A Simple Method to Predict Dissolved Phosphorus in Runoff from Surface-Applied Manures

P. A. Vadas,* P. J. A. Kleinman, and A. N. Sharpley

ABSTRACT

Computer models are a rapid, inexpensive way to identify agricultural areas with a high potential for P loss, but most models poorly simulate dissolved P release from surface-applied manures to runoff. We developed a simple approach to predict dissolved P release from manures based on observed trends in laboratory extraction of P in dairy, poultry, and swine manures with water over different water to manure ratios. The approach predicted well dissolved inorganic ($R^2 = 0.70$) and organic ($R^2 = 0.73$) P release from manures and composts for data from leaching experiments with simulated rainfall. However, it predicted poorly ($R^2 = 0.18$) dissolved inorganic P concentrations in runoff from soil boxes where dairy, poultry, and swine manures had been surface-applied and subjected to simulated rainfall. Multiplying predicted runoff P concentrations by the ratio of runoff to rainfall improved the relationship between measured and predicted runoff P concentrations, but runoff P was still overpredicted for dairy and swine manures. We attributed this overprediction to immediate infiltration of dissolved P in the freely draining water of dairy and swine manure slurries upon their application to soils. Further multiplying predicted runoff dissolved inorganic P concentrations by 0.35 for dairy and 0.60 for swine manures resulted in an accurate prediction of dissolved P in runoff ($R^2 = 0.71$). The ability of our relatively simple approach to predict dissolved inorganic P concentrations in runoff from surface-applied manures indicates its potential to improve water quality models, but field testing of the approach is necessary first.

O F THE APPROXIMATELY 22 000 impaired surface waters in the USA, 11% are due to nutrients (USEPA, 2003a), primarily agricultural N and P (USEPA, 2003b). Currently, one of the main water quality concerns is the accelerated eutrophication of fresh waters by P, which limits water use for drinking, recreation, and industry. Critical P levels in flowing (0.010–0.075 mg total P L^{-1}) and lake waters (0.008–0.038 mg total P L^{-1}; USEPA, 2001), above which eutrophication can be accelerated, are low relative to losses from agricultural sources (0.10–12.00 mg total P L^{-1}; Sharpley and Rekolainen, 1997). Thus, losses of P in agricultural runoff need not be high to impair the water quality of receiving waters (Carpenter et al., 1998; Gibson et al., 2000).

Given this low P threshold of water bodies and the fact that P losses can be highly variable within watersheds and among management practices, certain small, defined areas of the landscape can be major sources of P exported from watersheds (Pionke et al., 2000; Sharpley et al., 2002). The subsequent challenge for the agricultural community, from scientists to producers, is to iden-

tify agricultural areas with a high potential for P export, accurately quantify that P export, and assess the ability of alternative management practices to minimize P export (Coale et al., 2002; Gburek et al., 2000). Water quality simulation models are seen as one relatively rapid and cost effective way to help achieve these goals (Sharpley et al., 2002).

While significant loss of P from agricultural fields can occur through leaching in sandy soils (Novak et al., 2000), organic soils (Porter and Sanchez, 1992), and soils with artificial drainage (Heckrath et al., 1995), the primary pathway of P loss from the majority of agricultural soils is through surface runoff. The three major sources of P to surface runoff are soil, plant material, and applied fertilizers, manures, or biosolids (Hanson et al., 2002; Heathwaite and Dils, 2000; Withers et al., 2001). Research has clearly shown that even though soil and plant material can be significant sources of P to runoff, their effect is overwhelmed by P release from recently applied manures and fertilizers (Eghball and Gilley, 1999; Kleinman et al., 2002a; Moore et al., 2000). However, most water quality models do not simulate surface application of manures, a common practice in many areas of the USA, and therefore do not consider direct loss of P from manures to runoff. Instead, models incorporate manure P into soil P pools and adjust extraction coefficients of these pools. The result is a poor representation and often underprediction of P loss in runoff (Pierson et al., 2001b; Sharpley et al., 2002). Therefore, such models could be greatly improved by adding routines to simulate P loss directly from surface-applied manures to runoff.

The objective of this research was to develop a method to predict both P release to water from animal manures and dissolved P concentrations in runoff from soils where animal manures have been surface-applied.

MATERIALS AND METHODS

Model Development

Sharpley et al. (1981) proposed an equation to estimate inorganic P desorption from soil to water as:

$$P_d = Kt^\alpha W^\beta P_o \qquad [1]$$

where P_d is the amount of P desorbed (mg P kg^{-1} soil) in time t (min) at a water to soil ratio W (mL rainfall g^{-1} soil), P_o is the initial total amount of water desorbable P present in the soil (mg P kg^{-1} soil), and K, α, and β are empirical constants for a given soil. Equation [1] was developed based on the observations that P release from soil to water increases as both the water to soil ratio and the time of interaction between soil and water increase. Kleinman et al. (2002b) demonstrated similar relationships between time and water to manure ratio for P release from fresh dairy, swine, and poultry manures to water in laboratory experiments. Therefore, we

USDA-Agricultural Research Service, Pasture Systems and Watershed Management Research Unit, Building 3702, Curtin Rd., University Park, PA 16802-3702. *Corresponding author (Peter.Vadas@ars.usda.gov).

theorized that a model similar to Eq. [1] could accurately describe P release from manure to water.

Kleinman et al. (2002b) measured dissolved inorganic P release from fresh manures to water at shaking times ranging from 1 to 1440 min and a constant added deionized water to manure ratio of 200:1 and found that the relationship between P release and shaking time was described by lognormal equations, such that P release approached a maximum within a 24 h extraction. They also observed that more than 70% of this maximum P release occurred within 60 min. Elsewhere, Dou et al. (2002) conducted water extractions on dried and ground poultry and dairy manure with shaking times ranging from 1 to 16 h. Similar to Kleinman et al. (2002b), they found that more than 90% of the P extracted at 16 h had been extracted within 60 min.

In field situations, it is likely that the interaction between surface-applied manures and rain or surface runoff water will last at least 60 min for many rainfall events. Furthermore, the majority of water quality models rarely operate on less than an hourly time step. Given these considerations and the observations by Kleinman et al. (2002b) and Dou et al. (2002) that the majority of P release from manures to water will occur within 60 min, it is reasonable to omit a time parameter in an equation to predict P release from manure to water. Therefore, based on the concepts of Eq. [1] and the observations of Kleinman et al. (2002b), the release of P from manures to water can be described as simply a function of the water-extractable P concentration of manure and the ratio of the quantity of extracting water to the quantity of manure (water

to manure ratio). Such relationships between P release from fresh manures and water to manure ratio are shown in Fig. 1a for the experiments conducted by Kleinman et al. (2002b) for dairy, poultry, and swine manures. In this figure, the water to manure ratios take into account the liquid already present in the manures and the deionized water added during extractions.

Dou et al. (2000) conducted seven consecutive 60-min extractions of dried and ground dairy and poultry manures with water at a ratio of 100:1 (water to manure). By the final extraction, inorganic P release to water had essentially reached zero. Therefore, this procedure was a good estimate of the maximum amount of inorganic P in the manures that could be extracted by water. The authors observed that the amount of P extracted in the first 60-min extraction was about 70% of the total P extracted over the seven extractions for both dairy and poultry manures. Dou et al. (2002) observed similar results in separate experiments where dried and ground dairy manures were extracted at a water to manure ratio of 100:1 over six consecutive 60-min extractions. These findings show that a single extraction of manures with water at a water to manure ratio of 100:1 for 60 min should remove about 70% of the total water-extractable P.

Kleinman et al. (2002b) conducted 20-min water extractions of fresh dairy, poultry, and swine manures at water to manure ratios ranging from 10 to 250 (Fig. 1a). These ratios consider both water already in the fresh manures and deionized water added during extractions. Since the maximum water to manure ratio used was 250, we normalized the data of Kleinman et al. (2002b; Fig. 1a) by expressing the ordinate axis as the ratio of inorganic P released at a given water to manure ratio to the maximum P released at a 250:1 water to manure ratio (Fig. 1b). For these data, inorganic P release was best described by linear relationships for poultry and swine manures and by a power function equation for dairy manure. We then plotted the data from Dou et al. (2000, 2002) in the figure for comparison, and observed that their data fell relatively well in line with the trends in the Kleinman et al. (2002b) data (Fig. 1b). The combined findings of Dou et al. (2000, 2002) and Kleinman et al. (2002b) show that the maximum amount of manure P that can be released to water is reasonably estimated by a single extraction with water at a 250:1 water to manure ratio for 60 min. From the data in Fig. 1b, P release from dairy, poultry, or swine manure to water can thus be described by the equations:

$$\text{dairy: P release} = (0.184W^{0.307}) \times \text{manure water-extractable P} \qquad [2]$$

$$\text{poultry: P release} = (0.003W + 0.27) \times \text{manure water-extractable P} \qquad [3]$$

$$\text{swine: P release} = (0.004W + 0.04) \times \text{manure water-extractable P} \qquad [4]$$

where W is water to manure ratio (cm^3 water g^{-1} dry manure) and both P release and manure water-extractable P have the units mg kg^{-1} dry manure. On the right side of Eq. [2], [3], and [4], the expressions multiplied by manure water-extractable P can essentially be thought of as extraction coefficients that change as a function of the water to manure ratio. We tested Eq. [2], [3], and [4] to see if they could successfully describe both P release from manures alone during simulated rainfall and dissolved inorganic P concentrations in runoff from soils where manures had been surface-applied and subjected to simulated rainfall.
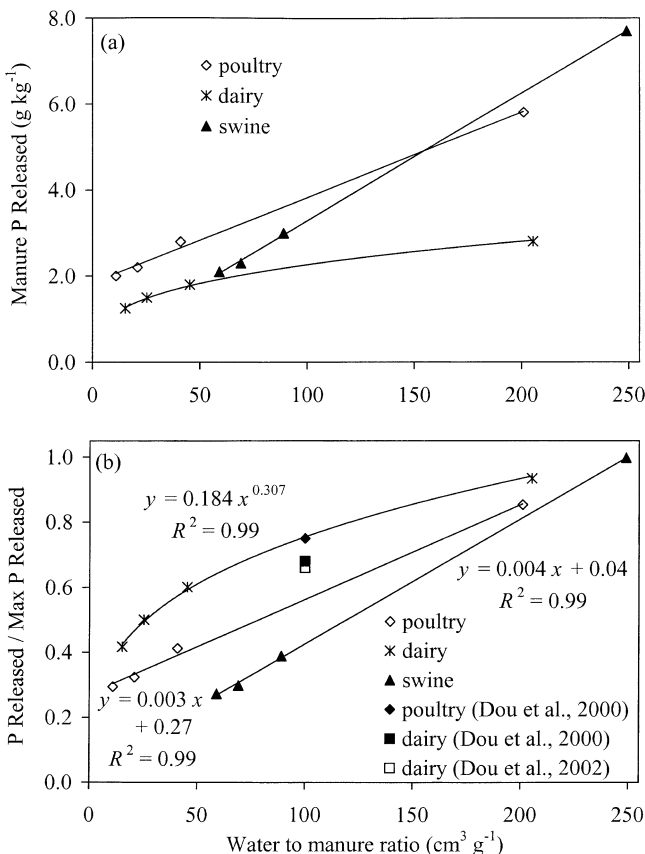

Fig. 1. (a) Dissolved inorganic P release from fresh dairy, poultry, and swine manures as a function of water to manure ratio during extraction, and (b) P release expressed as a fraction of the maximum release observed at a water to manure ratio of 250:1. Data are from Dou et al. (2000, 2002) and Kleinman et al. (2002b).

Model Testing

Leaching of Dissolved Phosphorus from Manure during Simulated Rainfall

We used data from Sharpley and Moyer (2000), who investigated the forms of P in various animal manures and composts and their release to water when subjected to simulated rainfall. They measured water-extractable inorganic and organic P in fresh manures and composts by shaking manure and deionized water for 60 min at an added water to manure ratio of 200:1. Afterward, they applied fresh manure and compost at a rate of 20 g dry weight basis to filter paper mounted on leaching columns and applied rainfall at a rate of approximately 70 mm h^{-1} for 30 min. All leachate was collected in one bulk sample, filtered through 0.45-μm filter paper, and analyzed for dissolved inorganic and organic P by the method of Murphy and Riley (1962). Manures and composts were then allowed to freely drain by gravity for 24 h at room temperature. The rainfall–draining cycle was repeated four more times for a total of five leaching events. Taking into account the initial moisture content of the manures and composts and the amount of rainfall applied in the experiments, the resulting W values for Eq. [2], [3], and [4] ranged from 31 to 40.

We used Eq. [2], [3], and [4] to predict P release from manures and composts for all five leaching events. For dairy composts, we used Eq. [2]; for poultry litter and composts, we used Eq. [4]. Although Eq. [2], [3], and [4] were determined using data from inorganic P release from manures, we used them to predict both inorganic and organic P release from manures. For organic P release predictions, water-extractable P in Eq. [2], [3], and [4] was organic P instead of inorganic P. For each manure or compost, we subtracted the amount of predicted P released from the first leaching event from the initial amount of manure water-extractable P on the right hand side of Eq. [2], [3], and [4]. We used the resulting differences as new values for manure water-extractable P to predict P release for the second leaching event. We carried this method through to predict both inorganic and organic P release for all five leaching events.

Dissolved Inorganic Phosphorus Loss in Runoff from Soils with Surface-Applied Manures

We used P runoff data from Kleinman et al. (2002a, 2004) and Kleinman and Sharpley (2003). All of these studies used boxes packed with soil and subjected to simulated rainfall that followed the protocol of the National P Research Project (National Phosphorus Research Project, 2003). Soils used were Buchanan (fine-loamy, mixed, semiactive, Aquic Fragiudult), Hagerstown (fine, mixed, semiactive, mesic Typic Hapludalf), Hartleton (loamy-skeletal, mixed, active, mesic Typic Hapludult), Honeoye (fine-loamy, mixed, active, mesic Glossic Hapludalf), and Lewbeach (coarse-loamy, mixed, semiactive, frigid Typic Fragiudept). Briefly, soils were packed into stainless steel runoff boxes that were 100 cm long by 20 cm wide by either 7.5 or 27.5 cm deep and had nine drainage holes. Soil in boxes was leveled to a depth of either 5 or 25 cm deep, with bulk densities between 1.2 and 1.4 g cm^{-3}. Soils were pre-wet 24 to 72 h before runoff experiments started. Boxes were placed at a 5% slope under a rainfall simulator based on the design of Miller (1987). Fresh dairy, poultry, or swine manure was surface-applied to boxes at a rate of 100 kg total manure P ha^{-1}. Kleinman and Sharpley (2003) also had manure application rates of 10, 50, 75, and 150 kg total manure P ha^{-1}. All manures had been analyzed for water-extractable P by shaking with deionized water for 60 min at an added water to manure ratio of 200:1. Seventy-two hours after manure

application to soils, simulated rainfall was applied at an approximate intensity of 75 mm h^{-1} until 30 min of runoff had been collected. The time until runoff initiation was recorded so that the total amount of rain falling on the boxes was known. All runoff was collected in a single container, and subsamples were filtered through 0.45-μm filter paper and analyzed for dissolved reactive P by the method of Murphy and Riley (1962). Kleinman et al. (2002a, 2004) conducted only one set of runoff experiments at 72 h after manure application, whereas Kleinman and Sharpley (2003) conducted three sets of runoff experiments at 3, 10, and 24 d after manure application.

To supplement the data from the above studies, we also conducted a series of runoff experiments whose protocol followed that of the previous experiments described above. Briefly, a Mardin channery silt loam soil (coarse-loamy, mixed, active, mesic Typic Fragiudepts) was packed into runoff boxes that were 100 cm long by 20 cm wide by 7.5 cm deep and had nine drainage holes. Soils in boxes were leveled to a depth of 5 cm and were pre-wet 24 h before runoff experiments started. Boxes were placed at a 5% slope under a rainfall simulator and fresh dairy, poultry, or swine manure was surface-applied to boxes at a rate of 100 kg total manure P ha^{-1}. Twenty-four hours later, simulated rainfall was applied at an approximate intensity of 75 mm h^{-1} until 30 min of runoff had been collected. Instead of one bulk sample, runoff was collected in discrete 5-min increments, and subsamples were filtered through 0.45-μm filter paper and analyzed for dissolved reactive P by the method of Murphy and Riley (1962).

Using data from the above studies, we tested Eq. [2], [3], and [4] for their ability to predict dissolved P concentrations in runoff from soils where manures had been surface-applied. None of the experiments estimated dissolved organic P concentrations in runoff, so we tested Eq. [2], [3], and [4] for their ability to predict only dissolved inorganic P in runoff. We calculated values for W in Eq. [2], [3], and [4] as the volume of rainfall (cm^3) divided by the dry weight mass (g) of manure applied to the boxes. For the consecutive runoff experiments of Kleinman and Sharpley (2003), we subtracted the amount of predicted P released from manures during the first runoff event from the initial amount of manure water-extractable P on the right hand side of Eq. [2], [3], and [4]. We used the resulting differences as new values for manure water-extractable P to predict P release for the second runoff event. We carried this method through to predict P release for the third runoff event. Values for W were held constant for all three runoff events. Finally, Eq. [2], [3], and [4] predict the amount of P release from manure in mg kg^{-1}, and dissolved inorganic P in runoff in all studies was measured as mg L^{-1}. Therefore, to convert mg kg^{-1} to mg L^{-1} to predict dissolved inorganic P in runoff, we divided the right sides of Eq. [2], [3], and [4] by their respective values of W.

RESULTS AND DISCUSSION

Leaching of Dissolved Phosphorus from Manure during Simulated Rainfall

Figure 2 compares dissolved inorganic and organic P release from poultry, dairy, and swine manures and composts subjected to five consecutive simulated rainfall leaching events as measured by Sharpley and Moyer (2000) and as predicted by Eq. [2], [3], and [4]. These data represent the gross release of manure or compost P to rainfall with no interaction of released P with soil. Figure 2 demonstrates that Eq. [2], [3], and [4] success-
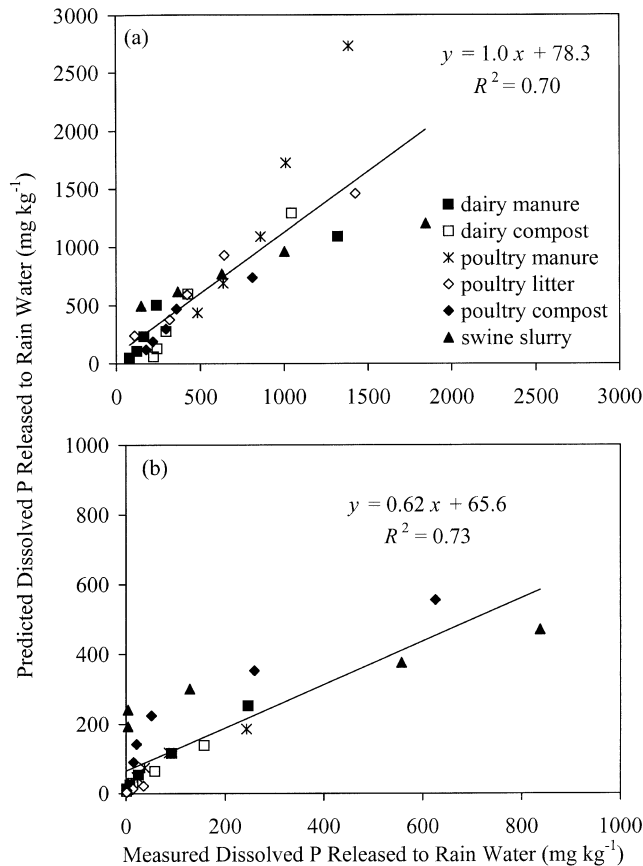
Fig. 2. Relationship between (a) dissolved inorganic and (b) organic P released from manures and composts subjected to five consecutive simulated rainfall leaching events as measured by Sharpley and Moyer (2000) and as predicted by Eq. [2], [3], and [4].
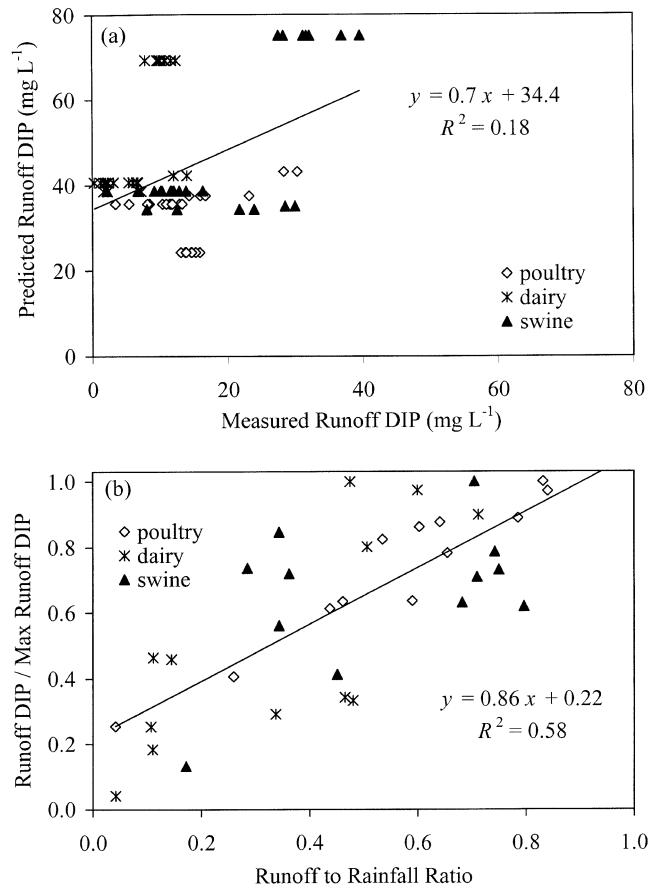

Fig. 3. (a) Relationship between dissolved inorganic phosphorus (DIP) concentrations in runoff from soil boxes where manures had been surface-applied and subjected to simulated rainfall as measured in this study and by Kleinman et al. (2003, 2002a) and Kleinman and Sharpley (2003) and as predicted by Eq. [2], [3], and [4]. (b) Relationship between runoff to rainfall ratio and dissolved inorganic P concentrations in runoff, expressed as a ratio of the maximum concentration, as measured by Kleinman et al. (2002a).

fully described both inorganic and organic P release from both manures and their composts during rainfall, even over five consecutive events. The organic P predictions are not quite as good as the inorganic P predictions, which is likely because Eq. [2], [3], and [4] were developed from data of inorganic P release from manures.

Dissolved Inorganic Phosphorus Loss in Runoff from Soils with Surface-Applied Manures

Ability of Equations [2], [3], and [4] to Predict Dissolved Inorganic Phosphorus Concentrations in Runoff

Figure 3a compares dissolved inorganic P concentrations in runoff for a single runoff event using several types of soil and surface-applied manures as predicted by Eq. [2], [3], and [4] and as measured in Kleinman et al. (2002a, 2004), the first runoff event of Kleinman and Sharpley (2003) at a manure application rate of 100 kg total manure P ha^{-1}, and the runoff experiments for this study. Clearly, Eq. [2], [3], and [4] by themselves do not accurately predict dissolved inorganic P concentrations in runoff under these conditions. For a given data set, the equations predicted relatively constant values of dissolved inorganic P concentrations in runoff while measured values varied considerably. The ability of Eq. [2], [3], and [4] to predict dissolved inorganic P release from

manures compared with their inability to predict P concentrations in runoff show that they are not able to account for the fate of P after being released from manure and during delivery to the edge of the runoff box.

We found that accounting for two aspects of soil hydrology and manure characteristics could greatly improve the ability of Eq. [2], [3], and [4] to predict dissolved inorganic P concentrations in runoff from surface-applied manures. These two aspects were (i) the varying amounts of runoff relative to the amount of rainfall applied to soil boxes and (ii) the presence of freely draining water in manures that infiltrates into soil upon manure application but before runoff and takes with it any P dissolved in the manure water. The following discussion details these two phenomena.

Effect of the Runoff to Rainfall Ratio on Dissolved Inorganic Phosphorus in Runoff

At the beginning of a rain event when soils are relatively dry and no runoff occurs, P released from manure to rain water will infiltrate into the soil. It is likely that the concentrations of P released from manure are greatest at this point. As soils become wetter and runoff

Table 1. Changes in runoff volume and dissolved inorganic phosphorus (DIP) concentrations in runoff for five incremental samples collected from soil boxes with surface-applied manures.

Elapsed time of runoff	Dairy		Swine		Poultry	
	Runoff DIP	Runoff	Runoff DIP	Runoff	Runoff DIP	Runoff
min	mg L^{-1}	L	mg L^{-1}	L	mg L^{-1}	L
5–10	22.2	1.2	37.1	1.4	42.7	1.1
10–15	13.2	1.2	28.2	1.2	28.1	1.1
15–20	13.3	1.2	21.6	1.2	21.9	1.1
20–25	10.8	1.2	17.9	1.2	19.9	1.1
25–30	8.8	1.2	15.6	1.2	16.5	1.1

begins, only a small proportion of rainfall is converted to runoff. At this point, P released from manure both enters the soil in infiltrating water and moves over the soil in runoff. Eventually, when soils become saturated, most of the rainfall is converted to runoff, and nearly all the P released from manure moves in runoff. At this point, P concentrations leaving manure will be significantly less than at the initial stages of the rainfall event (Sharpley and Moyer, 2000).

This phenomena of high initial P release from manure followed by decreasing P release is supported by data collected from our newly conducted runoff experiments. In this study, poultry, dairy, and swine manures were surface-applied to soil boxes at a rate of 100 kg total manure P ha^{-1} and subjected to simulated rainfall until 30 min of runoff had been collected. This provided the same conditions as the previous studies of Kleinman et al. (2002a, 2004) and Kleinman and Sharpley (2003), except that runoff was collected in discrete 5-min increments instead of one bulk sample. For all manures, incremental runoff volumes were fairly constant after 10 min, but incremental dissolved inorganic P concentrations in runoff were decreasing (Table 1).

The ultimate result of increasing incremental runoff relative to rainfall and decreasing incremental P release from manure during a runoff event is that the greater the ratio of total event runoff volume to total event rainfall volume, the greater the mean event P concentrations in runoff. This phenomenon is well-supported by the data of Kleinman et al. (2002a), which show that the mean event dissolved inorganic P concentration in runoff was greater when total event runoff volume (5.7–6.7 L) approached total event rainfall volume (8 L) than when runoff volumes were much less (0.3–1.4 L) relative to rainfall volumes. These data are shown in Fig. 3b where the absissa represents the ratio of runoff to rainfall. The ordinate represents the ratio of mean event dissolved inorganic P in runoff for a single soil–manure box to the maximum mean P in runoff observed for all soil boxes treated with that manure type. Both Pierson et al. (2001a) and Pote et al. (2001) observed the same phenomenon when monitoring P in runoff from soils where either poultry litter or swine manure had been surface-applied.

Figure 3a shows that Eq. [2], [3], and [4] essentially predict a constant rate of P release from manure for a rain event. Therefore, when all rainfall is converted to runoff, the equations provide a good prediction of dissolved inorganic P concentrations in runoff. However, when little rainfall is converted to runoff, the equa-
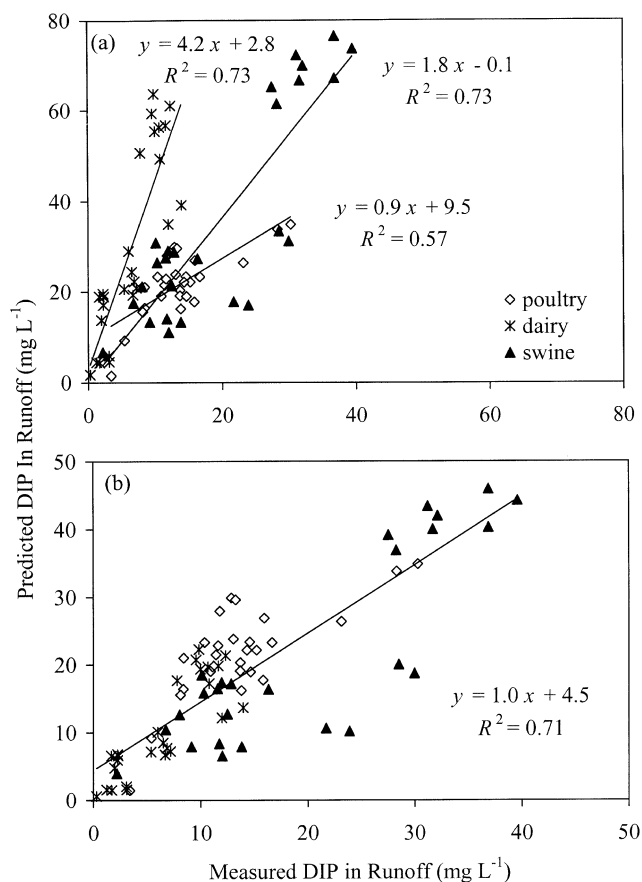

Fig. 4. Relationship between dissolved inorganic phosphorus (DIP) concentrations in runoff from soil boxes where manures had been surface-applied and subjected to simulated rainfall as measured in this study and by Kleinman et al. (2003, 2002a) and Kleinman and Sharpley (2003) and as predicted by Eq. [2], [3], and [4] with (a) an adjustment for the ratio of runoff to rainfall, and (b) a second adjustment based on the initial infiltration of manure dissolved P in the freely draining liquid of swine and dairy manures.

tions overpredict dissolved inorganic P concentrations in runoff. To account for increasing incremental runoff relative to rainfall and decreasing incremental P release from manure over a runoff event, we multiplied the concentrations of dissolved inorganic P in runoff predicted by Eq. [2], [3], and [4] for the data of our newly conducted runoff experiments and the experiments of Kleinman et al. (2002a, 2004), and the first runoff event of Kleinman and Sharpley (2003) where manure was applied at a rate of 100 kg total manure P ha^{-1} (Fig. 3a) by the ratio of runoff to rainfall. The predictions in Fig. 4a are much improved compared with those in Fig. 3a. However, runoff dissolved inorganic P concentrations for dairy and swine manures are overpredicted, while predictions for poultry manures are good. The disparity of these results leads to the second issue of the effect of manure characteristics on dissolved inorganic P in runoff.

Effect of Manure Characteristics on Runoff Dissolved Inorganic Phosphorus

In the newly conducted runoff box experiments and the experiments of Kleinman et al. (2002a, 2004) and Kleinman and Sharpley (2003), swine manures had an

average water content of 97%, dairy manures 84%, and poultry manures 54%. Therefore, swine and dairy manures were slurries that had large quantities of water that could freely drain into the soil when the manures were surface-applied. Conversely, the poultry manure had very little, if any, freely draining water. For all manures, manure water-extractable P in Eq. [2], [3], and [4] were measured by extracting fresh manures with water at an added deionized water to manure ratio of 200:1 for 60 min. For the dairy and swine manures, this procedure measured P both dissolved in the manures' freely draining liquid and associated with the manures' solids. Upon application of these manures to soils, dissolved P in the freely draining liquid portion of the manure should have infiltrated into the soil, leaving only the P associated with the wet manure's solids on the soil surface. Therefore, the quantity of P associated with solids, which is less than that determined by water extractions for the entire fresh manures, should have been used for manure water-extractable P in Eq. [2], [3], and [4].

Hill and Baier (2000) determined the fraction of P dissolved in the freely draining liquid portion of swine manure that had a water content of 98%. They found that as much as 80% of the water-extractable P in swine manure was in the freely draining liquid phase. In a series of experiments designed to determine how much of a manure slurry's water-extractable P is in its freely draining liquid phase, Vadas (unpublished data, 2003) observed that for dairy slurries, roughly 65% of water-extractable P is in the liquid phase; and for swine slurries, roughly 40% of water-extractable P is in the liquid phase.

In the 72 h between manure application and runoff events in our studies, this infiltrated P should have reacted with the soil and become much less available to loss in runoff compared with the P in the manure solids left on the soil surface. Westerman and Overcash (1980) applied liquid poultry and swine wastes to soils and flushed them with runoff water at different initial times ranging from 1 h to 3 d after application. They found that P concentrations in runoff at 1 h averaged 32 mg L^{-1} and were on average 15 times greater than P concentrations in runoff at 3 d. At 3 d, P concentrations in runoff from treated soils averaged three times those in runoff from control soils. Similarly, Edwards and Daniel (1993a) applied liquid swine manure to pasture plots at a rate of 46 kg total manure P ha^{-1} and collected runoff from simulated rainfall at initial times of 4, 7, and 14 d after application. They found that delaying the time to runoff had no effect on P concentrations in runoff, which averaged 12.9 mg L^{-1}, suggesting that any manure P that had infiltrated into the soil upon application had fully reacted within 4 d. Phosphorus concentrations in runoff from treated soils were about seven times those of control soils. Comparatively, Edwards and Daniel (1993b) applied liquid swine manure to pasture plots at a rate of 38 kg total manure P ha^{-1}, which is 17% less than Edwards and Daniel (1993a), and measured P concentrations in runoff after 24 h of 29.7 mg L^{-1}, which is 2.3 times greater than Edwards and Daniel (1993a).

The findings of Edwards and Daniel (1993a, 1993b) and Westerman and Overcash (1980) suggest that when the dairy and swine manures were surface-applied to soils in our investigated runoff box studies, water-extractable P in the freely draining manure liquid infiltrated into the soil, reacted with soil over the 72 h between manure and rainfall application, and became less available to runoff. This reaction was likely rapid enough that subsequent loss of dissolved inorganic P in runoff was much more from wet manure solids remaining on the soil surface than from the underlying soil. Even though the soil P likely increased from manure additions, it is unlikely that desorption of P from the soils accounted for a large proportion of the observed P loss in runoff. Kleinman et al. (2002a) clearly showed that compared with unamended soils, dissolved inorganic P concentrations in runoff are greater when manures are incorporated into soils. However, these incorporated runoff P concentrations are still much less compared with runoff P concentrations when manures are left unincorporated on soil surfaces. In their study, dissolved P concentrations in runoff after incorporating manures into soils averaged only 5% of dissolved P concentrations in runoff when manures were unincorporated. This discussion is not intended to suggest that soils will not contribute environmentally significant quantities of dissolve inorganic P to surface runoff. To the contrary, a vast amount of literature shows that soils with high concentrations of P are significant sources of dissolved inorganic P loss in runoff (Sharpley et al., 2002). However, the studies referenced above show that when manures are left unincorporated on the soil surface, their release of dissolved inorganic P to runoff is likely to overwhelm the release of dissolved inorganic P by the underlying soil.

For our predictions using the runoff data of newly conducted experiments and experiments of Kleinman et al. (2002a, 2004) and the first runoff event of Kleinman and Sharpley (2003) where manure was applied at a rate of 100 kg total manure P ha^{-1}, we multiplied measured values for manure water-extractable P in Eq. [2], [3], and [4] by 0.35 for dairy manures and 0.60 for swine manures. These adjustment factors are based on the results of Hill and Baier (2000) and the observations of Vadas (unpublished data, 2003) and represent the fact that 65% of water-extractable P in the diary slurries and 40% in the swine slurries were dissolved in the freely draining water. This P infiltrated into the soil upon slurry application and was rendered significantly less available to runoff between the time of slurry application and the beginning of simulated rainfall. No adjustment was made for the poultry manure because there was no freely draining water available for infiltration. The results of the 0.35 or 0.60 adjustment factor are shown in Fig. 4b. Compared with the results in Fig. 4a, there is now good prediction of dissolved inorganic P in runoff for all three manure types.

Figure 5 compares dissolved inorganic P concentrations in runoff for three consecutive runoff events using two types of soil and poultry, dairy, and swine manures surface-applied at five different rates as predicted by Eq. [2], [3], and [4] and as measured by Kleinman and

Sharpley (2003). The predictions for the first runoff event have been adjusted by factors of 0.35 for dairy manures and 0.60 for swine manures to account for immediate infiltration of P in the freely draining water of the manures. Predictions for all events have been adjusted by the runoff to rainfall ratio. Figure 5 shows that Eq. [2], [3], and [4], with appropriate adjustments, are able to accurately predict dissolved inorganic P concentrations in runoff from different soil types where three different manures have been surface-applied at several different rates and have been subjected to three consecutive runoff events.

When adjusted for the effect of runoff to rainfall ratio and the effect of freely draining water and subsequent P infiltration, Eq. [2], [3], and [4] exhibit a wide flexibility for accurately predicting inorganic P concentrations in runoff from surface-applied manures. The final versions of these equations are:

$$\text{dairy: runoff dissolved P} = [(0.24W^{0.27})$$
$$(\text{manure water-extractable P})$$
$$(\text{runoff/rainfall}) \times 0.35]/W \qquad [5]$$

$$\text{poultry: runoff dissolved P} = [(0.003W + 0.32)$$
$$(\text{manure water-extractable P})$$
$$(\text{runoff/rainfall})]/W \qquad [6]$$

$$\text{swine: runoff dissolved P} = [(0.004W + 0.23)$$
$$(\text{manure water-extractable P})$$
$$(\text{runoff/rainfall}) \times 0.60]/W \qquad [7]$$

where runoff dissolved P is in mg L^{-1} and manure water-extractable P is in mg kg^{-1}. From a modeling perspective, the only input data required for such predictions are the mass of manure on the soil surface on a dry-weight basis, the water-extractable P content of the manure, and the amount of rainfall and runoff. The only variable that may currently be unknown to most models or modelers is manure water-extractable P. However, this variable is easy to measure, and manure databases are increasingly reporting manure water-extractable P, as this property largely controls P loss in runoff from manured soils (Kleinman et al., 2002b; Wolf et al., 2002). However, this manure water extractable data should be taken from extractions conducted at a water to manure ratio of 250:1 ($cm^3 g^{-1}$) for 60 min. This water to manure ratio takes into account both liquid already present in the manure and added deionized water. Several states currently offer a P solubility test as part of their manure testing program, which provides information to determine the manure P availability factor used in the several adopted indices to identify and rank the risk of P loss from agricultural areas (Sharpley et al., 2003). Finally, the 0.35 or 0.60 adjustment factor for the dairy and swine manures should be used for only the first rainfall event. For subsequent events, this adjustment factor should be omitted.
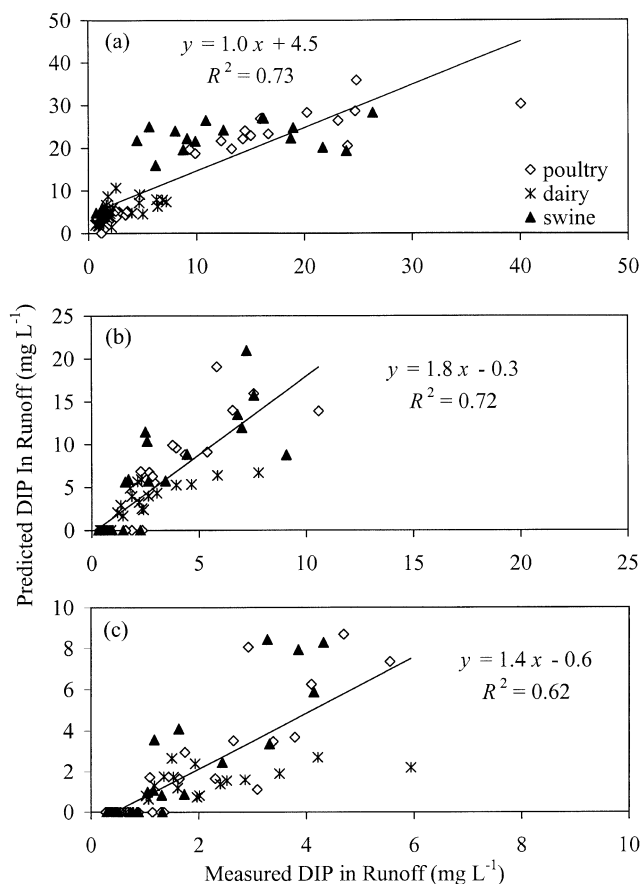

Fig. 5. Relationship between dissolved inorganic P concentrations in runoff from soil boxes where manures had been surface-applied and subjected to simulated rainfall as measured by Kleinman and Sharpley (2003) and as predicted by Eq. [2], [3], and [4] with adjustment factors for (a) a first runoff event 72 h after manure application, (b) a second consecutive runoff event 10 d after manure application, and (c) a third consecutive runoff event 24 d after manure application. DIP, dissolved inorganic phosphorus.

CONCLUSIONS

Phosphorus loss from agricultural soils to surface water continues to be an environmental concern. Intensive research has made significant progress toward understanding the sources and transport pathways of P export from agricultural areas. However, less progress has been made in incorporating this improved understanding into existing computer simulation models. This is especially true for P loss from areas subject to surface application of animal manures. We have developed a simple approach to predict dissolved P release from manures based on manure water-extractable P concentration and the amount of rain water that interacts with the manures. The approach provided a good prediction of dissolved inorganic and organic P release from manures and composts, but a poor prediction of dissolved inorganic P concentrations in runoff from soils where manures had been surface-applied. However, when predicted values of dissolved runoff P were adjusted for the effect of runoff to rainfall ratio and the effect of immediate infiltration of manure P in freely draining manure water, there was very good agreement between measured and predicted

values of dissolved runoff P. Overall, the relative simplicity and success of our approach to predict dissolved P loss from soils where manures have been surface-applied suggest it has potential to improve water quality models attempting to simulate these critical practices. However, further testing of the approach under natural rainfall conditions at field scale should be conducted before its incorporation into water quality models.

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