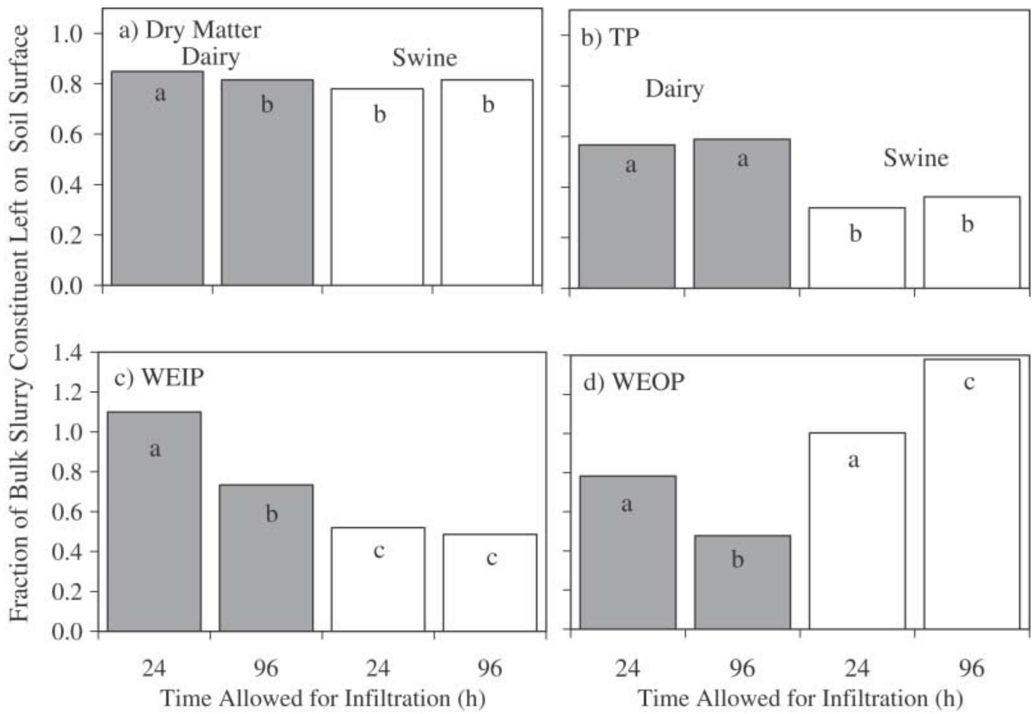

Fig. 2. Fraction of original dairy and swine slurry (a) dry matter, (b) total phosphorus (TP), (c) water-extractable inorganic phosphorus (WEIP), and (d) water-extractable organic phosphorus (WEOP) in slurry solids left on the surface of soil columns both 24 and 96 h after slurry application. Different letters indicate significant differences at the 0.05 level between P in solids left on the soil surface.

more slurry dry matter infiltrated after 96 h than after 24 h. This is likely because less bulk swine slurry was applied (300 vs. 1200 g), and because bulk swine slurry had less dry matter (Table 1). This allowed swine slurry to infiltrate more rapidly, whereas dairy slurry ponded more on the soil surface and infiltrated more slowly. Overall, about 20% of both dairy and swine slurry dry matter infiltrated into soil within 96 h.

About 40% of original dairy slurry TP and 65% of swine TP infiltrated into soil, with no effect of sampling time on TP infiltration (Fig. 2b). For swine slurry, there was no difference in WEIP infiltration into soil after 24 or 96 h (Fig. 2c). For dairy, more slurry WEIP infiltrated after 96 h than after 24 h. After 96 h, about 30% of dairy slurry WEIP and 50% of swine WEIP infiltrated into soil. We believe our water extraction of original slurries underestimated WEIP by 20 to 30% (see Fig. 3c and WEIP separation discussion below). Assuming this underestimation, these 30 and 50% WEIP infiltration values may actually be more like 40% for dairy and 65% for swine. These 40 and 65% values are consistent with values of TP infiltration. In their model to predict dissolved P in runoff from surface-applied manures, Vadas et al. (2004) assumed that 65% of dairy slurry WEIP and 40% of swine slurry WEIP infiltrated into soil after application and before the first rainfall and runoff event. Failure to reproduce the exact percentage assumptions as Vadas et al. (2004) is likely due to variability in soil and manure characteristics between the two studies. However, results from our present experiments and assumptions from Vadas et al. (2004) are both in the range of 40 to 65% infiltration of slurry P.

For dairy slurry, more WEOP infiltrated into soils after 96 h than after 24 h (Fig. 2d), which is consistent with dry matter and WEIP data. After 96 h, about 50% of dairy WEOP had infiltrated into soil, which is fairly consistent with TP and WEIP results. For swine slurry, more WEOP infiltrated into soils after 24 h than after 96 h, but the amount of WEOP calculated as remaining on the soil surface was greater than that measured in original slurries. We also observed large increases in WEOP extracted after laboratory slurry separation (see later discussion). Overall, these observations suggest that WEOP in manure slurries is a very dynamic factor that may be a function of animal type, manure management, and experimental conditions. For example, Ajiboye et al. (2004) observed decreases in WEOP after oven-drying pig slurry, but observed no change in WEOP after oven-drying dairy manure. McDowell and Stewart (2005) observed small but consistent increases in WEOP after air-drying sheep and deer dung collected from pastures. Therefore, results for WEOP in Fig. 2d may not give an accurate assessment of WEOP infiltration into soils.

Applying manure slurry to soil columns significantly increased both water-extractable P and Mehlich-3 P in the top 0 to 1 cm of soil (Table 2). Mehlich-3 P in swine slurry columns increased more than in dairy slurry columns, which is consistent with data in Fig. 2 showing that more swine slurry TP infiltrated into soil than dairy TP. However, there was no difference in the ability of slurries to increase water-extractable soil P in the top 0 to 1 cm. While there was no difference between Mehlich-3 P extracted at either 24 or 96 h after slurry application in the top 0 to 1 cm, water-extractable soil P

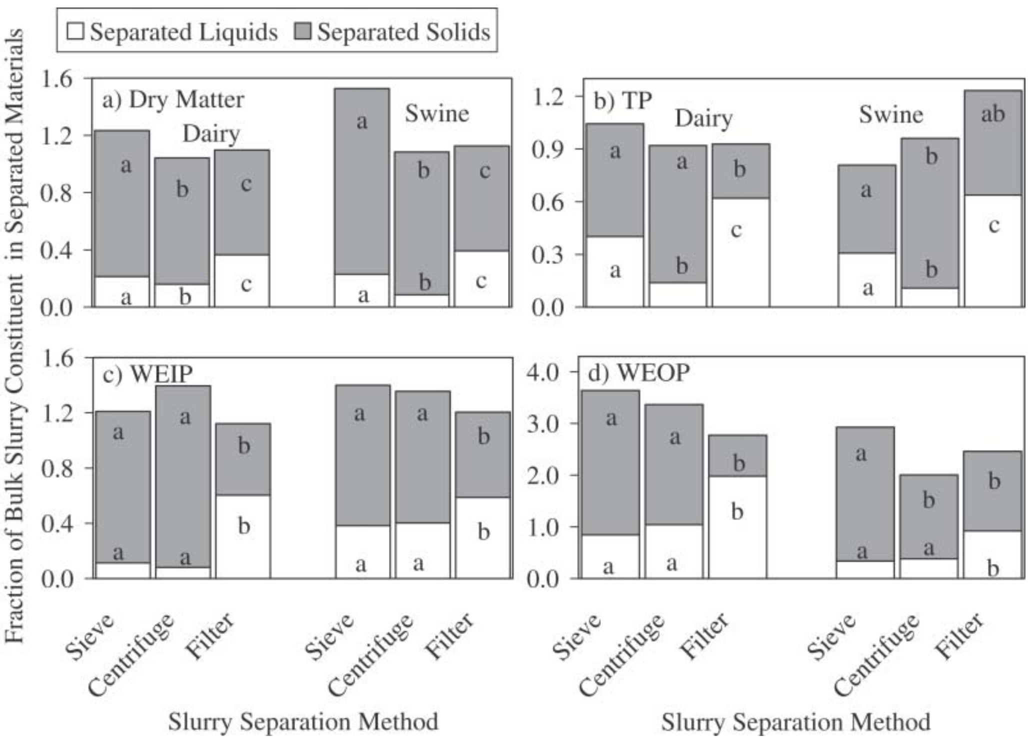

Fig. 3. Fraction of original dairy and swine slurry (a) dry matter, (b) total phosphorus (TP), (c) water-extractable inorganic phosphorus (WEIP), and (d) water-extractable organic phosphorus (WEOP) in slurry liquids and solids as separated by sieving, centrifuging, and suction-filtering. Different letters within slurry type only indicate significant differences between separation methods at the 0.05 level.

decreased from 24 to 96 h. This is likely due to rapid sorption of P forms that can be extracted by water (Sharpley, 1982). Because Mehlich-3 will extract more P than just the easily desorbable soil P of a water extraction, this rapid soil P sorption may not be manifested with similar decreases in Mehlich-3 soil P (Indiati et al., 1999).

At 1 to 2 cm in the soil columns, manure slurry application significantly increased water-extractable soil P, but not Mehlich-3 P. Apparently, only minimal amounts of slurry P infiltrated below 1 cm in the soil, which is consistent with the observations of Kleinman et al. (2004).

Table 2. Mehlich-3 and water-extractable soil P from 0- to 10-cm depth in control columns and columns treated with dairy and swine slurry, as sampled both 24 and 96 h after slurry application.

Manure slurry	Sampling time	Soil depth 0–1 cm	1–2 cm	2–3 cm	3–5 cm	5–10 cm
	h	mg kg^{-1}				
				Mehlich-3 P		
Control		47.6 a†	30.8 a	20.1 a	21.4 a	15.2 a
Dairy	24	101.3 b	35.3 a	22.9 a	21.6 a	17.0 a
Dairy	96	87.4 b	30.0 a	22.2 a	20.7 a	16.7 a
Swine	24	181.5 c	40.1 a	25.8 a	25.6 a	21.8 a
Swine	96	183.5 c	44.0 a	26.4 a	26.3 a	21.2 a
				Water-extractable P		
Control		3.4 a	1.9 a	2.7 a	1.8 a	2.4 a
Dairy	24	29.2 c	6.5 c	4.5 a	4.0 a	3.9 b
Dairy	96	18.6 b	5.0 bc	3.6 a	3.8 a	2.7 ab
Swine	24	29.2 c	4.9 bc	2.9 a	2.4 a	2.2 a
Swine	96	22.8 b	3.5 ab	2.4 a	2.3 a	1.6 a

† Different letters within a soil depth and soil P category denote significant differences at the 0.05 level.

This minimal P infiltration to 1 to 2 cm was able to significantly increase water-extractable soil P, but not Mehlich-3 soil P, which was always much greater than water-extractable soil P. Below 2 cm, manure slurry had little effect on soil P, except sometimes in the dairy slurry columns where the mass of slurry applied was much greater and where we observed some preferential leaching of slurry down through larger, continuous soil pores.

Slurry Separation Experiments

The fraction of original slurry dry matter in separated materials typically added up to 1.0 for centrifuging and suction-filtering, showing good recovery during separation (Fig. 3a). Recovery of dry matter in separated materials was greater than 1.0 for sieving. In soil column experiments, about 20% of dairy and swine slurry dry matter infiltrated into soil after 96 h (Fig. 2a). In separation experiments, both centrifuging and sieving allowed about 16% of slurry dry matter in separated liquids, which represents the portion of slurry that would infiltrate into soil. This considers that recovery of dry matter in separated materials was greater than 1.0 for sieving. Suction-filtering allowed about 35% of slurry dry matter in separated liquids. Therefore, no method exactly matched dry matter infiltration observed with soil columns, but suction-filtering was probably the best representation considering that cheesecloth applied to soil columns helped retain some dry matter on the soil surface that may have otherwise infiltrated into soil.

The fraction of bulk slurry TP in separated materials typically added up to 1.0, showing good recovery of TP during slurry separation (Fig. 3b). Therefore, differences observed in the distribution of water-extractable P among separated materials, as discussed below, are not a result of an inability to account for TP distribution after slurry separation. In column experiments, about 40 to 60% of manure slurry TP infiltrated into soils after 96 h (Fig. 2b). In separation experiments, centrifuging consistently allowed about 10 to 15% of slurry TP in separated liquids, sieving allowed 38%, and suction-filtering allowed 50 to 70%. Therefore, suction-filtering was the most representative method for estimating slurry TP infiltration into soil.

For both slurries, the sum of WEIP recovered in separated solids and liquids was 20 to 30% greater than WEIP in bulk slurries (Fig. 3c). Thus, our extraction method may underestimate total WEIP in manures by that amount (Dou et al., 2002; Kleinman et al., 2002b). However, Kleinman et al. (2002b) and Vadas et al. (2004, 2005) showed that such a water extraction provides good predictions of dissolved P in runoff from surface-applied manures. In column experiments, about 40 to 65% of manure slurry WEIP infiltrated into soils after 96 h (Fig. 2c). In separation experiments, sieving and centrifuging allowed about 10 to 30% of slurry WEIP in separated liquids, and suction-filtering allowed 50 to 60% (Fig. 3c). These values take into account the 20 to 30% underestimation of WEIP in original slurries. Therefore, suction-filtering was a good method for estimating slurry WEIP infiltration into soil.

Centrifuging slurry and analyzing the filtered supernatant for inorganic P has been used to estimate the potential for surface-applied manure slurry to contribute P to runoff (Smith et al., 2004). However, Fig. 3c shows that centrifuging may recover only 10 to 30% of the total WEIP in manure slurry. Furthermore, because any P in a liquid portion of a slurry may infiltrate into a soil when the slurry is land-applied and be unavailable for transport in runoff (Pote et al., 2001), centrifuging may in fact be estimating slurry WEIP that is unavailable to runoff instead of estimating WEIP in slurry solids that remain on the soil surface.

The fraction of original slurry WEOP in separated materials summed from 2.0 to almost 4.0 (Fig. 3d). This is much greater and more inconsistent than the 20 to 30% increase in WEIP after slurry separation (Fig. 3c). The ability to account for manure TP distribution after separation of slurries suggests that either manure P was transformed to WEOP during the separation and handling of manure slurries or that the original water extraction method greatly underestimates WEOP in manure slurries. The model proposed by Vadas et al. (2004, 2005) provided good prediction of WEIP leaching from manures by rainfall, but underestimated WEOP leaching by about 40%. These observations also suggest transformation of manure P to WEOP or underestimation of WEOP during extraction procedures. In either case, WEOP is clearly a dynamic manure P parameter that is difficult to quantify. Given this, it is not possible to say which separation method was a good estimation of manure WEOP infiltration into soil.

CONCLUSIONS

Commonly used water quality models do not simulate surface application of manures and P transport directly from manures to surface runoff. In continuing the effort to develop a model to predict P release from surface-applied manures to runoff, we conducted soil infiltration and manure slurry separation experiments to determine how much manure slurry P will infiltrate into soil after application, thus becoming less available to transport in surface runoff during the first rain event after manure application. About 20% of slurry solids and 40 to 65% of slurry TP and WEIP infiltrated into soil within 96 h. All of these infiltration values matched well with those observed for slurry separation by suction-filtering through a coarse screen with 0.75-mm-diameter openings. The extraction of manure WEOP changed too much after separation or infiltration into soil to make a good estimate of how much WEOP infiltrates into soil or what separation method can be used to estimate infiltration. Applying manure slurry to soil columns always increased soil P in the top 0 to 1 cm of soil, frequently in the 1- to 2-cm depth of soil, but rarely below 2 cm. Overall, results show that 40 to 65% of bulk manure slurry P will infiltrate into the soil after application, rendering this P much less available to transport in surface runoff. This slurry P will remain in the top 2 cm of soil, and mostly in the top 1 cm, where it will react with soil and further decrease in availability to runoff until a new soil P chemical equilibrium is established.

These results apply to only the infiltration of manure slurry P into soil after application and before any rain or runoff event. Such initial infiltration will be different from leaching of P from manure by the first rain and infiltration of that leached P into soil. Rain will leach P out of manure solids on the soil surface, but initial slurry infiltration is concerned with only the freely draining, liquid portion of manures. The model of Vadas et al. (2004, 2005) sufficiently describes the process of manure P leaching by rain. Furthermore, initial infiltration of slurry P needs to be simulated independent from rain leaching in models so that this infiltrated P can be simulated to react with soil before any rain event, as would actually occur in the field.

Caution should be used in extrapolating our slurry P infiltration results to soils of drastically differing structure or texture from the soils we used, or to manure slurry with much greater or less water content. For example, more P could be in the infiltrating, liquid portion of a slurry with low dry matter content (1–2%) (Kleinman et al., 2005). Also, slurry liquid and P may infiltrate deeper into sandier soils or soils with extensively connected, larger pores. Future research with such varying soil and manure slurry types would show how our results with limited soil and slurry types compare.

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