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ORIGINAL PAPER

Transformations of soil and manure phosphorus after surface application of manure to field plots

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Abstract Transfer of phosphorus (P) from surface-applied manures to runoff is an important source of pollution, but few studies have closely monitored P dynamics in manure, soil, and runoff through time. We monitored manure and soil P over 14 to 17 months in field experiments in Texas and Pennsylvania, USA following dairy and poultry manure surface application. Manure was applied to porous fabric that enabled discrete sampling of both manure and underlying soil. Manure mass consistently decreased while manure total P was essentially constant through time. Manure water extractable P decreased rapidly for the first two months, likely due to rainfall leaching, but then maintained stable concentrations thereafter, with other forms of manure P gradually transformed to water extractable forms. Soil P from the upper 2 cm rapidly increased after manure application in association with manure leaching by rain. After 2 to 3 months, soil P peaked and either remained constant or gradually declined. Similar trends occurred at 2–5 and 5–10 cm, but with lesser magnitudes. At 10–15 cm, soil P changed little over time. In Pennsylvania, naturally occurring runoff from 0.7-m × 1.3-m plots without and without manure was also monitored. Runoff dissolved P concentrations were greatest for the first event after manure application and decreased steadily through time, but remained greater than P concentrations from control plots, and were always well related to manure water extractable P. This study reveals that management practices for water quality protection must consider the potential for manure P transformations to contribute dissolved P to runoff long after manure is applied.

Keywords Animal manure · Field plots · Phosphorus · Surface runoff · Soil labile phosphorus

Abbreviations

P	phosphorus
WEP_I	inorganic manure water extractable P
WEP_O	organic manure water extractable P
TP	total manure P
DRP_I	dissolved inorganic P in runoff
DRP_O	dissolved organic P in runoff

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Introduction

Non-point source pollution by P is a water quality concern because it accelerates eutrophication of freshwater systems (Carpenter et al. 1998). A major pathway of P transfer from most agricultural soils is surface runoff. Contributions of P to runoff from animal manures that have been surface-applied and left unincorporated can overwhelm contributions from soil and plants, especially when runoff occurs soon after manure application (Eghball and Gilley 1999; Kleinman et al. 2002a, b; Moore et al. 2000).

Numerous studies of varied physical and time scales have investigated the effect of surface-applied manures on P in runoff (Table 1). Most studies used small soil boxes (Kleinman and Sharpley 2003; Penn et al. 2004; Vadas et al. 2004b) or field plots (Daverede et al. 2004; DeLaune et al. 2004; Moore et al. 2000), while fewer studies used larger field plots or whole fields (Harmel et al. 2004; McDowell and Sharpley 2002; Pierson et al. 2001; Wood et al. 1999). Soil-box and field-plot studies typically used rain simulators to produce runoff, while whole-field studies necessarily relied on natural rain. Most rain simulation studies conducted only one to three consecutive experiments spanning a maximum of several weeks following manure application. Few rain simulation studies continued experiments beyond this time scale (Schroeder et al. 2004). Because of greater physical and financial investments and the need to account for temporal variations in rain and runoff, field-scale studies were typically conducted over several years.

Regardless of differences in scale and scope, manure runoff studies reveal similar trends in P runoff. Dissolved P concentrations in runoff from the first rain event after a surface application of manure are much greater, often by orders of magnitude, than background P runoff concentrations when plants or soil are the only sources of P. In these situations, water-extractable P in applied manures is an important factor controlling dissolved P in runoff (DeLaune et al. 2004; Kleinman et al. 2002a, b). Following the first events, runoff P concentrations decrease, but remain greater than background concentrations. This decline in runoff P concentrations with time is attributed to leaching of manure P by rain (Sharpley and Moyer 2000; Vadas et al. 2004b, 2005a). In contrast, when soil and plants are the only sources, dissolved P concentrations in runoff typically remain fairly constant through time (Edwards et al. 1996b; Heathman et al. 1995).

The changes in runoff P with time after surface manure application are most likely due to changes in manure P content and chemical form. However, few studies have discretely sampled surface-applied manure to monitor its physical and chemical transformations, especially as related to transfer of manure P to soil and runoff (Tasistro et al. 2004). The objectives of this study were thus to: (i) establish small field plots where surface-applied manure and underlying soils could be discretely sampled through time, (ii) monitor physical and chemical changes in applied manure P, underlying soil, and runoff for a year or more, and (iii) relate manure P properties to P in runoff from natural rainfall. Data from this study were also intended to help develop a new model for manure and P transformations and loss in runoff following surface applications.

Materials and methods

Site selection and manure application

We established field plots at the USDA-ARS Grassland, Soil, and Water Research Laboratory in Riesel, Texas and at the Pennsylvania State University Russell Larson Research and Education Center in Rock Springs, Pennsylvania (Fig. 1). Riesel is in the heart of the Blackland Prairie in east-central Texas. Soils are predominantly Houston Black clays (Fine, smectitic, thermic, Udic Haplusterts) with strong shrink/swell potential. The Texas site has long, hot summers and short, mild winters, with daily high temperatures from 15°C in January to 35°C in July and August. Mean annual rainfall is 890 mm (Harmel et al. 2003). Spring (average of 290 mm) and fall (average of 230 mm) are the wettest periods. Winter and summer average less than

Table 1 Selected studies that have investigated the effect of surface application of manure on P loss in runoff

Reference	Manure type	Physical scale	Time scale	Rain type	Consecutive runoff events
Indoor box studies					
Kleinman and Sharpley (2003)	Poultry, swine, dairy manure	20 × 100- cm boxes	Up to 21 days after application	Simulated	Yes
Kleinman et al. (2002a, b)	Poultry, swine, dairy manure	20 × 100-cm boxes	Up to 3 days after application	Simulated	No
Kleinman et al. (2004)	Poultry, swine, dairy manure	20 × 100-cm boxes	Up to 2 days after application	Simulated	Yes
Penn et al. (2004)	Turkey Manure	20 × 100- cm boxes	Up to 21 days after application	Simulated	Yes
Vadas et al. (2004b)	Poultry manure	20 × 100- cm boxes	1 days after application	Simulated	No
Small field-plot studies					
Chaubey et al. (1994)	Swine Slurry	1.5 × 3.0-m field plots	5 days after application	Simulated	No
Chaubey et al. (1995)	Poultry Litter	1.5 × 3.0-m field plots	2 days after application	Simulated	No
Daverede et al. (2004)	Swine Slurry	1.5 × 2.0-m field plots	1 and 6 months after application	Simulated	Yes
DeLaune et al. (2004)	Poultry Litter	1.5 × 2.0-m field plots	Up to 10 days after application	Simulated	Yes
Ebeling et al. (2002)	Dairy Manure	2.4 × 2.4-m field plots	Up to 13 months after application	Simulated and Natural	Yes
Grande et al. (2005)	Dairy Slurry	1.5 × 2.0-m field plots	18 months study with four applications	Simulated	Yes
Little et al. (2005)	Beef Cattle Manure	1 × 1-m field plots	Up to 5 days after application	Simulated	No
Mueller et al. (1984)	Dairy manure	1.35 m^2 field plots	Up to 4 months after application	Simulated	Yes
Pote et al. (2001)	Swine Slurry	1.5 × 3-m	24 h after application	Simulated	No
Sauer et al. (2000)	Poultry Litter	1 × 2-m field plots	Up to 1 months after application	Simulated	Yes
Schroeder et al. (2004)	Poultry Litter	1 × 2-m field plots	Up to 8 months after application	Simulated	Yes
Tarkalson and Mikkelsen (2004)	Poultry Litter	3.0 × 3.0-m field plots	Immediately after application	Simulated	No
Torbert et al. (2005)	Turkey Litter	1.5 × 2.0-m field plots	24 h after application	Simulated	No
Large field-plot studies					
Bushee et al. (1998)	Horse Bedding	2.4 × 6.1-m field plots	Immediately after application	Simulated	No
Edwards and Daniel (1993a)	Swine Slurry	1.5 × 6.0-m field plots	Up to 14 days after application	Simulated	Yes
Edwards and Daniel (1993b)	Swine Slurry	1.5 × 6.0-m field plots	24 h after application	Simulated	Yes
Edwards et al. (1996a)	Poultry Litter	1.5 × 18.3-m field plots	Immediately after application	Simulated	No
Edwards et al. (2000)	Beef Cattle Manure	2.4 × 6.1-m field plots	Up to 3 months after application	Simulated	Yes
Eghball and Gilley (1999)	Beef Cattle Manure	3.7 × 10.7-m field plots	Up to 48 h after application	Simulated	Yes
Eghball et al. (2000)	Beef Cattle Manure	3.7 × 10.7-m field plots	Up to 48 h after application	Simulated	Yes
Gessel et al. (2004)	Swine Slurry	3.0 × 22.0-m field plots	3 year study with three applications	Natural	Yes
Heathman et al. (1995)	Poultry Litter	2 × 8-m field plots	Up to 3 months after application	Natural	Yes
Heathwaite et al. (1998)	Cattle Slurry and Manure	5.0 × 20-m field plots	Up to 6 days after application	Simulated	Yes
Lim et al. (1998)	Beef Cattle Manure	2.4 × 12.2-m field plots	Immediately after application	Simulated	No
Misselbrook et al. (1995)	Dairy Slurry	10.0 × 10.0-m field plots	Immediately after application	Natural	Yes

Table 1 continued

Reference	Manure type	Physical scale	Time scale	Rain type	Consecutive runoff events
Nichols et al. (1994)	Poultry Litter	1.5 × 6.0-m field plots	7 days after application	Simulated	No
Smith et al. (2004a)	Poultry Litter	1.5 × 6.0-m field plots	Upto 15 days after application	Simulated	Yes
Smith et al. (2004b)	Poultry Litter	1.5 × 6.0-m field plots	Up to 15 days after application	Simulated	Yes
Tabbara 2003	Swine Slurry	1.5 × 9.1-m field plots	1 days after application	Simulated	No
Withers et al. (2001)	Cattle Slurry	2 × 16-m field plots	22 months study with four applications	Natural	Yes
Whole field studies					
Edwards et al. (1996b)	Poultry litter and manure	1.1 and 1.2 ha fields	33 months study with 2 to 5 applications	Natural	Yes
Harmel et al. (2004)	Poultry Litter	2.3 and 8.0 ha fields	24 months study with two applications	Natural	Yes
Moore et al. (2000)	Poultry Litter	0.4 ha fields	3 year study with three applications	Natural	Yes
Pierson et al. (2001)	Poultry Litter	0.75 ha fields	4 year study with four applications	Natural	Yes
Vervoort et al. (1998)	Poultry Litter	0.45 ha fields	22 months study with three applications	Natural	Yes
Wood et al. (1999)	Poultry Litter	33 × 33-m fields	22 months study with two applications	Natural	Yes

200 mm of rain. The Rock Springs site is in central Pennsylvania on Hagerstown silt loam soils (Fine, mixed, semiactive, mesic, Typic Hapludalfs). The Pennsylvania site has four distinct seasons with hot summers and cold winters. Daily high temperatures range from 1°C in January to 28°C in July. Mean annual rainfall is 1,000 mm, which is distributed fairly evenly throughout the year. Both sites are in areas where surface application of manure is a routine agricultural practice.

At the Texas site, we laid out 40, 120 × 120 cm sheets of a porous DuPont® weed control fabric on both fallow, bare soils and grassed soils in early September 2003. The sheets were meant to physically separate surface-applied manure from underlying soil so that both could be discretely sampled through time. We applied poultry manure (mixture of poultry manure and wood chip and sawdust bedding material) uniformly on sheets by hand at a wet weight rate of 13 Mg ha^{-1}. This rate matched that for nearby field runoff studies (Harmel et al. 2004) so that data from the two projects could eventually be compared. We made a second application of poultry manure (13 Mg ha^{-1}) to 16 remaining Texas sheets in August 2004 to determine the effects of repeated annual applications, which is the typical practice in the region. In Pennsylvania in both the grassed and bare areas, we laid out 2 porous sheets in strips that were 120 cm wide and 15 m long in April 2005 and broadcast either poultry or dairy manure by a tractor-drawn box spreader. We applied poultry manure at a wet weight rate of 45 Mg ha^{-1} and dairy manure at a wet weight rate of 90 Mg ha^{-1}. These rates are greater than typical agronomic rates for the region, but provided even, consistent manure coverage along the entire length of the sheets. We applied dairy manure one week after poultry manure. At both sites, we covered manures with a porous Coolaroo® shade cover fabric. The underlying weed control fabric was slightly wider than the shade fabric so it could be rolled over the edge of the shade fabric, with both fabrics attached to the ground with long aluminum nails. The fabric prevented manure from washing away in storms while allowing rainfall to interact freely with manure and soil.

At the Pennsylvania site directly next to sheets, we applied poultry and dairy manure at the same

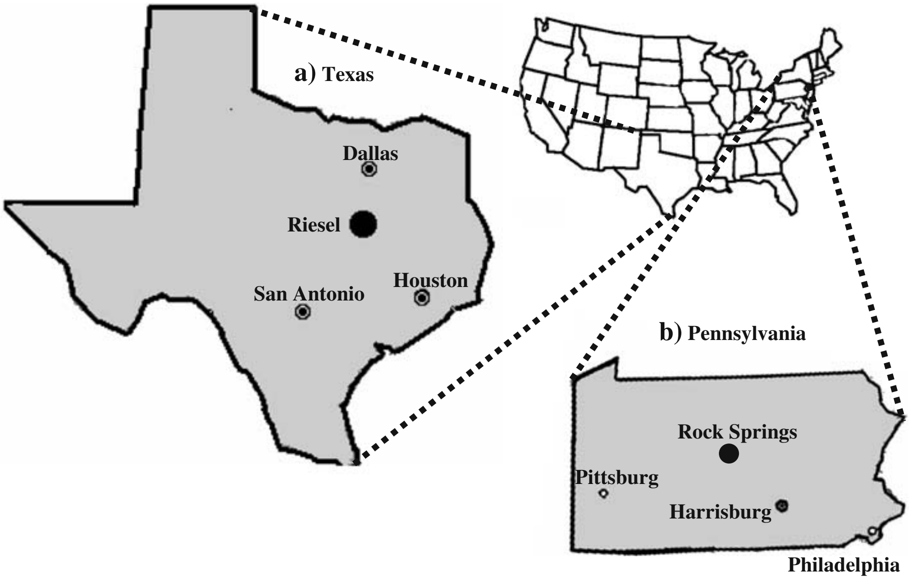


Fig. 1 Relative locations of field sites in (**a**) Texas and (**b**) Pennsylvania, USA

rates directly onto the bare soil or grassed surface, but without sheets. We then immediately installed steel-frame runoff boxes that were 0.7 m wide and 1.3 m long and had covered runoff collection gutters at the down-hill end. Runoff plot slopes averaged 5–10%. We installed runoff boxes by driving them 5 cm into the soil and allowing 5 cm to extend above the soil. Runoff flowed into plastic tubes that emptied into 5 l plastic containers installed in holes in front of the boxes. We intended these runoff areas to represent the same conditions as those in the manure sheet areas so that collected runoff would be as similar as possible to runoff that might be coming from manure sheet areas. We installed and sampled all runoff boxes in triplicate and also included three control runoff boxes in both grassed and bare areas where no manure had been applied.

Soil, manure, and runoff sampling and analysis

We intended the study to extend for at least a year, which we estimated to be 15–20, destructive sampling events. We sampled all manure sheets and underlying soils in duplicate, typically after each significant storm. If rain occurred over several days, we sampled at the end of the several days. In Pennsylvania, we at first sampled after each significant storm. After three months of sampling, we began sampling monthly so enough sheets would be available for a full year. In Texas, original manure sheets were sampled from September 2003 to July 2004, at which point enough sheets for four samplings remained. We left these sheets unsampled and re-applied poultry manure to them in September 2004 at the same rate as the previous year so that sheets contained manure from two applications. We then sampled these remaining sheets until February 2005. In Pennsylvania, there was no re-application of manures; and we sampled original sheets from April 2004 until June 2005.

At each sampling, we collected manure in sheets and underlying soil samples. In Texas, we removed the entire individual, pre-cut squares of manure sheets, and in Pennsylvania we randomly cut 90-cm sections from the 15-m long sheets. We weighed manure sheets and collected ~1 kg representative samples of manure. Underneath sheets, we collected 8–10 soil cores and divided them into depth increments of 0–2, 2–5, 5–10 and 10–15 cm. We bulked corresponding depth samples to ensure a representative sample from across the whole area under sampled sheets.

We determined moisture content in fresh, field-sampled manures by oven-drying subsamples at 80°C. We then ground the oven-dried samples with a mortar and pestle and analyzed them for total P by a semimicro–Kjeldahl procedure (Bremner 1996). We stored remaining field-sampled manures at 4°C. Within a week of sampling, we analyzed fresh manure for water extractable P (WEP) by shaking 5 g of manure with enough deionized water to achieve a 200:1 water to dry weight equivalent manure ratio. Vadas and Kleinman (2006) showed that such an extraction is a reasonable estimate of total manure WEP. We filtered solutions through 0.45 μm filters (Pall Corporation, Ann Arbor, MI) and analyzed them colorimetrically for P (Murphy and Riley 1962). We also digested filtered solutions with an alkaline persulfate method and analyzed them for P by colorimetry (Patton and Kryskalla 2003). We assumed undigested samples represented manure water extractable inorganic P (WEP_I) and the difference in P between undigested and digested samples represented water extractable organic P (WEP_O).

We determined moisture content in soils by oven-drying subsamples at 80°C. We air-dried remaining bulk soil samples, ground them to pass 2 mm, and analyzed them for Mehlich-3 P (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; Mehlich, 1984), water extractable P (60 min shaking at a water to air-dried soil ratio of 10:1), and Fe-oxide strip extractable P (Chardon 2000).

After rainfalls in Pennsylvania, we checked all runoff containers. If runoff occurred, we weighed the 5 l containers to determine total runoff volume and collected a representative runoff sample of at most 250 ml. Total runoff volumes were frequently less than 250 ml. Within 2 days of sampling, we filtered subsamples of runoff through 0.45 μm filters and analyzed them colorimetrically for P (Murphy and Riley 1962). We digested both filtered and unfiltered solutions by the alkaline persulfate method and analyzed the digests for P. We assumed filtered, undigested samples represented dissolved reactive inorganic P (DRP_I), the difference in P between filtered, undigested and filtered, digested samples represented dissolved reactive organic P (DRP_O), and that the difference between filtered, digested samples and unfiltered, digested samples represented particulate P. We determined sediment concentrations in runoff through evaporation of unfiltered samples at 80°C.

Statistical analysis

We evaluated differences in manure, soil and runoff properties related to field management (bare soil vs. grass) and manure type (dairy vs. poultry) by Student's t-test, and assessed differences related to sampling date by Analysis of Variance. Because we observed no consistently significant differences in any manure mass or P data between bare and grassed plots in Pennsylvania, we conducted statistical analyses of manure properties on the average of both types of plots for the Pennsylvania site. Due to great differences in soil P between grassed and bare soils in Texas, as discussed later, we conducted the manure and soil P analysis on Pennsylvania data only. We also evaluated associations between data by least squares regression, with differences in regression slopes assessed by homogeneity of variance test (Gomez and Gomez 1976). Differences discussed in the text were significant at $\alpha = 0.05$. We conducted all analyses with the SAS Version 8 system (SAS Institute 1999).

Results and discussion

Manure mass and phosphorus

In Texas, we sampled manures and soil at application and then 20 times during 18 months; and in Pennsylvania we sampled 20 times during 14 months (Fig. 2). For Texas bare plots, the mass of dry matter on manure sheets increased over time (Fig. 3a) due to underlying soil moving into sheets. The Texas site soil is a Montmorillonitic clay with high cation exchange capacity and shrink–swell properties, which contributed to soil migration into sheets. There was no evidence of soil movement into sheets for either bare plots in Pennsylvania or grassed plots at either site (Fig. 3a, b). When manure dry matter mass data, expressed as a fraction of initially applied manure mass, were plotted against time after surface application, consistent trends across manure types and locations could be effectively described by a single decay function (Fig. 3c). However, some differences in relative manure mass were evident between sites. Manure decomposition was ini-

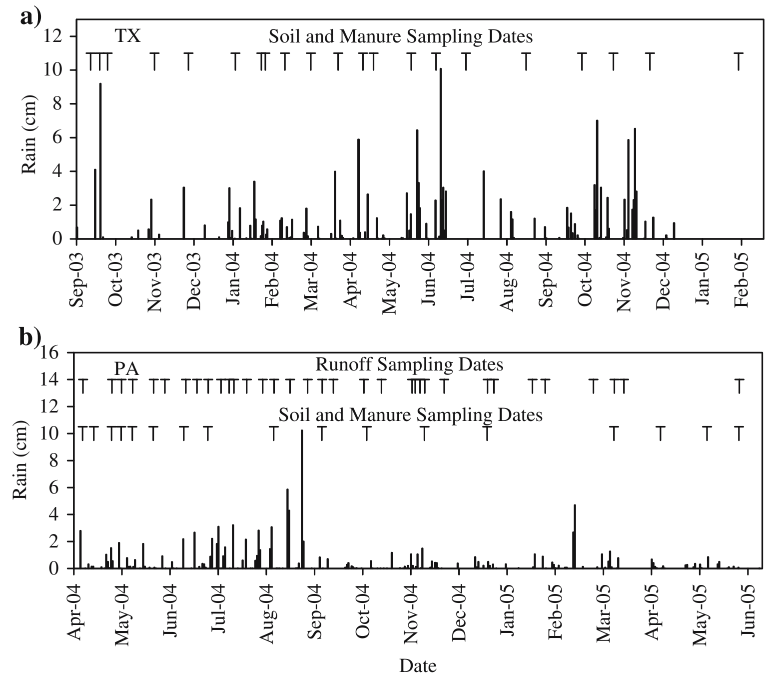


Fig. 2 Timeline of rainfall (cm) for (**a**) Texas and (**b**) Pennsylvania manure sheet experiments, including soil and manure sampling and runoff sampling dates

tially greater in Pennsylvania than Texas, but was greater in Texas later in the experiment, likely due to site climate variability relative to application date. Initial manure decomposition in Texas occurred during the cooler fall and early winter, but during the hotter spring and early summer in Pennsylvania. Conversely, later decomposition in Texas occurred during the hotter spring and summer, but during the cooler fall and winter in Pennsylvania.

For Texas bare plots, manure TP concentrations decreased with time due to dilution of the applied manure with underlying soil that moved into sheets (Fig. 4a). For Texas grassed plots (Fig. 4a) and all poultry plots in Pennsylvania (Fig. 5a), manure TP concentrations through time did not vary drastically from initial TP concentrations. This was true even after the new addition of poultry manure to Texas grassed sheets in August 2004. Because manure dry matter decreased with time, relatively constant TP concentrations show P was being removed from manure at the same rate as dry matter decomposition. Total P concentrations in Pennsylvania dairy manure consistently declined with time, showing P was removed from manure faster than dry matter decomposition (Fig. 5b).

For all Texas (Fig. 4b) and Pennsylvania (Fig. 5c) plots, manure WEP_I decreased rapidly for the first several months, then maintained steady base concentrations of approximately 10 to 20% of WEP_I concentrations in applied manures. Base WEP_I concentrations for Texas bare plots were less than grassed plots because of dilution by underlying soil. Texas Manure WEP_I concentrations increased when manure was re-applied in August 2004 (Fig. 4b). Trends in manure WEP_O concentrations were comparable to those in WEP_I (Figs. 4c and 5d), with WEP_O accounting for 4 to 28% of total manure WEP (total $WEP = WEP_I + WEP_O$).

Temporal trends in manure dry matter, TP, WEP_I, and WEP_O clearly show a gradual transformation of manure P from non-water extractable to water-extractable forms. For example, the mass of TP applied in poultry manure to a 1 m^2 area in Pennsylvania was about 100 g. After 14 months, TP mass had decreased to about 40 g, equating to a removal of 60 g of TP. Given the physical separation between soil and manure maintained by sheets, we assume P was removed from manure primarily by leaching and that rain primarily leached water extractable forms of manure P (WEP_I and WEP_O). Because the

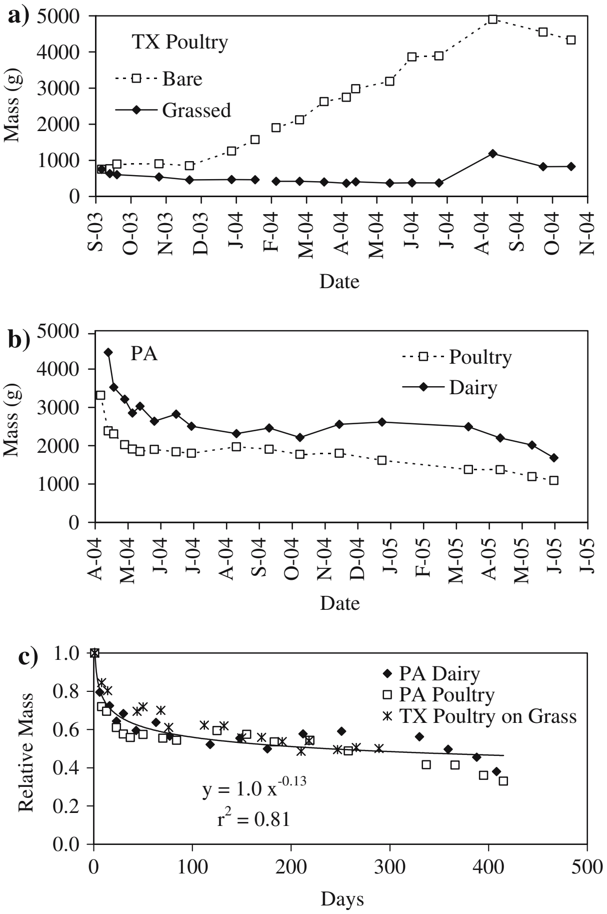


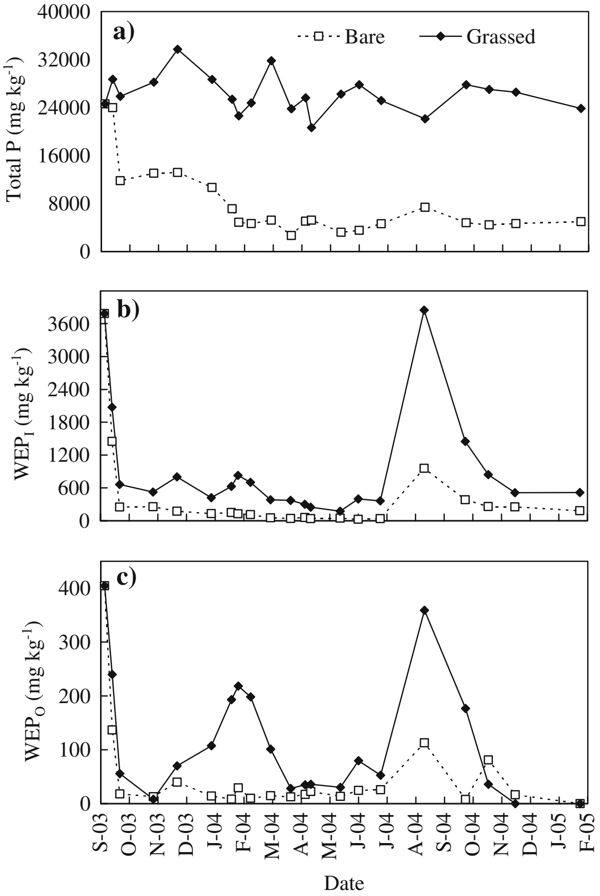
Fig. 3 Changes in the mass (*g*) of material on manure sheets in (**a**) Texas and (**b**) Pennsylvania, and (**c**) the change in mass relative to the mass of manure applied for Texas grassed plots and all Pennsylvania plots

combined amount of WEP_I and WEP_O applied in the Pennsylvania poultry manure was only about 15 g, this means that about 45 g of P in the poultry manure that was originally not water extractable was transformed over time to water extractable forms and leached from manure. This equates to a relative P transformation rate of 0.0013 $days^{-1}$. We determined similar non-WEP to WEP transformation rates of 0.0014 $days^{-1}$ for Texas poultry and 0.0016 $days^{-1}$ for Pennsylvania dairy manure. These calculated rates are likely less then maximum possible rates due to tempering by cold temperatures or dry conditions. The consistency of calculated rates suggests the nature of manure P transformations is similar across manure types and regions.

The transformation of manure P to water extractable forms over time has important implications to manure testing and management. Because studies have shown manure WEP is a dominant factor influencing dissolved P concentrations in runoff (Kleinman et al. 2002a, b), manure WEP data are increasingly being used to guide management decisions. For example, the Arkansas P Index for pastures relies heavily on manure WEP surface-applied to fields to determine potential P transport in runoff (Delaune et al. 2004). However, our results show that the manure non-water extractable P may also be important in the long-term because it is this P pool that maintains WEP concentrations after the initial WEP pool is leached.

A simple manure P and runoff model developed by Vadas et al. (2004b, 2005) assumes that the major mechanism of P removal from manure is leaching by rain. Other models have described P removal from manure as a decreasing function of time (Schroeder et al. 2004; Gérard-Marchant et al. 2005; Hively et al. 2005) that may capture the general decrease in manure WEP_I with time

Fig. 4 Changes in the concentrations (mg kg^{-1}) of (**a**) manure total P, (**b**) manure WEP$_I$, and (**c**) manure WEP$_O$ for Texas bare and grassed plots



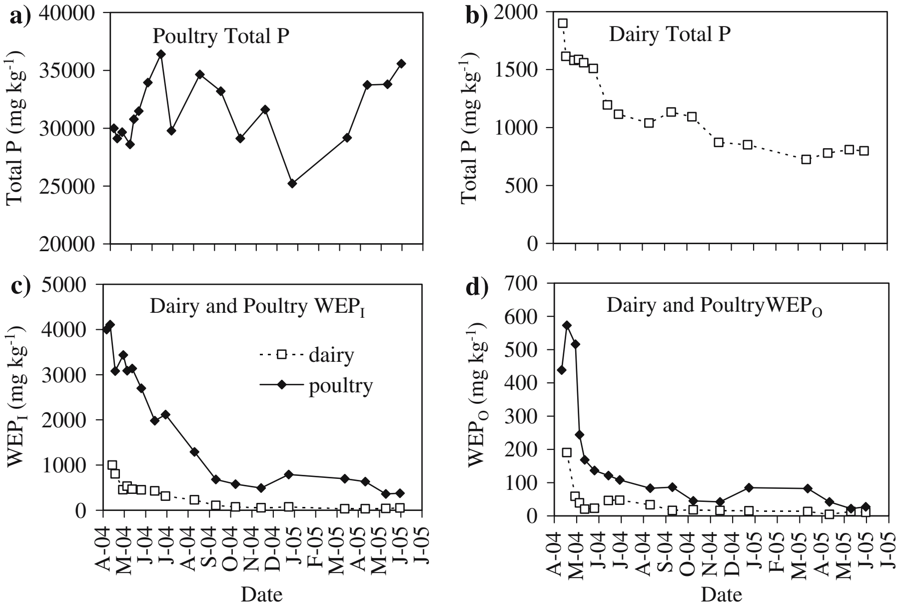


Fig. 5 Changes in the concentrations (mg kg^{-1}) of (**a**) poultry manure total P, (**b**) dairy manure total P, (**c**) dairy and poultry manure WEP$_I$, and (**d**) manure WEP$_O$ for Pennsylvania bare and grassed plots

(see Figs. 4b and 5c) but not the dynamic mechanism of rainfall leaching for individual storm events. Indeed, a decreasing time function assumes that regardless of how much (or little) rain falls over time, the decrease in manure WEP_I is the same. We plotted the fractional decrease in manure WEP_I (relative to WEP_I concentrations in originally applied manure) as a function of either cumulative rain (Fig. 6a) or time after manure application (Fig. 6b) for the Texas and Pennsylvania poultry sheets. We considered only the large, initial decreases in manure WEP_I that occurred over the first 60 days after application. The decrease in manure WEP_I as a function of cumulative rain was the same for both Texas and Pennsylvania plots, despite different poultry manures and climates. Conversely, there was an inconsistent, weaker relationship between the decrease in manure WEP_I and time after manure application. These data clearly demonstrate that decreases in manure WEP_I over time are controlled by rainfall leaching and should be described as such if models are to accurately predict manure P dynamics and dissolved P concentrations in runoff from manure.

Soil phosphorus

Similar temporal trends in soil P were observed with all extraction types (water, Fe-oxide strip, Mehlich-3 P), which were well correlated. The amount of soil P extracted by Mehlich-3 was consistently about 1.7 times that extracted by Fe-oxide strips (r^2 = 0.92), and Fe-oxide strip P was consistently about 3.6 times that extracted by water (r^2 = 0.87) (data not shown). For simulation models such as EPIC or SWAT, Fe-oxide strip P can represent the labile P pool (Vadas et al. 2005b), which is the source of dissolved inorganic P release from soil to surface runoff. For the sake of simplicity, we discuss only Fe-oxide strip P data in detail below, and refer to this P as Fe-strip P.

For the 0–2 cm Texas soils, Fe-strip P initially averaged 9 mg kg^{-1} (Fig. 7a). In bare plots, Fe-strip P increased dramatically at the first sampling to 130 mg kg^{-1}, likely representing physical mixing of manure from sheets and soil, as discussed with manure P data above. Following this peak, Fe-strip P decreased with time to 40 mg kg^{-1}. Iron-strip P peaked again after the second manure application in August 2004. Figure 4b shows manure WEP_I from Texas bare plots ranged from 40 mg kg^{-1} to 140 mg kg^{-1} from January to August 2004. During this time, Fe-strip P was in the same range, indicating that the material on manure sheets and in the underlying 2 cm was a similar mix of manure and soil. Therefore, Fe-strip P data for Texas bare plots best represent a situation where applied manure is tilled into the top few cm of soil (or ‘self incorporates’ due to rain impact or insect action), soil P increases greatly at first due to the P addition, and then decreases with time as added P transforms to less available forms in the soil or leaches into underlying soil layers (Vadas et al. 2005).

For the 2–5 cm soils of Texas bare plots, Fe-strip P also began at 9 mg kg^{-1} and increased at

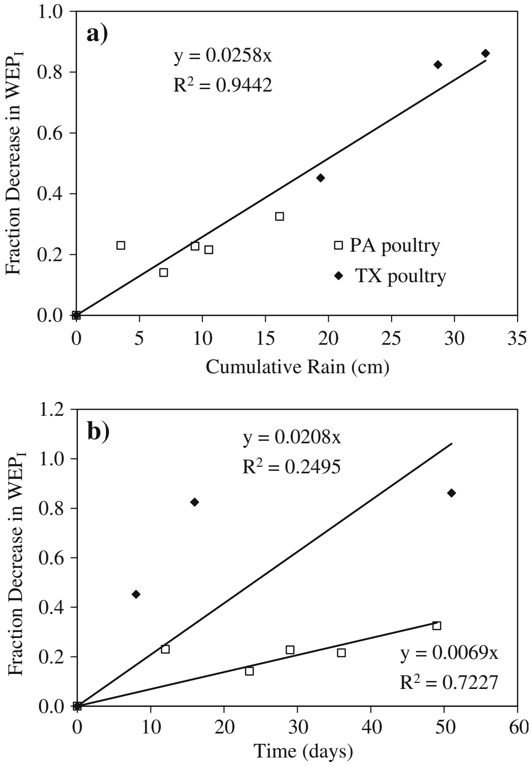


Fig. 6 The relationship between the fraction decrease in manure WEP_I during the experiments and (**a**) the cumulative precipitation (cm) or (**b**) time (days) for both Texas grassed plots and Pennsylvania grassed and bare plots

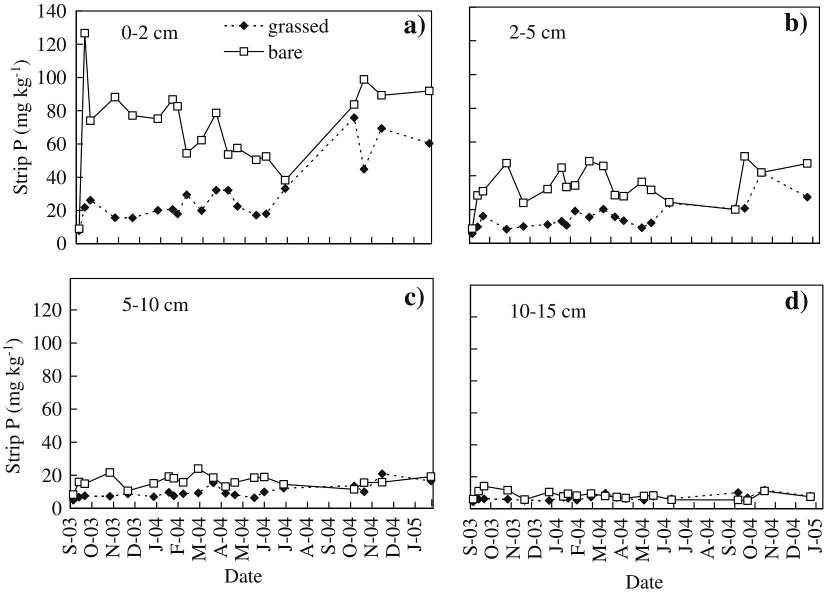


Fig. 7 Changes in Fe-oxide strip extractable soil P (mg kg^{-1}) with time for Texas bare and grassed plots for depths of (**a**) 0–2 cm, (**b**) 2–5 cm, (**c**) 5–10 cm, and (**d**) 10–15 cm

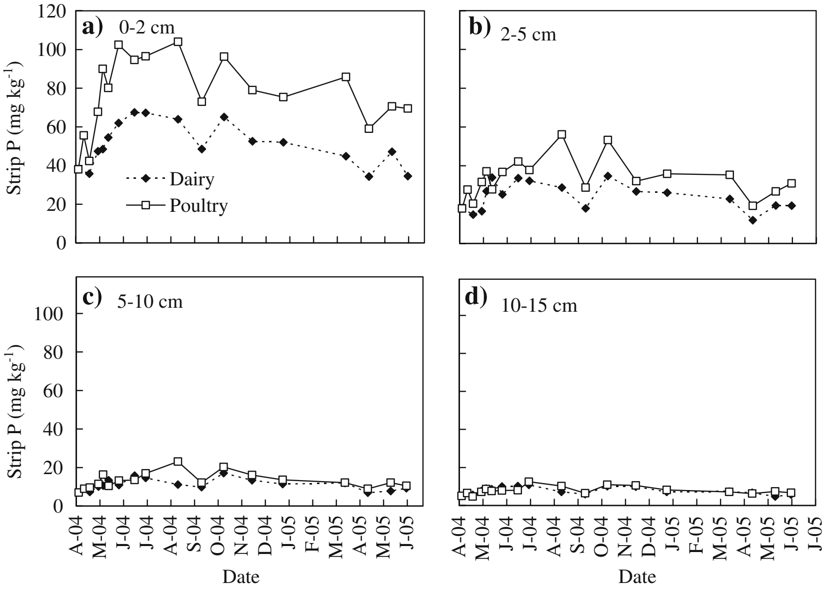
the first sampling to 30 mg kg^{-1} (Fig. 7b). For the remainder of the experiment, Fe-strip P fluctuated between 30 mg kg^{-1} and 50 mg kg^{-1}. This narrow fluctuation likely represents the counteracting inputs of P leached from the overlying 0–2 cm layer or manure, P sorption within the 2–5 cm layer, and P leaching outputs from the 2–5 cm layer. Similar Fe-strip P dynamics occurred in the 5–10 cm layer, but between 10 mg kg^{-1} and 25 mg kg^{-1}. In the 10–15 cm layer, Fe-strip P changed little during the experiment, showing the inability of P to leach down through this fine-textured soil.

For the Texas grassed soils from 0 cm to 2 cm (Fig. 7a), Fe-strip P also began at 9 mg kg^{-1}and increased to 20 mg kg^{-1} at the first sampling. Iron-strip P then fluctuated between 20 mg kg^{-1} and 35 mg kg^{-1}, until it increased again between 50 mg kg^{-1} and 75 mg kg^{-1} after the second manure application. These trends in Fe-strip P were similar to those in the 2–5 cm depth of the bare plots (Fig. 7b), and better represented a situation where applied manure does not physically mix with soil but incrementally adds P to soil through leaching of manure P by rain. For the 2–5 cm and 5–10 cm grassed soils, Fe-strip P began at 5 mg kg^{-1} and increased into a range of only 10 to 25 mg kg^{-1} over time, which shows that some P leached from surface manure or overlying soil layers. As for Texas bare plots, Fe-strip P in the 10–15 cm layer changed little over time.

In Pennsylvania for each sampling time, there were no consistently significant differences in Fe-strip P between grassed and bare plots. Therefore, we combined the data for the two types of plots. In general, trends in Fe-strip P with time were also similar for dairy and poultry plots, except that the magnitude of Fe-strip P was greater in poultry plots, especially for the 0–2 and 2–5 cm depths (Fig. 8). This is because there was more P applied to plots in poultry than in dairy manure, causing more P to leach into soil under poultry sheets. However, similarities in Fe-strip P dynamics for dairy and poultry plots show the fate of P applied to soil in manures is controlled by the same fundamental processes regardless of manure type.

In the 0–2 cm Pennsylvania soils, Fe-strip P was initially about 40 mg kg^{-1} before manure was applied, indicating some enrichment of this soil from past fertilization (Fig. 8a). Within the first two months after manure application, Fe-strip P from 0 cm to 2 cm increased dramatically, undoubtedly due to substantial P leaching from manure when manure WEP concentrations were greatest. After 2 to 3 months, Fe-strip P peaked at 100 mg kg^{-1} in poultry plots and 70 mg kg^{-1} in dairy plots, and then steadily declined thereafter. These later trends suggest that, likely due to the

Fig. 8 Changes in Fe-oxide strip extractable soil P (mg kg^{-1}) with time for Pennsylvania dairy and poultry plots for depths of (**a**) 0–2 cm, (**b**) 2–5 cm, (**c**) 5–10 cm, and d) 10–15 cm



lesser manure WEP concentrations, P leaching inputs from manure into soil was less than P sorption or downward leaching outputs.

Trends in Fe-strip P with time in the 2–5 cm Pennsylvania soils were similar to those in the 0–2 cm depth (Fig. 8b). Iron-strip P increased from an initial average of 20 mg kg^{-1} to 30 mg kg^{-1} to 40 mg kg^{-1} after 3 months. Iron-strip P stayed relatively constant or declined slightly thereafter. Iron-strip P concentrations were greater in poultry than in dairy plots, but the difference was not as marked as in the 0–2 cm depth. This suggests that the 0–2 cm soil layer was able to buffer P leaching outputs enough that P concentrations in exiting water were more similar in poultry and diary plots than P concentrations in entering water. For the 5–10 cm depth, Fe-strip P concentrations increased slightly during the course of the experiment, with increases the same for both poultry and dairy plots (Fig. 8c). This again suggests that overlying soil layers buffered leaching waters enough that P concentrations entering the 5–10 cm layer in both poultry and diary plots were the same. In the 10–15 cm layer, Fe-strip P concentrations changed little during the experiment, showing surface applications of manure will not greatly affect Fe-strip P in the short term even at this relatively shallow depth in these types of soils (Fig. 8d).

Runoff phosphorus at the Pennsylvania site

Runoff volumes were consistently greater from bare areas (average of 2,200 ml or 2.9 mm) than grassed areas (average of 1500 ml or 2.0 mm). Grassed plot runoff from was often less than 100 ml (0.13 mm; 46% of samples) and often contained insects and worms that contaminated runoff with P. This problem did not occur on bare plots, where only 8% of samples had runoff volumes less than 100 ml. For data analysis, we thus used runoff P data from grassed plots only when runoff P concentrations were not substantially different from P concentrations from bare plots, which always coincided with winter samples or samples with greater runoff volumes. For these data, we averaged P concentrations across all bare and grassed plots. Given the concern about contamination of runoff from grassed plots, we estimated DRP_O and particulate P in runoff from only bare plots.

Phosphorus concentrations in digested and undigested runoff samples from bare Pennsylvania plots were strongly correlated (Digested = 1.07 × undigested, $r^2 = 0.99$, data not shown). Therefore, trends in DRP_O concentrations over time were the same as for DRP_I concentrations. Runoff sediment concentrations (mg l^{-1}) were well related to runoff particulate P concentrations (mg l^{-1}) (data not shown). The relationship was different for control plots (Particulate P = 0.31 × Sediment + 1.7, $r^2 = 0.63$) and manure plots, but was the same for diary and poultry plots (Particulate P = 4.93 × Sediment –0.95, $r^2 = 0.73$). The greater regression slope for manure plots suggests erosion of manure particles themselves or enrichment of eroded soil particles with manure P.

Observed runoff dissolved P concentrations do not necessarily reflect those generated from typical agronomic manure application rates, as our manure was applied at greater rates. Our objectives were not to mimic actual agronomic conditions, but to observe and develop a model to simulate relative, long-term manure and runoff P dynamics. Runoff DRP_I concentrations from dairy (12 mg l^{-1}) and poultry (25 mg l^{-1}) plots were greatest for the first event after manure application and decreased steadily through time (Fig. 9a). The first runoff occurred within a week of application, which represents a worst-case scenario for manure P loss. On a relative event basis, runoff DRP_I concentrations from dairy plots averaged only 55% of that from poultry plots, which is consistent with research showing runoff P from poultry is greater than from dairy manure (Kleinman and Sharpley 2003; Kleinman et al. 2002a, b). Runoff DRP_I concentrations from all plots at the end of the experiment ranged from 1 mg l^{-1} to 2 mg l^{-1} (Fig. 9a) and were always significantly greater than concentrations from control plots, which were less than 1 mg l^{-1}.

Research has shown that manure WEP is a dominant factor influencing dissolved P concentrations in runoff from surface-applied manure, typically by linear regression between measured manure WEP_I and runoff P for single events (Kleinman and Sharpley 2003). These studies have focused on only the first few runoff events following manure application. In our study,

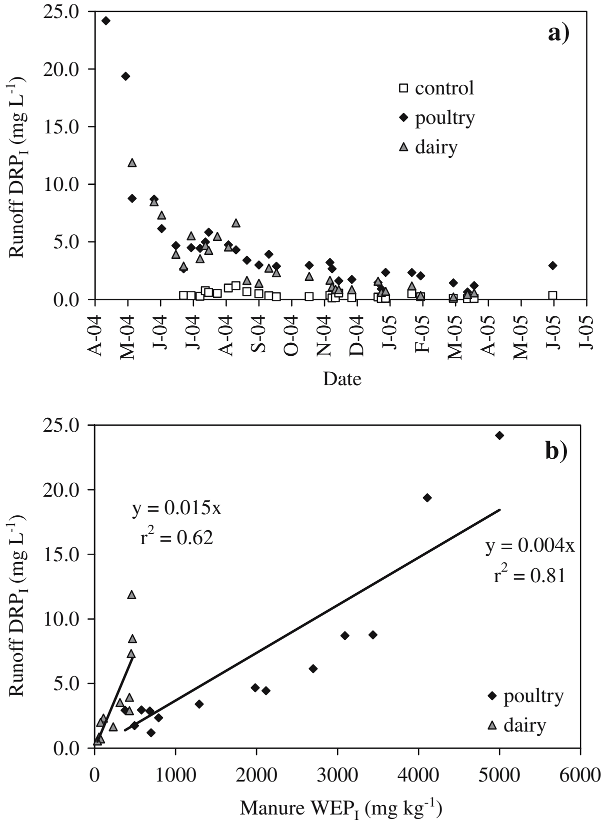


Fig. 9 For Pennsylvania plots, (**a**) changes in runoff DRP_I concentrations (mg l^{-1}) with time, and (**b**) the relationship between runoff DRP_I concentrations (mg l^{-1}) and manure WEP_I concentrations (mg kg^{-1}) measured at about the same time as the runoff samples were collected

repeated sampling of manures and runoff supports the assessment of runoff P and manure $\mathrm{WEP_I}$ relationships, but over much longer periods. Across our 34 runoff events, runoff $\mathrm{DRP_I}$ was strongly related to manure $\mathrm{WEP_I}$ measured at the nearest sampling date (Fig. 9b). These runoff data combined with the manure P data discussed earlier clearly show that long-term manure P transformations maintain a manure $\mathrm{WEP_I}$ pool that can supply P to runoff for many months after manure application. Our soils undoubtedly contributed P to runoff, but they likely did not maintain observed runoff $\mathrm{DRP_I}$ concentrations, even towards the end of the experiment when manure WEP and runoff P concentrations declined. For example, average runoff $\mathrm{DRP_I}$ concentrations on April 4, 2005, almost one year following manure application, were 0.6 mg $\mathrm{l^{-1}}$ from dairy plots and 1.2 mg $\mathrm{l^{-1}}$ from poultry plots. A literature review of Vadas et al. (2004b) suggests that soil Mehlich-3 P concentrations would have to be about 300 mg $\mathrm{kg^{-1}}$ for dairy and 600 mg $\mathrm{kg^{-1}}$ for poultry plots to maintain these runoff $\mathrm{DRP_I}$ concentrations. Measured soil Mehlich-3 P from 0 cm to 2 cm at this time was only 83 mg $\mathrm{kg^{-1}}$ in dairy and 157 mg $\mathrm{kg^{-1}}$ in poultry plots.

Figure 9b shows that dairy manure maintained a greater concentration of $\mathrm{DRP_I}$ in runoff per unit of manure $\mathrm{WEP_I}$ than poultry manure, as evidenced by significantly different regression slopes. These findings are consistent with those of Vadas et al. (2004a, 2005a) describing a $\mathrm{WEP_I}$-based model to predict $\mathrm{DRP_I}$ concentrations in runoff from manures. That model predicts storm-event manure P release with relationships based on the ratio of rain volume to manure mass. The relationships are different for poultry and dairy manure, with dairy manure releasing relatively greater P for a given ratio of rain to manure mass. The physical mechanisms controlling relatively greater P release from dairy manure are unclear. The differential in turn maintains relatively greater runoff $\mathrm{DRP_I}$ concentrations from dairy manure, although absolute concentrations may be less from diary manure because manure $\mathrm{WEP_I}$ concentrations are typically less than in poultry manure.

Summary and conclusions

We conducted 14 to 17 months field experiments in Texas and Pennsylvania to investigate P dynamics in manure, soil, and runoff following surface applications of dairy and poultry manure. Manure dry matter mass decreased through time, indicating physical decay is controlled by the same climate and manure properties regardless of manure type or site location. Manure TP concentrations were essentially constant through time, meaning P was removed from manure at the same rate that manure decomposed. Manure $\mathrm{WEP_I}$ decreased rapidly for the first two months, and then reached steady base concentrations of 10 to 20% of $\mathrm{WEP_I}$ concentrations in applied manures. These $\mathrm{WEP_I}$ decreases were clearly controlled by rainfall leaching and not time per se. Manure mass and P data show manure P transformed from non-water extractable to water extractable forms over time. About 40 to 60% of original manure non-water extractable P transformed to water extractable forms, translating to a transformation rate of 0.0013 to 0.0016 $\mathrm{days^{-1}}$ that was consistent across site locations and manure types. Transformation of manure P to water extractable forms over time has important implications for assessing the effects of manures on P loss in runoff. Future research should investigate specific inorganic or organic forms of manure P involved in transformations, perhaps in an effort to minimize long-term availability of manure P to loss in runoff.

Soil P rapidly increased in the 0–2 cm depth after manure application due to leaching of manure P by rain. Within 2 to 3 months of manure application, surface soil P peaked and either remained fairly constant or gradually declined thereafter, showing P leaching from manure into soil became less than the combination of P sorption and downward leaching. For the 2–5 cm and 5–10 cm soil layers, we observed similar soil P trends, but with lesser magnitudes, especially from 5 cm to 10 cm, showing that some P did leach from surface manure or overlying soil layers. Soil P in the 10–15 cm layer changed little over time. Overall, soil P was most affected by manure application at the 0–5 cm depth. Showing manure application will affect P transfer to runoff directly through manure P loss and indirectly through soil P enrichment.

For runoff data, eroded sediment concentrations were well related to particulate P concentrations. The relationship was different between control and manure plots, suggesting P enrichment of eroded soil particles or erosion of manure itself from manure plots. Runoff $\mathrm{DRP_I}$ concentrations were greatest for the first runoff after manure application and decreased steadily through time, but were still greater than $\mathrm{DRP_I}$ concentrations from control plots even after 14 months. Runoff $\mathrm{DRP_I}$ concentrations from dairy plots were typically less than from poultry plots. However, dairy manure maintained greater runoff $\mathrm{DRP_I}$ concentrations per unit of manure $\mathrm{WEP_I}$ than poultry manure. Runoff $\mathrm{DRP_I}$ concentrations were well related to manure $\mathrm{WEP_I}$ concentrations throughout the experiment. Therefore, manure P transformations over time maintain a manure $\mathrm{WEP_I}$ pool that supplies runoff with P many months after manure application. Soil will also contribute P to runoff, but it is not likely that the soil maintained the runoff $\mathrm{DRP_I}$ concentrations, even towards the end of the experiment. Therefore, manure management must consider both short-term and long-term influences of surface applications on P transfer to runoff. Given the timely and focused nature of our soil and manure sampling, our results should help fill important gaps in understanding and modeling manure, soil, and runoff P dynamics after surface applications of animal manures.

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