Runoff Phosphorus Losses from Surface-Applied Biosolids
H. A. Elliott,* R. C. Brandt, and G. A. O’Connor

ABSTRACT

Runoff losses of dissolved and particulate phosphorus (P) may occur when rainfall interacts with manures and biosolids spread on the soil surface. This study compared P levels in runoff losses from soils amended with several P sources, including 10 different biosolids and dairy manure (untreated and treated with Fe or Al salts). Simulated rainfall (71 mm h⁻¹) was applied until 30 min of runoff was collected from soil boxes (100 × 20 × 5 cm) to which the P sources were surface applied. Materials were applied to achieve a common plant available nitrogen (PAN) rate of 134 kg PAN ha⁻¹, resulting in total P loading rates from 122 (dairy manure) to 555 (Syracuse N-Viro biosolids) kg P ha⁻¹. Two biosolids produced via biological phosphorus removal (BPR) wastewater treatment resulted in the highest total dissolved phosphorus (13-21.5 mg TDP L⁻¹) and total phosphorus (18-27.5 mg TP L⁻¹) concentrations in runoff, followed by untreated dairy manure that had statistically (p < 0.05) higher TDP (8.5 mg L⁻¹) and TP (10.9 mg L⁻¹) than seven of the eight other biosolids. The TDP and TP in runoff from six biosolids did not differ significantly from unamended control (0.03 mg TDP L⁻¹ and 0.95 mg TP L⁻¹). Highest runoff TDP was associated with P sources low in Al and Fe. Amending dairy manure with Al and Fe salts at 1:1 metal-to-P molar ratio reduced runoff TP to control levels. Runoff TDP and TP were not positively correlated to TP application rate unless modified by a weighting factor reflecting the relative solubility of the P source. This suggests site assessment indices should account for the differential solubility of the applied P source to accurately predict the risk of P loss from the wide variety of biosolids materials routinely land applied.

More than six million metric tons of biosolids are generated annually in the United States (Epstein, 2003), and they are frequently applied to cropland to provide nutrients and organic matter to the soil. Biosolids are typically applied at rates to supply the nitrogen (N) requirements of crops. These application rates result in excessive phosphorus (P) additions due to the imbalance of N and P in biosolids relative to crop needs. While not usually an agronomic problem, elevated soil P can increase the risk of off-site migration of P to aquatic systems, increasing the rate of eutrophication in freshwater systems (Carpenter et al., 1998). Phosphorus moves from agricultural fields in dissolved form or attached to soil particles, the latter being predominant in many situations. However, dissolved P in runoff from intensively farmed areas, particularly those with extensive histories of manure application, can exceed critical levels that trigger eutrophic effects in surface waters (McDowell and Sharpley, 2001).

A recent survey by Shober and Sims (2003) found that 24 states have existing regulations to limit biosolids application rates based on P levels in the soil. These states typically have established numerical environmental thresholds of soil test P levels beyond which biosolids application is prohibited. However, the current consensus among states is that a comprehensive approach using P site indices is a more effective way to identify agricultural fields vulnerable to P loss. These P site indices evaluate the relative risk to P loss based on site characteristics influencing P transport, the type of P source applied, and various crop and management practices (Lemunyon and Gilbert, 1993; Leytem et al., 2004). According to Sharpley et al. (2003), 47 states have adopted a P index approach. Although efforts so far have targeted manures and commercial fertilizers, P-based management will likely apply to all land-applied residuals including biosolids. Relatively few states have explicitly addressed biosolids, despite the prevalence of land application for biosolids disposal. This is unfortunate since the solubility, bioavailability, and transport potential of P vary significantly among biosolids types (Leytem et al., 2004; Brandt et al., 2004). Coale et al. (2002) predicted that P indices will be deployed as regulation long before being objectively validated. Quantifying P losses from application of biosolids to agricultural land is critical to promote scientifically sound P management policies.

Recent studies have used simulated rainfall onto packed soil boxes and field plots to evaluate P transport in surface runoff (Kleinman and Sharpley, 2003; Kleinman et al., 2004). Runoff dissolved P concentrations from simulated rainfall have been found to be correlated to the water-extractable phosphorus (WEP) content of the organic P source (Kleinman et al., 2002b; Brandt and Elliott, 2003). The WEP content of manures and biosolids treated with Al and Fe salts or by-products is lower than their untreated counterparts (Codling et al., 2000; Elliott et al., 2002; Sims and Luka-McCafferty, 2002). Penn and Sims (2002) found that biosolids containing high amounts of Fe consistently had the lowest WEP and exhibited the lowest runoff dissolved P when added to soils. Besides metal salt additions, other processes used in wastewater treatment and biosolids generation influence biosolids P solubility and runoff potential (Penn and Sims, 2002; Brandt et al., 2004).

The objective of this study was to determine P levels in runoff from soil amended with biosolids and dairy manure under simulated rainfall. Selected biosolids represented a wide range of materials routinely applied to

Abbreviations: BPR, biological phosphorus removal; PAN, plant available nitrogen; PP, particulate phosphorus; PSC, phosphorus source coefficient, TDP, total dissolved phosphorus; TP, total phosphorus; WEP, water-extractable phosphorus.
agricultural soils. Most simulation studies (Penn and Sims, 2002; Kleinman et al., 2004; Leytem et al., 2004) employ a common total P application rate; however, this study examined P loss from organic P sources applied at a common plant available N rate, consistent with biosolids recycling practice. A further objective was to provide quantitative evidence for the use of weighting coefficients in P site assessment indices to reflect differences in P solubility of organic amendments.

MATERIALS AND METHODS

Soil and Phosphorus Source Collection and Characterization

The surface horizon (0-20 cm) of Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) soil was collected, sieved (6.4 mm), air-dried, and mixed for use in the runoff experiments. The soil was analyzed (Table 1) by standard methods through the Penn State Agricultural Analytical Service Laboratory. Total elemental contents was determined using acid digestion (USEPA Method 3051) followed by elemental analysis via inductively coupled plasma (ICP) (USEPA Method 6010). Mehlich-3 extracts (Mehlich, 1984) were also analyzed using ICP.

Ten biosolids from eight wastewater treatment plants were chosen to represent the range of materials typically applied to agricultural soils. Two biosolids, Largo pellets and Danville limed cake, were also selected to assess the effects of heat-drying and lime stabilization on runoff P loss. Three biosolids cake materials (Bellefonte, Danville, and University) were generated by conventional aerobic or anaerobic digestion stabilization. The Largo facility employs biological phosphorus removal (BPR) where the P removed from wastewater as part of the microbial biomass, is highly water soluble (Brandt et al., 2004). Three materials were used as heat-dried pellets (Largo, Patapasco, Back River) and the Syracuse biosolids was processed by advanced alkaline stabilization (the N-Viro process; N-Viro International, Toledo, OH).

Total Al, Fe, Ca, and P of the P sources was determined by acid digestion followed by elemental analysis via ICP using USEPA Methods 3051 and 6010, respectively (USEPA, 2000). Total N was determined by combustion at 1100°C using an Elementar (Hanau, Germany) CNS Analyzer. Solids content (103–105°C, 15 h) and pH (1:2 P source to distilled water) were determined by standard methods. All analyses noted above were performed in duplicate and rerun when results differed by more than 15%.

For WEP analysis, distilled and deionized water was added to 0.5 g (dry weight equivalent) of P source (as received) to give a 1:200 solid to solution ratio. Samples were agitated for 1 h at room temperature (end-over-end shaker at approximately 15 rpm), centrifuged (15 min at approximately 1250 rpm), and vacuum-filtered through prewetted 0.45-μm filter paper. Samples were prepared for ICP analysis by adding 0.5 mL HCl (1:1) to 24.5 mL of filtrate. Two replicates of WEP extractions were performed.

All P sources were applied to the soil trays at a rate equivalent to 134 kg PAN ha⁻¹, a typical recommendation for corn in Pennsylvania. For the biosolids, agronomic N availability was based on state regulatory prescriptions for ammonia availability and organic N mineralization. Dairy manure N availability was based on recommendations provided in Beegle (2002). The resulting P application rates ranged from 122 (dairy manure) to 555 (Syracuse N-Viro biosolids) kg P ha⁻¹ (Table 2).

The dairy manure was treated with alum and FeCl₃ solutions, designated as DMA and DMF, respectively. Just before application of the manure to the soil boxes, the salt solutions were mixed into the manure such that the combined molar concentrations of the added Al and Fe were equal to the total molar P in the dairy manure (0.18 mol P kg⁻¹).

Table 1. Properties of unamended Hagerstown soil.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.2</td>
</tr>
<tr>
<td>Acidity, cmol kg⁻¹</td>
<td>2.0</td>
</tr>
<tr>
<td>Caution exchange capacity, cmol kg⁻¹</td>
<td>12.6</td>
</tr>
<tr>
<td>Water-extractable P, mg kg⁻¹</td>
<td>0.02</td>
</tr>
<tr>
<td>Elemental levels, g kg⁻¹</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>32.9</td>
</tr>
<tr>
<td>Fe</td>
<td>26.2</td>
</tr>
<tr>
<td>Ca</td>
<td>2.2</td>
</tr>
<tr>
<td>Mg</td>
<td>3.6</td>
</tr>
<tr>
<td>P</td>
<td>0.90</td>
</tr>
<tr>
<td>Mehlich-3 extractable, mg kg⁻¹</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>95.0</td>
</tr>
<tr>
<td>K</td>
<td>299.0</td>
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<tr>
<td>Mg</td>
<td>168.0</td>
</tr>
<tr>
<td>Ca</td>
<td>1694</td>
</tr>
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Table 2. Phosphorus source characteristics and loadings.

<table>
<thead>
<tr>
<th>P source</th>
<th>Label</th>
<th>Description</th>
<th>WEP †</th>
<th>Solids</th>
<th>Al/kg tray⁻¹</th>
<th>Fe/kg tray⁻¹</th>
<th>Ca/kg tray⁻¹</th>
<th>N/kg tray⁻¹</th>
<th>P/kg tray⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>University cake</td>
<td>UC</td>
<td>conventional treatment without Al/Fe addition</td>
<td>0.36</td>
<td>12.2</td>
<td>5.5</td>
<td>9.1</td>
<td>32.8</td>
<td>70.9</td>
<td>17.6</td>
</tr>
<tr>
<td>Danville cake</td>
<td>DC</td>
<td>anaerobic digestion</td>
<td>0.38</td>
<td>12.7</td>
<td>11.1</td>
<td>15.1</td>
<td>25.6</td>
<td>65.8</td>
<td>19.8</td>
</tr>
<tr>
<td>Largo pellets</td>
<td>LP</td>
<td>heat-dried BPR</td>
<td>4.55</td>
<td>94.6</td>
<td>5.9</td>
<td>10.4</td>
<td>22.6</td>
<td>73.5</td>
<td>34.9</td>
</tr>
<tr>
<td>Danville limed cake</td>
<td>DL</td>
<td>lime stabilized</td>
<td>0.20</td>
<td>26.8</td>
<td>5.0</td>
<td>5.4</td>
<td>115.0</td>
<td>26.8</td>
<td>8.6</td>
</tr>
<tr>
<td>Patapasco (Baltimore) pellets</td>
<td>PB</td>
<td>heat-treated, low Fe</td>
<td>0.64</td>
<td>95.0</td>
<td>7.5</td>
<td>12.5</td>
<td>13.3</td>
<td>58.1</td>
<td>17.2</td>
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<tr>
<td>Largo cake</td>
<td>LC</td>
<td>BPR wet-side processing</td>
<td>6.76</td>
<td>16.9</td>
<td>5.5</td>
<td>9.2</td>
<td>22.6</td>
<td>78.2</td>
<td>33.4</td>
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<tr>
<td>Bellefonte cake</td>
<td>BC</td>
<td>aerobic digestion, high Al</td>
<td>1.31</td>
<td>15.3</td>
<td>25.9</td>
<td>7.3</td>
<td>20.6</td>
<td>63.8</td>
<td>29.4</td>
</tr>
<tr>
<td>Back River (Baltimore) pellets</td>
<td>BR</td>
<td>heat-treated, high Fe</td>
<td>0.26</td>
<td>90.1</td>
<td>5.9</td>
<td>15.1</td>
<td>31.4</td>
<td>53.7</td>
<td>29.4</td>
</tr>
<tr>
<td>Philadelphia cake</td>
<td>PC</td>
<td>anaerobic digestion, high Fe</td>
<td>0.19</td>
<td>26.3</td>
<td>14.3</td>
<td>72.3</td>
<td>18.7</td>
<td>36.9</td>
<td>26.4</td>
</tr>
<tr>
<td>Syracuse N-Viro</td>
<td>SN</td>
<td>advanced alkaline stabilization</td>
<td>0.01</td>
<td>60.5</td>
<td>8.2</td>
<td>21.9</td>
<td>26.0</td>
<td>7.2</td>
<td>6.7</td>
</tr>
<tr>
<td>Dairy manure</td>
<td>DM</td>
<td>fresh dairy manure</td>
<td>3.41</td>
<td>13.0</td>
<td>1.3</td>
<td>1.5</td>
<td>22.3</td>
<td>33.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Dairy manure + Fe</td>
<td>DMF</td>
<td>FeCl₃-treated dairy manure</td>
<td>1.07</td>
<td>13.0</td>
<td>1.3</td>
<td>11.8</td>
<td>22.3</td>
<td>33.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Dairy manure + Al</td>
<td>DMA</td>
<td>alum-treated dairy manure</td>
<td>0.31</td>
<td>13.0</td>
<td>6.3</td>
<td>1.5</td>
<td>22.3</td>
<td>33.1</td>
<td>5.7</td>
</tr>
</tbody>
</table>

† Water-extractable P.
‡ Phosphorus source coefficient from the Pennsylvania P index. A PSC value of 0.1 for Syracuse N-Viro, though not currently in the index, has been proposed for P sources with extremely low WEP.
§ Biological phosphorus removal.
**Rainfall Simulation Experiment**

The rainfall simulation followed the National Phosphorus Research Project indoor runoff box protocol (National Phosphorus Research Project, 2001). Stainless steel runoff trays (20 × 100 × 7.5 cm deep) were packed with 5 cm of the soil and the P sources were uniformly applied to the surface of the soil. Three trays were prepared for each treatment and three trays with unamended soils served as controls. The trays were first saturated until ponding was observed and the rainfall events were conducted 3 and 5 d after the initial wetting. Trays were sloped at 3% and rainfall was delivered at 71 mm h⁻¹. For each event, the initial 30 min of runoff was collected and a subsample was immediately filtered (0.45 μm) and acidified (pH < 2). Total dissolved phosphorus (TDP) was determined on the filtered samples by ICP. Total phosphorus (TP) was measured on the unfiltered runoff samples by ICP following digestion using USEPA Method 3051 (USEPA, 2000). The difference between TP and TDP for any sample was assumed to represent particulate phosphorus (PP). Two rainfall-runoff simulations were performed, but discussion focuses on the first rainfall event since most P is lost in the initial rainfall event for biosolids-amended soils (Sims et al., 2003). Since differential effects of P sources are generally the same based on runoff P loads (mg) or concentrations (mg L⁻¹) (Kleiman et al., 2002a), we have, like other recent rainfall simulation studies (Kleiman and Sharpley, 2003), confined the discussion to runoff P concentrations.

**RESULTS AND DISCUSSION**

**Soil and Phosphorus Source Properties**

General properties and elemental levels for the soil are shown in Table 1. The Mehlich-3 P concentration (95 mg kg⁻¹) exceeded typical crop nutritional requirements (Beegle, 2002), but fresh P-source additions tend to mask impacts initial soil test P levels have on runoff dissolved P (Andraski and Bundy, 2003). The Hagerstown is typical of arable soils in Pennsylvania, and has been used in other P runoff studies (McDowell and Sharpley, 2003).

Although nutrient content, physical properties, and chemical constituents differ because of various wastewater and stabilization processes (Table 2), the biosolids used in this study are typical of those produced nationally and applied to agricultural land (USEPA, 1995). The solids content ranged from dewatered moist “cake” materials (13–27%) to heat-dried products (>90%). Mean total P content for the biosolids was 23 g kg⁻¹, in close agreement with median P of 22 g kg⁻¹ reported by Stehouwer et al. (2000) for all biosolids submitted during 1997 to the Penn State Agricultural Analytical Services Laboratory. Lower concentrations of P in Danville limed cake (DL) and Syracuse N-Viro (SN) reflect dilution from addition of lime and alkaline by-products. The WEP levels in the biosolids were typically below 1 g kg⁻¹, with the BPR-produced Largo materials being significantly higher. The Al and Fe contents were variable, reflecting additions of Al₂O₃ and Fe-salts in wastewater treatment and solids processing or, in the case of Philadelphia cake (PC), the discharge of Fe-based water treatment residuals to sanitary sewers. The TP and WEP of the dairy manure fall within the range of values previously reported (Sharpley and Moyer, 2000; Brandt et al., 2004).

**Phosphorus Source Effects on Runoff Phosphorus**

The effect of P sources on TDP and TP concentrations in runoff followed a similar trend for the first (Fig. 1a) and second rainfall events (Fig. 1b). The P concentrations in runoff were generally lower for the second event, however. Other studies have documented that total and dissolved P in runoff decreased with successive rainfall events following surface application of livestock manures (Sharpley, 1997) and biosolids (Rostagno and Sosebee, 2001; Penn and Sims, 2002). For biosolids-amended field plots, Sims et al. (2003) found the initial event accounted for 52 to 73% of the total runoff P collected over four rainfall events.

Most of the runoff P in the unamended control treatments was in the particulate form with <10% as TDP. However, where P sources were surface-applied, the proportions of TDP in runoff increased to 12 to 84% of TP. Because the P sources had variable N and solids contents, trays received different dry matter application rates (Table 2). Sources that effectively covered the tray surface (e.g., dairy manure) had particulate phosphorus (PP) lower than that of the control treatments, likely due to a melching effect on the soil surface. For such P sources, the PP was likely derived primarily from the P source rather than from the soil. For three P sources with the lowest mean TDP levels (PC, UC, and SN), the proportion of PP to TDP was much greater than P sources with high TDP concentrations. Withers et al. (2001) similarly found that surface-applied P sources with the lowest TP losses had higher proportions of particulate P than dissolved P loss.

Although the dairy manure (DM) had the lowest total P rate (122 kg P ha⁻¹), it had greater TDP than all biosolids except the Largo cake and pellets (LC, LP), and the Baltimore Patapasco pellets (PB). The generally greater P concentration for dairy manure compared with biosolids was shown previously where the P sources were all applied at 100 kg P ha⁻¹ (Brandt and Elliott, 2003). In this study, the lower water solubility of the P in most biosolids offset the higher total P application rates relative to the dairy manure. The TDP of the PB was statistically comparable with the dairy manure treatment, despite a 61% greater total P application rate for PB. Notably, the TP and TDP for six of the biosolids treatments (UC, DC, DL, BR, PC, SN) applied at 154 to 555 kg P ha⁻¹ were not statistically different from the control soil treatment (Fig. 1). Elsewhere, Withers et al. (2001) reported that P in runoff from biosolids-treated field plots was not significantly different from the control plot.

The Largo BPR materials (LP and LC) produced statistically greater TDP and TP than the dairy manure treatment (Fig. 1). As a category, BPRs have the greatest WEP values among biosolids types (Brandt et al., 2004). The WEP values for the LP and LC biosolids were 4.55 and 6.76 g kg⁻¹, respectively. The greater...
Fig. 1. Effect of P source on total dissolved phosphorus (TDP) and total phosphorus (TP) concentrations in runoff of (a) Rainfall Event 1 and (b) Rainfall Event 2. LP, Largo pellets; LC, Largo cake; DM, dairy manure; PB, Patapsco Baltimore pellets; BC, Bellefonte cake; DMA, aluminum-treated dairy manure; DMF, iron-treated dairy manure; BR, Back River Baltimore pellets; DC, Danville cake; DL, Danville limed cake; PC, Philadelphia cake; UC, University cake; C, control; SN, Syracuse N-Viro cake.

WEP values of the LC and LP coupled with the higher total P application rates to meet the common PAN requirement (Table 2) resulted in greater TDP compared with the dairy manure (WEP = 3.41 g kg⁻¹). However, the low WEP for most biosolids (WEP < approximately 1 g kg⁻¹) suggests lower P runoff potential compared with typical livestock manures, assuming biosolids and dairy manure have no effect on runoff amount. Penn and Sims (2002) also found that biosolids produced by treatment of wastewater using biological nutrient removal exhibited the greatest TDP in runoff from rainfall simulation experiments.

The Danville cake and limed biosolids (DC and DL) exhibited TDP and TP concentrations that were not statistically different (Fig. 1) where P application rates were nearly identical (Table 2). Other studies have generally found that P solubility is greater in soils amended with limed biosolids, at least relative to Fe- or Al-dominated biosolids systems (Penn and Sims, 2002). Jokinen (1990) assessed the influence of treatment process on extractable soil P in biosolids-amended soils and concluded that, while Al-sludges tended to reduce P solubility, Ca-sludge increased soluble P values in soils. Soon and Bates (1982) reported that the extractability of P from soils amended with chemically treated, anaerobically digested sludges followed the order: Ca-sludge > Fe-sludge ≥ Al-sludges. The presence of lime in biosolids treated with metal salts tended to result in higher
water soluble P in the amended soils (Maguire et al., 2000). Leytem et al. (2004) suggested that the higher solubility was due to the release of Ca–P complexes in response to the acidity of the amended soils. Such a mechanism would not apply to our study since the materials were not incorporated into the soil. In this case, the similar runoff P concentrations from the limed and unlimed Danville biosolids (Fig. 1) reflects the nearly equal WEP values (Table 2).

The Syracuse N-Viro (SN) had the greatest total P application rate (555 kg P ha\(^{-1}\)), but resulted in negligible soluble P in runoff (Fig. 1). This was a reflection of the extremely low WEP concentration (0.01 g kg\(^{-1}\)) of the N-Viro material (Table 2). Richards et al. (1997) attributed the low extractability and mobility of P in the Syracuse N-Viro product to P precipitation reactions occurring at elevated pH and Ca levels. Advanced alkaline stabilization (e.g., the N-Viro process) involves mixing biosolids with large quantities of alkaline materials so that the mixture is dried and pasteurized though heat generation. Although not statistically different \((p = 0.05)\), the mean TDP and TP concentrations of the SN treatment were lower than the control treatment. Maguire et al. (2000) suggested that some biosolids increase the P sorption capacity of the soils and thus reduce P into runoff and drainage waters.

Treatment of the dairy manure with Al (DMA) or Fe (DMF) reduced P concentrations in runoff by about one-half compared with the unamended manure (Fig. 1). This reduction likely reflected the lower WEP concentrations of the amended dairy manure (Table 2). Alum additions to poultry manure have been shown to reduce runoff P (Moore et al., 1999). Here, we demonstrate that TDP concentrations in runoff can potentially be reduced by adding Al and Fe salts to materials such as dairy manure that have high concentrations of watersoluble P.

The importance of P-source Al and Fe content is further illustrated in Fig. 2, which shows that the TDP levels for the first runoff event were consistently lower when the total molar Al + Fe content of the P sources was high. The critical role of Al and Fe in determining P solubility and release from biosolids-amended soils has been documented previously (Maguire et al., 2001; Brandt and Elliott, 2003). Note that several materials with molar Al + Fe contents about 0.3 to 0.4 had widely varying TDP concentrations. While very high Al + Fe contents may result in low runoff TDP, other factors (P loading rate, wastewater treatment, and solids processing) also influence susceptibility to P loss.

**Effect of Phosphorus Application Rate**

Runoff TDP and TP concentrations generally increase with P application rate when manures are surface broadcast. Edwards and Daniel (1993) reported dissolved reactive phosphorus (DRP) levels in runoff of 0.8, 11.9, and 29.4 mg L\(^{-1}\) from grassed plots broadcast with swine manure at rates of 0, 19, and 38 kg TP ha\(^{-1}\), respectively. Rostagno and Sosebee (2001) found that DRP and TDP in runoff water increased with biosolids application rates (0–90 Mg ha\(^{-1}\)). Kleinman and Sharpely (2003) reported that the concentrations of DRP and TP in runoff increased as the total P application rate from broadcast manures increased from 0 to 150 kg P ha\(^{-1}\). They attributed this to an increase of soluble manure P to runoff water as more manure was applied, because DRP became a higher proportion of runoff TP as application rate increased. The effect was particularly pronounced for total P application rates of >75 kg ha\(^{-1}\).

A positive correlation between runoff dissolved P and application rate (Kleinman and Sharpely, 2003) is logical for a given P-source type since the amount of soluble P available to runoff water is dependent on the application rate. Such a relationship should not necessarily hold for a broad range of P sources where the potential to release P into runoff water is highly variable. Figures 3a and 3b show the TDP and TP concentrations in runoff for
Rainfall Event 1 for all 14 treatments (10 biosolids, 3 manures, and 1 control) as a function of the total P application rate (kg ha\(^{-1}\)). Clearly, there is no positive correlation between runoff P and the total P application rate. The Syracuse N-Viro treatment had the highest total P application rate (555 kg ha\(^{-1}\)), but the lowest TDP concentrations in runoff (<0.1 mg L\(^{-1}\)). There were seven biosolids types with similar total P application rates (approximately 180-220 kg ha\(^{-1}\)), but the mean runoff TDP values ranged from <1 to >20 mg L\(^{-1}\) (Fig. 3a). Others have also shown that biosolids applied at the same total P rate exhibit significantly different runoff P losses (Penn and Sims, 2002; Brandt and Elliott, 2003; Sims et al., 2003).

Runoff P concentrations were related to the WEP levels of the various P sources, however (Fig. 4). For the wide range of materials in this study, WEP and TDP were linearly related \((r^2 = 0.83)\) for the first rainfall event (Fig. 4a). Because TDP comprised most of the TP (Fig. 1a), a similarly strong relationship \((r^2 = 0.81)\) was found between WEP and TP in runoff (Fig. 4b). Kleinman et al. (2002a) observed that dissolved reactive P losses from soils surface-amended with dairy, poultry, and swine manures (all at 100 kg P ha\(^{-1}\)) were proportional to the WEP of the applied P sources. Withers et al. (2001) reported that differences in runoff P from triple superphosphate fertilizer, cattle slurry manure, and two biosolids were more related to their WEP than total P application rates, even though the latter ranged from 150 to 329 kg P ha\(^{-1}\).

Some states (Pennsylvania, Arkansas) use P-source WEP concentration as an indicator of P loss potential in site assessment indices (Weld et al., 2000). In Pennsylvania, the WEP values have been used to develop phosphorus source coefficients (PSCs) as quantitative indicators of the relative availability of the P in land-applied materials to be transported in runoff and drainage. These PSCs are fractional values referenced to mineral fertilizer (i.e., fertilizer PSC = 1.0). In the Pennsylvania P index, PSCs are multiplied by the organic P-source application rate to obtain the fraction of total applied P available for transport. The PSCs for the materials in this study are given in Table 2. When the total P application rate is multiplied by the respective PSC, the materials should theoretically be normalized on a soluble-P application rate basis.

Figures 5a and 5b show that TDP and TP are strongly correlated with total P application rates for multiple sources when multiplied by the respective PSC values. Data clearly illustrate that runoff P losses from most biosolids (8 of 10) are less than from dairy manure (DM), despite greater total P application rates for the biosolids. The BPR biosolids (LC and LP) had greater total P application rates than the DM (Table 2), but also exhibited high concentrations of TDP and TP in runoff. In the current Pennsylvania P index, dairy manure and BPR biosolids both have PSC values of 0.8. The data point for Philadelphia cake (PC) does not fit well in the correlation. This material has exceptionally high Fe (72.3 g kg\(^{-1}\)) for biosolids because Fe-based water treatment residuals are disposed into the sanitary sewers in Philadelphia. Such high Fe causes the WEP to be very low (0.19 mg kg\(^{-1}\)), which translates into low
potential for P loss. The PSC used in this correlation was 0.3 for conventionally treated biosolids because no category currently exists for “high Fe” biosolids in the Pennsylvania P index. The results of Leytem et al. (2004) suggest that biosolids containing high levels of Fe should have lower PSC values than conventionally treated materials.

The correlations in Fig. 5 are remarkably good considering that the PSC values are default values. Actual P sources tend to defy rigid categorization and, ideally, PSC values should be used that are unique to the specific P source under evaluation. Efforts are currently underway to develop algorithms for converting laboratory-determined WEP values into material-specific PSC values for use in P indices. This approach would also resolve the problem of defining compositional thresholds for classifying a material as a “high Fe” biosolids.

CONCLUSIONS

There are significant differences in runoff P concentrations among biosolids types following surface application to soil boxes exposed to simulated rainfall. Experimental conditions mimic spreading of biosolids without incorporation, but Penn and Sims (2002) found differences in runoff P losses even when various biosolids types were mixed thoroughly with soil before simulated rainfall. The P concentration in runoff from biosolids-amended soils depends on the types of wastewater and solids processing methods used to generate the biosolids. Some biosolids types (e.g., BPR products) resulted in higher runoff P concentrations than dairy manure applied at the same PAN rate. Other biosolids, because of additions of Al and/or Fe during wastewater treatment, or through solids processes like heat-drying, produced runoff P losses not statistically different from unamended soil treatments. The data provide strong evidence that the solubility of the P in the organic amendment exerts a major influence on the potential for off-site migration of P at land application sites.

Findings of this and other (Leytem et al., 2004) studies confirm the need to incorporate weighting coefficients into P site indices to reflect the portion of total applied P susceptible to off-site transport. Of the 41 state P indices evaluated by Sharpley et al. (2003), only 9 states (Arkansas, Delaware, Florida, Georgia, Louisiana, Maryland, Pennsylvania, Tennessee, and Virginia) include an estimate of the availability or solubility of the P applied to the site. Of these states, not all make specific reference to biosolids or, if they do, a single coefficient is used for all types of biosolids. If P index use is confined to phosphorus availability, the P index coefficient (PSC) for phosphorus added with biosolids should be increased for high Fe biosolids.

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