Estimating Source Coefficients for Phosphorus Site Indices

H. A. Elliott,* R. C. Brandt, P. J. A. Kleinman, A. N. Sharpley, and D. B. Beegle

ABSTRACT

Phosphorus release to runoff varies widely for different land-applied organic P sources even when spread at equivalent total P rates. To address this variability, some P site indices include tabulated P source coefficients (PSCs) for differential weighting of applied P materials based on their runoff enrichment potential. Because runoff P can vary widely even within source categories depending on composition, storage, and treatment differences, this study explored a method for estimating PSCs based on the water-extractable P (WEP) content of the applied amendment. Using seven published rainfall-runoff studies that followed National Phosphorus Research Project protocols, runoff dissolved P (RDP) was correlated (\(r^2 = 0.80\)) with WEP for multiple surface-applied manures and biosolids. Assuming amendments with WEP > 10 g kg\(^{-1}\) behave as highly soluble P sources and have a maximum PSC of 1.0, an empirical equation was developed for computing source-specific PSCs from laboratory-determined WEP values (PSC = \(0.102 \times \text{WEP}^{0.99}\)). For two independent runoff experiments, correlations between RDP loss and P source loading rate were improved when loading rates were multiplied by the computed (\(r^2 = 0.73-0.86\)) versus generic (\(r^2 = 0.45-0.48\)) PSCs. Source-specific PSCs should enhance the ability of assessment tools to identify vulnerable sites and P loss management alternatives, although the exact inclusion process depends on index scaling and conceptual framework.

Runoff from agricultural areas continues to be a major nonpoint nutrient source contributing to water quality degradation. The widespread development of P site assessment indices, referred to as “P indices,” represents a key advance in managing land application of organic P sources for water quality protection. Nearly all states in the US have adopted a P indexing approach to guiding P-based management (Sharpley et al., 2003). The underlying P index concept is that effective management of agricultural P should target “critical source areas” of watershed P export, where high availability of P to runoff (overland or subsurface) and high transport potential for runoff coincide (Lemunyon and Gilbert, 1993). Although the format of P indices varies across states, all identify “source” and “transport” factors affecting P loss. Key source factors include (a) soil P content, (b) P application rate (mineral and organic sources), (c) method of P application, and (d) timing of P application (Sharpley et al., 2003).

Concentration of runoff P can be dramatically different for applied P sources even when they are spread at equivalent total P (TP) rates. For instance, Moore et al. (2000) observed that concentrations of P in runoff from pasture soils broadcast with poultry litter were nearly three times lower when the same litter was treated with alum to reduce water soluble P in the litter. Thus, the Arkansas P index for pastures considers the water soluble, rather than TP application rate in calculating a site’s P loss vulnerability (DeLaune et al., 2004). Other site assessment tools allow for differential weighting of applied P sources to account for the observation that P release to runoff from applied sources varies significantly (Sharpley et al., 2003). In the context of the P index, the weighting factor that differentiates P sources based on their relative potential to release P into runoff has been called the P source coefficient, or PSC (Leytem et al., 2004). In the index calculation, the PSC of an amendment is multiplied by the TP application rate, with the product viewed as the applied P susceptible to off-site transport. Thus, a PSC, as the fraction of the total applied P available for transport, can take on any value between zero and 1.0. Because the WEP content of the applied material is correlated with dissolved P in runoff (Kleinman et al., 2002a), WEP is seen as a key means of developing PSCs in the P index (Leytem et al., 2004).

To develop PSCs for Pennsylvania’s P index (Weld et al., 2003), studies were conducted in which manures were surface applied to soils at an agronomically high rate of total P (100 kg TP ha\(^{-1}\)) and simulated rainfall was applied within 72 h of manure application to generate runoff (Kleinman et al., 2002a; Kleinman and Sharpley, 2003; Kleinman et al., 2004). On average, similar relationships between dissolved P in runoff and WEP in applied manure were observed in the three studies, which included 10 different soils of varying mineralogies and P sorption properties. In two of the three studies, dissolved P in runoff and WEP followed the trend: swine > layer poultry > dairy (Kleinman et al., 2002a, 2004). In Kleinman and Sharpley (2003), differences in dissolved P in runoff from layer poultry and swine manure treatments were not significant (\(p = 0.05\)), and the WEP of the two manures was quite similar. In Kleinman et al. (2002a), dissolved P in runoff from soils receiving surface applications of mineral fertilizer (diammonium phosphate) did not differ from the swine manure treatment. Based on these results, PSCs for generic categories of manures were standardized relative to the mineral fertilizer, which was expected to represent maximum availability of dissolved P to runoff (i.e., PSC = 1.0). The similar P loss from fertilizer granules and manure slurries has been explained on the basis of differing adsorption potentials of organic and inorganic P forms (Preedy et al., 2001).

Abbreviations: PSC, phosphorus source coefficient; RDP, runoff dissolved phosphorus; TP, total phosphorus; WEP, water-extractable phosphorus.
Additional subcategories of poultry and dairy manures were further distinguished based on the WEP values from a large survey of manures (Kleinman et al., 2006). Alum-treated manures were assigned a unique PSC to reflect the broad body of research documenting reductions in dissolved P losses when alum was applied to manures (Moore et al., 2000; Smith et al., 2001; DeLaune et al., 2004; Elliott et al., 2005). Laboratory and runoff studies with biosolids (Brandt and Elliott, 2003; Brandt et al., 2004) were used to set PSC values for major categories of biosolids (Table 1). For now, only generic PSCs, ranging from a high of 1.0 to a low of 0.2, are permitted in the Pennsylvania P index (Table 1). Runoff dissolved P and TP were not correlated ($r^2 = 0.02$) with the total applied P in the absence of PSCs, but were strongly correlated ($r^2 = 0.71–0.80$) when the application rates of several biosolids and manures were multiplied by their respective table value PSCs (Elliott et al., 2005).

Generic PSCs are suitable when the P loss potential is relatively consistent for a particular category of P source. However, P loss potential as measured by WEP is a dynamic variable influenced by animal diets, storage time and conditions, and treatment such as composting and alum treatment (Vadas et al., 2004). For biosolids, runoff potential varies with wastewater treatment methods, solids dewatering and processing operations, and chemical additions during treatment (Brandt et al., 2004). The contents of Al and Fe have a decisive influence on the WEP, and in turn the P runoff behavior of applied nutrient sources. Treatment of swine (Smith et al., 2001), poultry (DeLaune et al., 2004), and dairy (Elliott et al., 2005) manures with Al and Fe salts have been shown to reduce runoff P. 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. The Fe content of biosolids, however, can vary from ~2 g kg$^{-1}$ (dry weight equivalent) to >83 g kg$^{-1}$ (Brandt et al., 2004). DeLaune et al. (2004) found that mean concentrations of the first runoff event after poultry litter application were 26.0 mg P L$^{-1}$ for untreated poultry litter compared to 15.0, 13.4, and 0.9 mg P L$^{-1}$ for litter treated with 5, 10, and 20% alum, respectively. While the use of generic PSC values for categories of P sources dramatically improves the ability of a P index to discern gross differences in P source runoff potentials, such an approach is unlikely to be generally applicable or practical for the wide range of amendments routinely spread on agricultural soils.

One of the major changes in P index development since the original (Lemunyon and Gilbert, 1993) model has been the inclusion of continuous, rather than discrete input factors (Sharpley et al., 2003). Continuous factors provide for smoother model output and avoid subjectivity in assigning a factor to a particular category. Because it is not realistic to provide discrete PSC values for all types of manures, biosolids, composts, and other land-applied P sources, the predictive capability of P site indices should be improved if PSCs could vary continuously to describe amendments with the entire spectrum of P solubilities. Therefore, the objective of the present work was to describe a methodology for developing source-specific PSCs based on runoff and WEP data. Besides the inherent advantages in predicting P loss vulnerability, the ability to adjust PSCs for individual manures and other by-products by chemical addition and other treatment strategies before land application provides another management option for reducing a site’s P index score.

**MATERIALS AND METHODS**

A substantial body of literature addresses the role of WEP in P runoff, with studies ranging from those that describe the effect of material processing on P solubility to those that describe the inherent runoff potentials of different manures and biosolids. A literature survey was conducted to develop a database relating WEP of applied P sources to dissolved P in runoff. To ensure the comparability of findings, a subset of studies was ultimately selected for our analysis (Table 2). We considered only those studies that were conducted in accordance with the guidelines of the National Phosphorus Research Project (NPRP) protocol (National Phosphorus Research Project, 2006). Both field runoff plots and indoor packed soil box experiments (see below) were considered. Numerous manures (dairy, poultry, swine, and turkey) and biosolids from various wastewater and solids treatment processes have been used in the reported studies with dry matter contents ranging from 31 g kg$^{-1}$ (swine slurry) to 970 g kg$^{-1}$ (heat-dried biosolids). The P sources were surface applied to various agricultural soils. The reader is referred to the cited studies (Table 2) for information on specific P sources and soils.

It is well established that the measurement of manure and biosolids WEP is affected by a variety of methodological factors (Kleinman et al., 2002b; Haggard et al., 2005), particularly extraction ratio (solids/solution). To ensure the comparability of WEP results from the different studies reported in the literature, only studies employing a WEP method similar to that recommend by Wolf et al. (2005) were selected for inclusion in the present analysis. The Wolf et al. (2005) method utilizes a 0.5-g sample (dry weight equivalent basis) and a final mixture mass of 100.5 g to achieve a 1:200 solids/solution extraction ratio.

**Indoor Packed Runoff Box Studies**

The analysis in this study relied on several rainfall simulation experiments conducted using the NPRP packed box pro-

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**Table 1. Organic P source coefficients (PSCs) in the Pennsylvania P index. (Weld et al., 2003).**

<table>
<thead>
<tr>
<th>P source</th>
<th>PSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swine slurry</td>
<td>1.0</td>
</tr>
<tr>
<td>Poultry</td>
<td>0.8</td>
</tr>
<tr>
<td>Broiler</td>
<td>0.8</td>
</tr>
<tr>
<td>Layer</td>
<td>0.9</td>
</tr>
<tr>
<td>Turkey</td>
<td>0.9</td>
</tr>
<tr>
<td>Duck</td>
<td>0.9</td>
</tr>
<tr>
<td>Dairy</td>
<td></td>
</tr>
<tr>
<td>Liquid</td>
<td>0.9</td>
</tr>
<tr>
<td>Bedded pack</td>
<td>0.8</td>
</tr>
<tr>
<td>Beef</td>
<td>0.8</td>
</tr>
<tr>
<td>Alum treated manures</td>
<td>0.5</td>
</tr>
<tr>
<td>Biosolids</td>
<td></td>
</tr>
<tr>
<td>Biological P removal</td>
<td>0.8</td>
</tr>
<tr>
<td>Alkaline stabilized</td>
<td>0.4</td>
</tr>
<tr>
<td>Conventionally stabilized</td>
<td>0.3</td>
</tr>
<tr>
<td>Composted</td>
<td>0.3</td>
</tr>
<tr>
<td>Heat-dried</td>
<td>0.2</td>
</tr>
<tr>
<td>Advanced alkaline stabilized</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Field Runoff Study

The field runoff experiment (Study 6 in Table 2) also followed the NPRP protocol, with rain simulator characteristics similar to those used in the indoor packed soil box experiments. Field plots (1 by 2 m) had an established stand of mixed grasses with slopes from 3 to 8% (Logan, 2004). The field plots were hydrologically isolated on the upper three sides by steel frames driven 5 cm into the soil and extending 5 cm above the soil. At the lower end of each plot, a gutter, equipped with a canopy to exclude direct rainfall, was installed and had a 2-cm plastic tube for conveying runoff water to plastic collection vessels. More detailed discussion of the use of the rainfall simulator for field plot experiments is given in Kleinman et al. (2004).

RESULTS AND DISCUSSION

Deriving PSCs from the Relationship of RDP with WEP

Developing an empirical relationship between the WEP of a land-applied material and its PSC was a two-step process. First, based on several rainfall simulation studies representing 52 different applied P sources and 6 different soils (Table 2), the functional relationship between RDP and the applied source WEP was established. The applied sources spanned the entire range of P solubilities and included materials that contain inert P which does not react with rain water (e.g., high Fe biosolids) as well as materials containing predominantly readily soluble P (e.g., swine slurries). These two extremes represent the boundary conditions for the second step of developing an expression between the WEP of an applied material and its corresponding PSC.

Relationship between RDP and WEP

Figure 1a shows the relationship between RDP (mg L$^{-1}$) and the WEP (g kg$^{-1}$) of the P sources for Studies 1 through 7 (Table 2). The progressive increase of RDP with P source WEP has been widely documented, and serves as the basis for the use of WEP as a quantitative indicator of the potential for manures and biosolids to release dissolved P to runoff (Kleinman et al., 2005). Scatter in the data can be attributed to several factors, including variable rates of P application,
different soils and soil conditions (P sources were applied to both bare soils and grassed field plots), manure handling methods, and different methods (ICP vs. colorimetric) of P determination (Kleinman et al., 2005; Wolf et al., 2005). Additionally, the composition and transport of water soluble P in applied P sources may differ. For instance, P sources with low solids content may have a greater tendency to infiltrate soluble P into the subsoil when they are applied, reducing the availability of soluble P to runoff at the soil surface (Kleinman et al., 2004). Despite these confounding factors, the data are described reasonably well by a linear equation (RDP = 2.54 × WEP; \( r^2 = 0.68 \)). A power function expression gave an improved correlation (RDP = 2.11 × WEP\(^{0.99}\); \( r^2 = 0.80 \)).

**Fixing Boundary Conditions**

Developing PSCs from the data in Fig. 1a requires fixing boundary conditions by considering the range of WEP values represented by materials that are routinely land applied. A survey of 140 manures of different types (Kleinman et al., 2005) found that swine manure had the highest average WEP (9.2 g kg\(^{-1}\)), followed by turkey (6.3), layer chickens (4.9), dairy cattle (4.0), broiler chickens (3.2), and beef cattle (2.3 g kg\(^{-1}\)). Brandt et al. (2004) reported WEP in 41 biosolids representing a variety of wastewater and solids treatment processes ranging from 0.01 to 8.86 g kg\(^{-1}\). Based on these results a WEP range of 0 to 10 g kg\(^{-1}\), as determined by the 1:200 extraction procedure (Wolf et al., 2005), can be expected to encompass nearly all manures and biosolids with the upper WEP values typical of materials that mimic mineral fertilizer in runoff potential. The upper boundary condition was therefore set such that source materials with WEP \( \geq 10 \) g kg\(^{-1}\) are considered to have the maximum PSC of 1.0. Logically, materials that do not result in increased RDP would be assigned a PSC value of zero.

**Deriving PSCs from WEP**

To develop a functional relationship between PSC and WEP, the ordinate of Fig. 1a can be re-scaled such that a WEP of 10 g kg\(^{-1}\) coincides with a PSC of 1.0. This simply involves changing the coefficient of the power function in Fig. 1a. The resulting data and empirical equation [PSC = 0.102 × WEP\(^{0.99}\)] are shown in Fig. 1b. The use of this WEP-to-PSC conversion equation is restricted to WEP values between 0 and 10 g kg\(^{-1}\). Under these conditions, materials (e.g., swine slurries) where WEP values are occasionally reported to be greater than 10 g kg\(^{-1}\) (Kleinman et al., 2005), would be assigned a PSC value of 1.0. Evidence to support this comes from the observation that high WEP swine slurries have runoff P concentrations similar to inorganic P fertilizers (WEP ~160 to 180 g kg\(^{-1}\)) applied at the same total P rate (Kleinman et al., 2002a; O’Connor and Elliott, 2006). In the Pennsylvania P index, swine slurries and inorganic fertilizers are effectively both given a PSC of unity.

**PSC Estimation Equation Testing**

The equation for computing PSCs from source WEPs was tested on two independent sets of runoff data (Studies 8 and 9, Table 2). Study 8 (Elliott et al., 2005) involved 10 biosolids and three manure sources that were applied at a common plant available N application rate, resulting in TP loading rates from 122 (dairy manure) to 555 (N-Viro advanced alkaline stabilized biosolids) kg P ha\(^{-1}\). To express the amount of applied P susceptible to runoff, the TP loading rates were first multiplied by the appropriate categorical PSC from the Pennsylvania index (Table 1). This product can be viewed as the effective, or runoff soluble P loading rate. The relationship between the RDP and effective loading rate based on table PSCs is shown in Fig. 2a. Although the positive slope of the relationship is consistent with expectations (RDP increased with the amount of runoff soluble P applied), the regression relationship is weak (\( r^2 = 0.45 \)). However, when the P loading rates were multiplied by the PSCs computed from the estimation equation, a much stronger relationship (\( r^2 = 0.86 \)) was observed (Fig. 2b). Because RDP comprised most of the TP in this study (Elliott et al., 2005), a similarly strong relationship (\( r^2 = 0.81 \)) was found between the runoff TP and the PSC-modified P loading rate (Fig. 2c).

Figure 3 presents a similar evaluation for a recent investigation (Study 9, Table 2) involving 10 manures and five biosolids samples from locations in the US and Canada (Kleinman et al., unpublished data, 2006). Figure 3a shows the runoff dissolved P versus the soluble...
applied P determined by multiplying the common TP loading (75 kg ha\(^{-1}\)) times the appropriate discrete PSC value from Table 1. Multiple data points appear for some abscissa values because different P source types have the same PSC (Table 1) and all amendments shared a common TP application rate in this study. Again, the relatively weak correlation shown in Fig. 3a (\(r^2 = 0.48\)) was significantly improved (\(r^2 = 0.73\)) when the PSCs were computed from the conversion equation. Total P runoff data were not reported in this study. The weaker correlation in Fig. 3b compared to Fig. 2b likely reflects the fact that the materials in Study 9 were predominantly manures with widely varying solids content (25 to 816 g kg\(^{-1}\)). Manures with low solids contents (e.g., swine slurry) have the tendency to carry P through infiltration below the soil surface where it is unavailable to surface runoff. Study 8 materials were predominantly dewatered biosolids with no free draining liquid to infiltrate the soil.

A detailed examination of individual data points reveals at least two situations where the computed PSC are clearly superior to default table values from the PA index. Some biosolids have very high Fe or Al content because of the composition of the influent or intentional additions of salts during wastewater treatment. The Philadelphia cake (labeled PC in Fig. 2) has very high Fe (72.3 g kg\(^{-1}\)) which resulted in low RDF. Although the Pennsylvania P index has a unique PSC value for alum-treated manures (Table 1), there is no analogous PSC for biosolids with high Al and/or Fe. Another problem with tabulated PSCs is the confusion arising when a material appears to fit in more than one category. The Largo pelletized biosolids (labeled LP in Fig. 2) is a heat-dried product (PSC = 0.2, Table 1) generated in a biological P removal wastewater treatment process (PSC = 0.8). Source coefficients based on testing of the actual materials obviate development of a comprehensive categorization scheme to accommodate the wide array of land-applied P sources.

Application to P Indices

The P indexing concept has been broadly adopted across the US, but translation into field assessment tools has followed several different approaches (Sharpley et al., 2003). The use of a continuous PSC input factor is most easily incorporated in indices of states (Pennsylvania, Maryland, Virginia, Delaware, Florida, Wisconsin, New Hampshire, Georgia, Louisiana, Tennessee) that already account for the relative solubility of applied P. The foregoing analysis has addressed indices for which source coefficients range between zero and 1.0. However, the general approach is adaptable to P indices with different PSC range scales. The P index for Virginia, for example, uses PSCs with a maximum value of 0.25, whereas the maximum value of a PSC in Maryland and Delaware is 0.6. The inclusion of adjustable PSCs is clearly inappropriate for some states, like New Jersey, where the P application rate is not one of the P index inputs.

In P indices, the relative proportion of the applied P subject to runoff loss is typically determined as the
product of the organic source P application rate and the corresponding PSC. For treated manures and biosolids with negligible WEP, the estimation equation yields PSC values approaching zero. When PSC = 0, the impact on the P index calculation is to effectively eliminate the organic P source contribution to the site index value. This might be justified when the applied P source contains enough Fe and Al to actually reduce runoff P losses below unamended soil levels. Evidence for such a phenomena has been documented (Maguire et al., 2000; Elliott et al., 2005). However, some states may consider it appropriate to set a minimum PSC value. A minimum PSC of 0.1 has been proposed (Coale and Elliott, 2004). Since some indices do not differentiate between particulate and soluble P, maintaining a minimum non-zero PSC threshold assumes that at least some level of P loss potential (from particulate P) is taken into account.

The WEP-to-PSC conversion equation developed in this study is nearly linear. A good approximation of PSC could simply be obtained by multiplying the WEP in g kg\(^{-1}\), determined by the Wolf et al. (2005) method, by 0.1. As a guide to P management practices, indices should reliably assess site P loss vulnerability and be easily usable by nutrient management practitioners.

CONCLUSIONS

Because P solubility varies widely across nutrient source types and treatments, dissolved P loss from a site can be very different even when P sources are applied at a common TP application rate. To account for these differences, some state field assessment tools include PSC categories for types of P sources that are used to convert the total applied P into soluble P applied. We have demonstrated a methodology for developing a source-specific PSC based on simple WEP testing of the applied materials. Because materials defy rigid categorization, the WEP of a material can be used to assign a PSC having any value between zero and 1.0, rather than relying on discrete table value PSCs. Tabulated PSCs are inherently problematic for biosolids and alum-treated manures. If a conventionally stabilized biosolids product is subsequently heat dried, selecting an appropriate PSC (e.g., Table 1) is not obvious. A unique PSC value for alum-treated manures presents another dilemma, since variable alum dosing rates to manures produce widely differing P loss reductions (DeLaune et al., 2004). Efforts to modify livestock diets will also affect manure WEP and preclude assigning unique PSCs to specific manure types. No state P indices include PSCs for food-processing residuals which are routinely recycled on land.

Source-specific PSCs based on WEP testing will account for the variable runoff potential of the wide array of agricultural, municipal, and industrial by-products managed via land application. Adjustable PSCs provide an additional management strategy which can be implemented to reduce the calculated risk of P loss from a farm. Previously (Elliott et al., 2005), dairy manure was amended with alum to achieve a 1:1 Al/P ratio and this reduced the WEP 10-fold (from 3.41 to 0.31 g kg\(^{-1}\)). A WEP-to-PSC conversion algorithm allows determination of the amount of alum or other P-sorbing amendment needed to achieve a target P index score. When the final site rating is highly sensitive to the PSC in a P index (Brandt and Elliott, 2005), subtle changes in PSC substantially impact a site’s P index score.

Finally, the overarching finding of this work is that estimating PSCs using measured data is superior to tabulated values for differentiating organic amendments based on P loss potential. The exact functional relationship between PSCs and measured WEP values depends on the experimental conditions of the WEP methodology (Kleinman et al., unpublished data, 2006), the nature of the corresponding P loss data (e.g., runoff versus leaching), and the conceptual framework and scaling of the site P index. Continuous improvement of tools for evaluating P loss potential from agricultural lands is essential as P nutrient management policies are implemented.

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REFERENCES


