Phosphorus Runoff from Incorporated and Surface-Applied Liquid Swine Manure and Phosphorus Fertilizer


ABSTRACT

Excessive fertilization with organic and/or inorganic P amendments to cropland increases the potential risk of P loss to surface waters. The objective of this study was to evaluate the effects of soil test P level, source, and application method of P amendments on P in runoff following soybean [Glycine max (L.) Merr.]. The treatments consisted of two rates of swine (Sus scrofa domestica) liquid manure surface-applied and injected, 54 kg P ha

1 triple superphosphate (TSP) surface-applied and incorporated, and a control with and without chisel-plowing. Rainfall simulations were conducted one month (1MO) and six months (6MO) after P amendment application for 2 yr. Soil injection of swine manure compared with surface application resulted in runoff P concentration decreases of 93, 82, and 94%, and P load decreases of 99, 94, and 99% for dissolved reactive phosphorus (DRP), total phosphorus (TP), and algal-available phosphorus (AAP), respectively. Incorporation of TSP also reduced P concentration in runoff significantly. Runoff P concentration and load from incorporated amendments did not differ from the control. Factors most strongly related to P in runoff from the incorporated treatments included Bray P1 soil extraction value for DRP concentration, and Bray P1 and sediment content in runoff for AAP and TP concentration and load. Injecting manure and chisel-plowing inorganic fertilizer reduced runoff P losses, decreased runoff volumes, and increased the time to runoff, thus minimizing the potential risk of surface water contamination. After incorporating the P amendments, controlling erosion is the main target to minimize TP losses from agricultural soils.

INTENSIVE LIVESTOCK FARMING enterprises that concentrate large numbers of animals indoors, particularly non-ruminants, have emerged as a result of improvements in animal housing and the success of crop production on cash-crop farms (Beegle et al., 2000). The cost of transporting low-density manure more than short distances from livestock farms to cash-crop farms exceeds its nutrient value. Therefore, most animal waste is land-applied near the animal production facility. The dominant geology, soils, and topography of the local area are often not considered before manure application (Sharpley et al., 1994). Continued inputs of fertilizer and manure in excess of crop P requirements have led to a buildup of soil P levels, which are of environmental rather than agronomic concern (Sharpley et al., 1994).

Phosphorus transported by surface runoff to streams and lakes often accelerates eutrophication, thus affecting the usage of water resources for many purposes such as drinking, fishing, and recreation (Foy and Withers, 1995). The transport of P occurs in dissolved and particulate forms. Particulate phosphorus (PP) encompasses all solid-phase forms and includes P sorbed by soil particles and organic matter eroded during runoff. While dissolved P is, for the most part, immediately available for biological uptake, PP can provide a long-term source of P for aquatic plant growth. Algal-available P represents the dissolved phase and the amount of PP that is potentially available for algal uptake (Sharpley et al., 1991).

The main factors controlling P movement in surface runoff are transport (runoff and erosion) and source factors (surface soil P content and method, rate, and timing of fertilizer and animal manure applications) (Sharpley et al., 1993). High rates of P applied either as a fertilizer or manure, particularly if it is left on the soil surface, will exacerbate the potential for movement of DRP from fields (Baker and Laflen, 1982; Mueller et al., 1984). Incorporation of P materials either through tillage or through injection will generally reduce the potential for DRP runoff (Eghball and Gilley, 1999; Withers et al., 2001; Tabbara, 2003). On the other hand, tillage operations may increase the potential for TP loss, especially on highly erosive sites. Eghball and Gilley (1999) found that runoff DRP and AAP concentrations were greater for no-till than disked treatments during two consecutive simulated rainfall events on wheat (Triticum aestivum L.) residue plots with a 6% slope. In contrast, concentrations of TP and PP were greater for the disked treatments compared with the no-till plots. Cox and Hendricks (2000) reported a more than threefold increase in TP concentration in runoff from conventionally tilled compared with no-till soils for a wide range of soil P levels on 2 to 6% slopes.

Runoff transport of P from surface-applied manure increases with the application rate. Edwards and Daniel (1993) observed that DRP and TP concentration in runoff from fescue (Festuca arundinacea Schreb.) plots was directly related to swine slurry application rate. Tabbara (2003) also found a proportional increase in TP, PP, AAP, and DRP concentration and load in runoff from fallow soils when surface-applied liquid swine manure rates were doubled.

Phosphorus losses from treatments that compare inorganic versus organic amendments tend to vary among different experiments. Eghball and Gilley (1999) observed that the concentrations of DRP and AAP in

Abbreviations: AAP, algal-available phosphorus; DRP, dissolved reactive phosphorus; HM, high manure rate; LM, low manure rate; 1MO, first rainfall simulation (one month after treatment application); 6MO, second rainfall simulation (six months after treatment application); PP, particulate phosphorus; TP, total phosphorus; TSP, triple superphosphate.


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runoff were significantly greater for a fertilizer treatment than two rates of beef cattle feedlot manure when all were surface-applied before an initial rainfall event. However, in a second rainfall event, increased DRP and AAP in runoff resulted from the highest manure rate. Withers et al. (2001) observed that P runoff from TSP was similar to liquid cattle manure when it was either surface-applied or incorporated with a rotovator. Tabbara (2003) found higher concentrations and load of all P forms from plots receiving broadcast P fertilizer compared with plots receiving surface-applied liquid swine manure.

Rainfall frequency and time of rainfall occurrence after the application of manures or fertilizers have also been shown to affect P runoff. Sharpley (1997) studied the effects of rainfall frequency and timing on P runoff after poultry litter had been applied to different soils. He observed decreasing concentration of P after successive rainfall events. Dissolved reactive P and AAP decreased when the rainfall event occurred 35 d compared with 1 d after the poultry litter had been applied. Similar trends were reported by Westerman and Overcash (1980) for TP runoff from swine and poultry wastes applied over fescue grass.

The objectives of this study were to (i) determine the effect of placement of P-containing materials on the concentration and load of three P forms (DRP, AAP, and TP); (ii) determine the effect of P source and rate on P in runoff; (iii) determine the relationship between soil test P levels and P in runoff; and (iv) evaluate P in runoff 1 and 6 mo after the treatment application.

**MATERIALS AND METHODS**

**Study Site and Experimental Design**

The study was conducted from 1999 to 2001 at the Northwestern Illinois Agricultural Research and Demonstration Center, Monmouth, IL, on a Tama silt loam soil (fine-silty, mixed, mesic Typic Argiudoll). The texture of the A horizon has an average of 24% clay, 70% silt, and 6% sand. Average pH and organic matter content are 6.1 and 37 g kg⁻¹, respectively. Mean annual precipitation in the area is 940 mm. Figure 1 details monthly averages of natural rainfall and air temperatures measured at the study site.

The experiment was done as a randomized complete block design with two repetitions and two observations per plot (1 and 6 mo after P amendment applications). The treatment structure was a 4 × 2 × 4 × 2 × 2 factorial arrangement generated from four P source amendments (HM, LM, TSP, and a control), two application methods (chisel plow or injection and surface application), four Bray P1 extraction levels, two years, two blocks per year, and two times (1 and 6 mo after P amendment application). Each block contained thirty-two 9- by 6-m unit plots, with a 5.5% mean slope.

**Plot Establishment and Treatment Application**

To obtain four categories of soil P levels ranging from 30 to 300 mg kg⁻¹, each 9- by 6-m main plot was soil sampled from 0 to 2.5 cm on 3 May 1999 and sent to a commercial lab (for rapidity), to be analyzed by the Bray and Kurtz P1 soil extraction method. Triple superphosphate was broadcast to every main plot based on the soil test and every treatment combination was then randomly assigned to each soil P level category. A field cultivator was used to mix and prepare the soil that was going to be used for Year 1, and soybean was planted on 19 May 1999 at 38-cm row spacing. Meanwhile, the adjacent field that was going to have soybean planted in 2000 to repeat the experiment was being planted with corn (Zea mays L.), having being filled with a field cultivator to incorporate the phosphorus fertilizer.

In early October 1999, after the soybean crop was harvested, soil samples were collected from the outside perimeter of the microplots of Year 1 to be analyzed for Bray P1 soil extraction levels and by a water-extractable P method. Simulated rainfall collection microplots 2 by 1.5 m were delimited by flags at the center and lower part of the 9- by 6-m main plots. Simulated rainfall took place only on the 2- by 1.5-m microplots. The shorter sides of microplots and main plots were perpendicular to the slope. The same experimental design was set up again in late September 2000 on an adjacent site to repeat the experiment. This field had residue from soybean that had been planted on no-till at 38-cm row spacing. Before the first rainfall simulation, soil samples were collected from the outside perim-

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*Fig. 1. Mean monthly rainfall and air temperature measured at the Northwestern Illinois Agricultural Research and Demonstration Center, Monmouth, IL, from May 1999 to May 2001.*
eter of the Year 2 microplots and were later analyzed for Bray P1 soil extraction levels and by a water-extractable P method. The range of Bray P1 soil extraction values for both years was 27 to 1248 mg kg\(^{-1}\), which was many times greater than the range sought originally. We found out that the commercial lab had not been diluting the samples with high P levels so many of the Bray P1 extraction values from May 1999 were extremely underestimated. The corrected Bray P1 extraction values for each category are found in Table 1.

In mid-October 1999 and early October 2000, after the plots had been delimited but before framing the microplots, liquid swine manure with 98% moisture (SD = 0.28) was surface-applied and row-injected at rates of 46 680 and 93 370 L ha\(^{-1}\) and 54 kg ha\(^{-1}\) of P as TSP was surface-broadcast. In 1999, the manure volumes represented 39.4 and 76.6 kg P ha\(^{-1}\) for LM and HM, respectively, and in 2000, they represented 33.1 and 66.2 kg P ha\(^{-1}\) for LM and HM, respectively. The TSP and control treatments included both no-till and chisel plow to a depth of 25 cm, perpendicular to the slope. Manure was injected in a horizontal band at a 10-cm depth and 76-cm spacing using an injector with disk sweeps. Plots with injected manure were not chisel-plowed. Manure was surface-applied by spreading it back and forth within the plot limits and across the slope with a hand-held hose connected to a supply tank for a certain amount of time, depending on the rate assigned to the plot.

After the P amendments were applied, each microplot was isolated with three plastic frames: the 2-m-long and 20-cm-wide frames were set along the slope and the 155-cm-long and 15-cm-wide frame was set across the slope and at the top side of the microplot. A 155-cm-wide by 76.2-cm-long collection triangle was attached at the downhill side above a 50.2-cm-diameter filtering, samples were stored at 4°C for a certain amount of time, depending on the rate assigned to the plot.

Water and Soil Analysis

Within 12 h after sample collection, portions of the runoff samples for DRP analysis were filtered through Whatman (Maidstone, UK) no. 1 filter paper and then vacuum-filtered by drying 10 mL of unfiltered water sample at 110°C until constant weight. The Bray and Kurtz P-1 test for extracting soil P was used (Frank et al., 1998). Water-extractable P was determined by slightly modifying the method of Pote et al. (1996) by mixing 1 g of soil with 25 mL of distilled water, shaking for 1 h, and syringe-filtering through a 0.45-μm Millipore filter paper. The ascorbic acid method procedure was used for the color development of Bray P1 and water-extractable P. The ascorbic acid method procedure was used for the color development of Bray P1 and water-extractable P. When the transmittance exceeded the standard curve, the extractant was diluted as needed. Soil organic matter was estimated as the weight loss on ignition (Combs and Nathan, 1998). Total P in manure was analyzed by the inductively coupled plasma atomic emission spectroscopy method SW846-6010B (USEPA, 1992). Soil pH was measured in a 1:1 soil to water slurry (Watson and Brown, 1998). Eight subsamples from around the microplot were collected for each soil sample, which was subsequently air-dried, crushed, and sieved to pass a 2-mm
sieve. Clay content was determined by the hydrometer method (Klute, 1986) on 10 samples.

**Data Analysis**

The mixed model analysis for repeated measures was performed using the MIXED procedure of SAS (Littell et al., 2000; SAS Institute, 2001). Bray P1 extraction level was used as a covariate. The variance–covariance matrix was modeled with the unstructured option in SAS. Year and block within year were considered random variables. Time (1MO and 6MO), P source (HM, LM, TSP, and control), and two application methods (chisel plow or injection, and surface application or no-till) were considered fixed variables. The model included all possible interactions between time, P source and application method, and Bray P1 as a covariate. The repeating subject was the microplot nested in year × P source × application method. Means comparisons were performed using the Scheffé method (Scheffé, 1953) because it provides a conservative experimentwise error protection for any number of contrasts. P values < 0.1 were considered significant when comparing means.

The incorporated data were analyzed by regression procedures using PROC REG (SAS Institute, 2001) with the stepwise selection method to select the independent variables that significantly affected the dependent variables (P = 0.05). Bray P1 soil extraction value, residue cover, and sediment concentration and load were used in the regression model as independent variables for DRP, AAP, and TP concentration and load. The Type II sums of squares were taken into account when assessing the relative contribution of each term in explaining the dependent variable.

**RESULTS AND DISCUSSION**

**Time to Runoff, Runoff Volume, Sediment Concentration, and Residue Cover**

The F and P values for the fixed effects in time to runoff, runoff volume, and sediment concentration are found in Table 2. The three-way interaction time × P source × application method was significant for time to runoff (P < 0.1). The longest time to runoff occurred in the incorporated amendments and the chisel-plowed control, averaging 1 h compared with an average of 9 min for the surface-applied treatments (Table 3). The interaction time × application method was significant for runoff volume, and the highest runoff volume resulted for the surface-applied treatments in 1MO, averaging 16.5 mm. Plots with incorporated treatments in 1MO and all the plots in 6MO resulted in significantly lower runoff volumes, averaging 5.9 mm.

The interaction P source × application method was significant for sediment concentration, and the highest values were observed for the chisel-plowed plots (control and TSP), averaging 4.1 g L⁻¹, followed by injected LM, HM, and the surface-applied treatments (that were not significantly different at P = 0.1) that altogether averaged 1.8 g L⁻¹ (Table 3).

Residue cover was only measured before 1MO, and the interaction P source × application method was significant (P < 0.0001). The highest residue cover was observed in the no-till plots (surface-applied amendments and control) with an average of 92%, followed by the injected manure plots with an average of 61%, and the least residue cover was observed in the chisel-plowed plots, averaging 37% (Table 3). Residue cover was negatively correlated to sediment concentration (r = −0.41, P < 0.0001), and positively correlated to runoff volume (r = 0.54, P < 0.0001). The positive correlation of residue cover with runoff volume is most probably due to the relationship between residue cover percentage and application method since the highest residue cover percentage was measured in the no-till, surface-applied plots, which had the highest runoff volumes.

**Soil Phosphorus**

The relationship between Bray P1 soil extraction (mg kg⁻¹) and water-extractable soil P (mg kg⁻¹) in 2.5-cm-deep soil samples was linear, and the following equation was found:

\[
B1 = 6.2 + 5.3WEP
\]

where B1 (mg kg⁻¹) is Bray P soil extraction value and WEP (mg kg⁻¹) is water-extractable P (R² = 0.96, P < 0.0001).

**Dissolved Reactive Phosphorus**

Time × P source × application method interaction was significant for DRP concentration and load in runoff (Table 4). High DRP concentrations and loads were observed in runoff from plots that had been amended with surface-applied TSP and manure one month earlier (1MO) (Fig. 2 and 3). When these amendments were

<table>
<thead>
<tr>
<th>Time</th>
<th>Numerator</th>
<th>Denominator</th>
<th>Value</th>
<th>Time to runoff</th>
<th>Runoff volume</th>
<th>Sediment</th>
</tr>
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<tr>
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<td>Time × PS</td>
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<td></td>
<td>7.9**</td>
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<tr>
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<td>194.2†</td>
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</tr>
<tr>
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<td>230</td>
<td></td>
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<td>75.6***</td>
<td>2.4 (P &lt; 0.12)</td>
</tr>
<tr>
<td>PS × AM</td>
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<td>230</td>
<td></td>
<td>3.0†</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Time × PS × AM</td>
<td>3</td>
<td>230</td>
<td></td>
<td>NS</td>
<td>NS</td>
<td></td>
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<tr>
<td>Bray P1</td>
<td>1</td>
<td>230</td>
<td></td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Type 3 tests of fixed effects for time to runoff, runoff volume, and sediment concentration as affected by time of rainfall simulation (1 and 6 mo after P amendment application); four phosphorus sources (PS) (control, triple superphosphate, and two manure rates); two application methods (AM) of P amendments (incorporation and surface application); and Bray P1 as a covariate.**

**Table 2 Notes:**

**Significant at the 0.01 probability level.**

**Significant at the 0.001 probability level.**

† Significant at the 0.1 probability level.
incorporated, DRP concentration and load were greatly reduced in 1MO, showing no difference with the control plots. The differences in DRP concentration and load between surface-applied and incorporated treatments were only significant for HM at 6MO (Fig. 2 and 3). Eghball and Gilley (1999), working on wheat and sorghum [Sorghum bicolor (L.) Moench.] residues, also found that DRP concentrations in runoff from surface-applied cattle manure and inorganic fertilizer were significantly greater than those from incorporated treatments. This application method effect was observed again in a second rainfall simulation 24 h after the first one, but as occurred in the 6MO event in our study, the differences among the tillage treatments in the second rainfall simulation were smaller. Concentration and load of DRP in runoff from surface-applied HM were not significantly greater than those from surface-applied LM (Fig. 2 and 3). Dissolved reactive P concentration from surface-applied TSP was smaller than for surface-applied HM (P < 0.01). Withers et al. (2001) surface-applied TSP and liquid cattle manure at rates of 60 kg ha⁻¹ P on a growing crop of winter wheat. The first 25 mm of natural rainfall occurred 3 wk after the treatment application and the DRP concentrations in runoff were 6.5 and 3.8 mg L⁻¹ for TSP and liquid cattle manure, respectively. In our study, the average DRP concentrations for the surface-applied HM, LM, and TSP were 10.3, 7.6, and 5.6 mg L⁻¹, respectively. The TSP concentration was very similar to Withers et al. (2001), and the differences between the manure treatments are probably due to the higher content of water soluble P in the swine manure compared with cattle manure. In our 6MO simulation event, we observed DRP concentration in runoff to be around 1.3 mg L⁻¹ from TSP and manure treatments. These results were very similar to the ones observed by Withers et al. (2001) after two subsequent runoff events.

The incorporated treatments showed no differences in DRP concentration or load between time or P sources. However, there was a linear effect of Bray P1 soil extraction value on the concentration of DRP in runoff from incorporated treatments (Fig. 4). The data were fit separately by chisel-plowed plots and injected manure plots since the injected manure plots had a higher slope compared with the chisel-plowed plots. Andraski and Bundy (2003) also observed a strong relationship between Bray P1 soil extraction value and DRP concentration in runoff from a Typic Argiudoll soil that had recently incorporated dairy manure (with a chisel plow). Sharpley and Smith (1995) found that labile and chemisorbed inorganic P increased when soils were amended with feedlot wastes. In addition, Reddy et al. (1980) reported that a soil receiving high rates of manure sorbed less P and desorbed more P. In our study, the amendments probably increased P desorption in the soils, and this

### Table 3. Mean values for time to runoff, residue cover, runoff volume, and sediment concentration.†

<table>
<thead>
<tr>
<th>Surface-applied</th>
<th>Incorporated: chisel plow (control, TSP); injected (LM, HM)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Incorporation methods (incorporation and surface application)</td>
</tr>
<tr>
<td>Time to runoff, min</td>
<td>Control (TSP), LM, HM</td>
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<tr>
<td>1MO§</td>
<td>129b</td>
</tr>
<tr>
<td>6MO§</td>
<td>38b</td>
</tr>
<tr>
<td>Residue cover, %¶</td>
<td>Control (TSP), LM, HM</td>
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<tr>
<td>1MO and 6MO</td>
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<tr>
<td>Runoff volume, mm</td>
<td>Control (TSP), LM, HM</td>
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<td>1MO and 6MO</td>
<td>3.9bc</td>
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<tr>
<td>Sediment, g L¹</td>
<td>Control (TSP), LM, HM</td>
</tr>
<tr>
<td>1MO and 6MO</td>
<td>3.9bc</td>
</tr>
</tbody>
</table>

† Values across each variable that are followed by the same letter are not significantly different at P = 0.1, determined by the Scheffe test.
‡ TSP, triple superphosphate; LM, low manure rate; HM, high manure rate.
§ Rainfall simulation one month (1MO) and six months (6MO) after P amendment application.
¶ Residue cover was only measured before 1MO rainfall simulation.

...
Effect was evidently enhanced at increasing Bray P1 soil extraction levels.

Dissolved reactive P load in runoff from the incorporated treatments was linearly related to Bray P1 soil extraction levels, but the model did not explain a large amount of the variability ($P < 0.001$, $R^2 = 0.25$). Dissolved reactive P load in our study was more variable than concentration since DRP load is related to runoff volumes, which depend on residue cover, slope, and surface roughness, all of which differed among plots.

**Total Phosphorus**

Time $\times$ P source $\times$ application method interaction was significant for TP concentration and load in runoff

(P < 0.001; Table 4). In 1MO, surface-applied manure produced greater TP concentration and load in runoff compared with injected manure (Fig. 5 and 6). In 6MO, no differences were found for TP concentration or load in runoff between surface and incorporated treatments.

In a study where beef cattle manure and fertilizer P had been surface-applied and disked up and down the slope, Eghball and Gilley (1999) found that TP concentration and load were not influenced by the application method when running off sorghum residue. Moreover, when working on wheat residue, they reported that concentration and load of TP were less for no-till than for disked treatments, because greater erosion from the disked soils resulted in more PP and TP being carried by runoff. In our study, the incorporated manure was injected on the contour, and the residue cover doubled.

**Fig. 2.** Mean dissolved reactive phosphorus (DRP) concentration in runoff as affected by time of rainfall simulation (one [1MO] and six months [6MO] after P amendment application); P source (control, TSP = 54 kg P ha$^{-1}$ as triple superphosphate, LM = low swine manure rate, and HM = high swine manure rate); and application method (surface-applied and incorporated, where the control and TSP were chisel-plowed, and LM and HM were injected). Mean values ($n = 16$) that have the same letters are not significantly different ($P < 0.1$) as determined by the Scheffé test.

**Fig. 3.** Mean dissolved reactive phosphorus (DRP) load in runoff as affected by time of rainfall simulation (one [1MO] and six months [6MO] after P amendment application); P source (control, TSP = 54 kg P ha$^{-1}$ as triple superphosphate, LM = low swine manure rate, and HM = high swine manure rate) and incorporation method (surface-applied and incorporated, where the control and TSP were chisel-plowed, and LM and HM were injected). Mean values ($n = 16$) that have the same letters are not significantly different ($P < 0.1$) as determined by the Scheffé test.

**Fig. 4.** Relationship between runoff dissolved reactive phosphorus (DRP) concentration and Bray P1 soil extraction values for incorporated treatments (chisel-plowed control, TSP = chisel-plowed 54 kg P ha$^{-1}$ as triple superphosphate, LM = injected low swine manure rate, HM = injected high swine manure rate).

**Fig. 5.** Mean total phosphorus (TP) concentration in runoff as affected by time of rainfall simulation (one [1MO] and six months [6MO] after P amendment application); P source (control, TSP = 54 kg P ha$^{-1}$ as triple superphosphate, LM = low swine manure rate, and HM = high swine manure rate); and application method (surface-applied and incorporated, where the control and TSP were chisel-plowed, and LM and HM were injected). Mean values ($n = 16$) that have the same letters are not significantly different ($P < 0.1$) as determined by the Scheffé test.
the one used in the study by Eghball and Gilley (1999). In addition, the injection and chisel-plowing in our study produced high surface roughness whereas the disked soils in Eghball and Gilley (1999) probably produced a smooth surface. These facts may explain why the TP concentration and load running off our chisel-plowed and injected plots were less than half of the TP concentration for the tilled plots reported for their plots.

No differences were found for TP concentration between surface-applied and chisel-plowed TSP in 1MO (Fig. 5). This was mainly caused by the high TP concentration from the chisel-plow treatments that equaled the TP from the surface-applied TSP. Ninety percent of the TP from chisel-plow plots was PP, and only 33% of the TP from surface-applied TSP was PP. So evidently what caused the high TP concentration in runoff was the erosion coming off the chisel-plow treatments. However, if we take into account that the time to runoff for the chisel-plowed TSP treatment was in average 126 min compared with 14 min for the surface-applied TSP (Table 3), it is clear that incorporating TSP is the preferred practice to reduce P runoff. The TP load was much lower in the chisel-plowed TSP compared with the surface-applied TSP (Fig. 6). This was caused by the very low runoff volumes coming off chisel-plow plots, which were about one-fifth the runoff volumes from no-till plots.

Total P concentration and load in runoff did not differ between the two surface-applied manure rates (Fig. 5 and 6). Higher TP concentration was observed in HM compared with the TSP treatment in 1MO, whereas no differences were observed among the surface-applied amendments for TP load ($P < 0.1$).

Total P concentration and load in runoff from incorporated treatments showed no differences between times or P sources. However, sediment concentration and Bray P1 soil extraction level were related to TP concentration from all the incorporated treatments including the control (Fig. 7). The following equation was found:

$$TPC_{inc} = 0.0025B1 + 0.571SED \quad \text{[2]}$$

where $TPC_{inc}$ (mg L$^{-1}$) is TP concentration from incorporated treatments in runoff, $B1$ (mg kg$^{-1}$) is Bray P1 soil extraction value, and SED (g L$^{-1}$) is sediment concentration in runoff. The adjusted $R^2$ was 0.91 ($P < 0.001$). Sediment concentration explained three times more variability (Type II sums of squares) than did Bray P1 soil extraction value. The close association between sediment and TP concentration has also been observed in other studies (Aase et al., 2001; Andraski and Bundy 2003; Andraski et al., 1985; Cox and Hendricks 2000).

Total P load was related to sediment load and Bray P1 soil extraction value (Fig. 8). The following equation explained the relationship between the variables:

$$TPL_{inc} = 0.114B1 + 0.456SED \quad \text{[3]}$$

where $TPL_{inc}$ (g ha$^{-1}$) is total P load from incorporated treatments in runoff, $B1$ (mg kg$^{-1}$) is Bray P1 soil extraction value, and SED (kg ha$^{-1}$) is sediment load in runoff. The adjusted $R^2$ was 0.72 ($P < 0.001$). Sediment load explained nine times more variability (Type II sums of squares) than Bray P1 soil extraction value. It is clear that erosion control is the main target when the objective is to minimize TP loss from agricultural soils where nutrients have been incorporated.

### Algal-Available Phosphorus

Algal-available phosphorus (AAP) concentration and load in runoff were similar to DRP concentration and load. For surface-applied amendments, DRP constituted an average of 81% of AAP, while for incorporated treatments, DRP was 55% of AAP. Sediment concentration in runoff and Bray P1 soil extraction value were the
[4] was therefore simplified to Eq. [5], where sediment concentration was removed from the model:

\[ \text{AAPC}_{\text{inc}} = 0.00224B1 \]  

where \( \text{AAPC}_{\text{inc}} \) (mg L\(^{-1}\)) is algal-available P concentration from incorporated treatments in runoff, and \( B1 \) (mg kg\(^{-1}\)) is Bray P1 soil extraction value. The adjusted \( R^2 \) decreased to 0.82 (\( P < 0.001 \)). The slope for DRP concentration as a function of Bray P1 soil extraction levels (0.012) was approximately half the slope for AAP concentration (Eq. [5]), which may reflect the adsorbed orthophosphates in the sediment matrix that diffused into solution during the AAP extraction process.

Algal-available P load in runoff was related to sediment load, Bray P1 soil extraction levels, and the interaction between Bray P1 and sediment load (Fig. 10):

\[ \text{AAPL}_{\text{inc}} = 0.041B1 + 0.056\text{SED} + 0.00043B1 \times \text{SED} \]

where \( \text{AAPL}_{\text{inc}} \) (g ha\(^{-1}\)) is AAP load from incorporated treatments in runoff, \( B1 \) (mg kg\(^{-1}\)) is Bray P1 soil extraction value, \( \text{SED} \) (kg ha\(^{-1}\)) is sediment load in runoff, and \( B1 \times \text{SED} \) is the interaction between sediment load in runoff and Bray P1 soil test values. The adjusted \( R^2 \) was 0.80 (\( P < 0.001 \)). The interaction between Bray P1 and sediment load explained four times more variability than each factor separately. Sediment load is the product of sediment concentration and runoff volume, so Bray P1 soil extraction value interacts with sediment load because at low runoff volumes (and therefore low sediment load), there will be low AAP load regardless of the Bray P1 soil extraction value. Only at increasing sediment load does Bray P1 soil extraction value influence AAP load. Increasing water infiltration to reduce runoff is therefore an important management practice to reduce AAP load in runoff.
CONCLUSIONS

Injection of manure was very effective in reducing DRP, TP, and AAP concentration and load in runoff. The same trends were observed when inorganic fertilizer was incorporated with a chisel plow. Concentration and load of DRP, TP, and AAP for the high surface-applied manure rate were not significantly different compared with the low surface-applied manure rate. The high rate of surface-applied manure produced generally more DRP, TP, and AAP concentration in runoff than the inorganic fertilizer P, whereas the P concentration in runoff from the latter was similar to the low rate of surface-applied manure. Runoff volumes introduced variability when calculating P load in runoff, and no significant differences were observed between surface-applied P amendments.

Phosphorus losses one month after surface amendment applications were greater than the P losses after six months, when only small or no differences were observed between surface-applied and incorporated treatments for DRP, TP, and AAP concentration and load. Therefore, the residual effect of the surface-applied amendments for this scenario was very small.

Soil test P levels and sediment content in runoff influenced P loss from incorporated treatments. Only Bray P1 soil extraction value influenced DRP concentration and load in runoff from injected manure and chisel-plowed TSP and control, and the relationship was linear. Bray P1 soil extraction value and sediment concentration and load in runoff from the incorporated treatments were significantly related to TP and AAP concentration and load. Sediment concentration and load were the most important variables in explaining TP concentration and load in runoff. In contrast, AAP concentration was highly associated with Bray P1 soil extraction value, and to a much lesser extent with sediment concentration. The interaction between sediment load and Bray P1 soil extraction value was most important in explaining AAP load in runoff.

Incorporating organic and inorganic amendments was shown to be an acceptable technique to reduce P losses from agricultural fields. Injecting manure and chisel-plowing inorganic P fertilizer on the contour was not only effective in reducing P losses, but it also increased the time to runoff and decreased the runoff volumes. However, this practice should be accompanied by Bray P1 soil extraction levels below 100 mg kg\(^{-1}\) (0–2.5 cm) and by keeping residue cover on the field to prevent sediment losses.

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