ABSTRACT

Growing interest in corn (Zea mays L.) silage utilization on Wisconsin dairy farms may have implications for nutrient losses from agricultural lands. Increasing the silage cutting height will increase residue cover and could reduce off-site migration of sediments and associated constituents compared with conventional silage harvesting. We examined the effects of residue level and manure application timing on phosphorus (P) losses in runoff from no-till corn. Treatments included conventional corn grain (G) and silage (SL; 10- to 15-cm cutting height) and nonconventional, high-cut (60- to 65-cm) silage (SH) subjected to different manure application regimes: no manure (N) or surface application in fall (F) or spring (S). Simulated rainfall (76 mm h⁻¹; 1 h) was applied in spring and fall for two years (2002–2003), runoff from 2.0 × 1.5-m plots was collected, and subsamples were analyzed for dissolved reactive phosphorus (DRP), total phosphorus (TP), and P mass distribution in four particle size classes. Total P and DRP loads were inversely related to percent residue cover, but both TP and DRP concentrations were unaffected by residue level. Manure application increased DRP concentrations in spring runoff by two to five times but did not significantly affect DRP loads, since higher concentrations were offset by lower runoff volumes. Spring manure application reduced TP loads in spring runoff by 77 to 90% compared with plots receiving no manure, with the extent of reductions being greatest at the lower residue levels (~24%). The TP concentration in sediments increased as particle size decreased. Manure application increased the TP concentration of the 0- to 2-μm fraction by 79 to 125%, but elevated the 2- to 10- and 10- to 50-μm fractions to a lesser extent. Recent manure additions were most influential in enriching transported sediments with P. By itself, higher residue cover achieved by high-cutting silage was often insufficient to lower P losses; however, the combination of manure application and higher residue levels significantly reduced P losses from corn fields harvested for silage.

Phosphorus is essential for agricultural production; however, its oversupply is of great concern, especially in areas with high-density livestock operations, due to its tendency to contribute to degradation of water bodies. Agriculture is a significant source of both dissolved and sediment-bound P delivered to surface water (USEPA, 2003). Phosphorus enrichment of surface water that exceeds a critical threshold of 0.01 mg P L⁻¹ (Sharpley and Rekolainen, 1997) can lead to nuisance algal and aquatic weed growth, a condition referred to as eutrophication. Aesthetically displeasing, eutrophication also degrades aquatic ecosystems and leads to im paired uses of water for drinking, agriculture, industry, and recreation (Carpenter et al., 1998).

Livestock manure contains valuable plant nutrients and organic matter that can improve crop production and soil properties. It can substantially increase the organic matter content of soil, improve aggregation, lower soil bulk density, and increase infiltration (Gilley et al., 2002). Although runoff and soil erosion rates are generally lower following manure application, the extent of reductions is influenced by manure characteristics, loading rates, degree of incorporation, and the timing of application relative to runoff events (Gilley and Risse, 2000; Grande et al., 2005). Addition of manure, however, is not always environmentally beneficial. Incongruence between the N to P ratio of manure (3:1) and crop requirement (8:1) has led to excess P application when N-based manure application rates are used (Daniel et al., 1994). Repeated manure application in excess of crop P removal has resulted in elevated soil P levels that pose a threat to aquatic ecosystems (Sharpely et al., 1999; Bundy and Sturgul, 2001). Gilley and Risse (2000) reported that higher manure loading rates reduced sediment loss; however, high manure P levels can offset these reductions and lead to greater P losses on a mass basis (Mueller et al., 1984). One of the more significant effects of manure, particularly when it is surface-applied without any incorporation, is a higher DRP concentration in runoff (Mueller et al., 1984; Eghball and Gilley, 1999).

Since the majority of P is transported attached to small soil particles and organic matter (Alberts and Mollenhauer, 1981; Sharpley et al., 1992), simply reducing erosion often may be insufficient to limit P losses and transport. For example, Sharpley et al. (1992) found that even though no-till could reduce TP losses, it increased the proportion of bioavailable P in runoff, thereby reducing potential benefits of P reductions through erosion control. Similarly, management practices that enrich runoff with fine-grained (clay or colloidal-sized) particles by promoting the preferential deposition of coarser sediments are unlikely to produce substantial P loss reductions. Small aggregates, and the primary clay particles that constitute them, have a high specific surface area and greater P sorption potential than sand or silt (Young and Onstad, 1976). Consequently, clay and silt fractions have higher TP concentrations than the coarser fractions of soil and sediment (Dong et al., 1983; Pierzyinski et al., 1990). Once entrained in runoff, fine-grained particles represent an important potential source of exportable P because

Abbreviations: AARS, Arlington Agricultural Research Station; DRP, dissolved reactive phosphorus; F, fall-applied manure; G, corn grain; N, no manure application; S, spring-applied manure; SL, corn silage, high-cut; SH, corn silage, low-cut; TP, total phosphorus.
they resist settling and remain in suspension as long as water is moving (Gabriels and Moldenhauer, 1978).

Changes in livestock farm dynamics and more favorable economics compared with alfalfa have resulted in increasing use of corn silage. Klemme (1998) reported a net advantage of $100 acre$^-1$ ($250 ha$^-1$) for growing corn silage rather than alfalfa, due primarily to the difference in dry matter yield. A 15% increase in land use for corn silage production in Wisconsin from 1994 to 1998 (Battaglia, 1999) and a survey of nutritional consultants (Shaver, 2000) strongly support this trend. Also, land used for corn silage in Wisconsin has increased an additional 20% since 1998 (USDA, 2004). Since the extent of residue cover influences runoff production and soil erosion losses, the trend of increasing corn silage production may affect P export from croplands.

Crop residue cover can be an important component of management practices aimed at reducing the off-site migration of nutrients from agricultural lands. Phosphorus is transported in soluble and particulate forms; however, a majority of P (75–95%) lost from row-crop agriculture is associated with sediments (Daniel et al., 1994). Compared with clean tilled, residue-free conditions, corn residue cover even at a 20% surface coverage level has reduced erosion by up to 50% under a variety of tillage practices (Dickey et al., 1984). Crop residue insulates the soil surface from raindrop impact, thereby reducing soil particle detachment. Crop residue also inhibits the development of a surface seal by minimizing soil slaking, which quickly fills macropores (Potter et al., 1995). These benefits associated with higher levels of residue promote infiltration while reducing runoff, sediment export, and transport of associated constituents.

Increasing the silage cutting height at harvesting would enable producers to harvest silage while maintaining a greater level of soil surface residue cover. On-going research in Wisconsin and other states shows that improved silage quality concomitant with increased milk production can be obtained when the cutting height is raised from the conventional height (10–15 cm) to 45 cm or higher (Curran and Posch, 2000; Neylon and Kung, 2003). Greater residue cover associated with increasing silage cutting height could reduce water quality degradation that would otherwise result from harvesting corn for silage instead of grain.

With a few notable exceptions (e.g., Bundy et al., 2001), studies that involve the simultaneous evaluation of residue cover and manure application on P losses are rare. Some earlier research investigated the impact of residue on P mass distributions in different size classes of eroded sediments (Alberts and Moldenhauer, 1981; Alberts et al., 1981); however, there is little published literature on the impact of manure application on these factors. Therefore, the major goal of this study was to evaluate potential environmental benefits associated with higher crop residue cover achieved by high-cutting silage. The impact of manure application and timing on P losses over a range of crop residue levels resulting from three harvesting methods, namely, corn-grain (G), high-cut silage (SH), and conventional silage (SL) was also investigated. We previously reported on runoff and sediment losses (Grande et al., 2005), and this article will focus on P losses. Our specific objectives included examining the effect of residue cover on (i) runoff DRP and TP concentrations and loads, (ii) P partitioning among four particle size classes, and (iii) P enrichment of sediments. Two different seasons were compared, fall (after harvesting) and spring (before planting), to determine the effectiveness of increasing silage cutting height in reducing P losses from no-till cropland.

**MATERIALS AND METHODS**

Field experiments were conducted at the University of Wisconsin (UW) Arlington Agricultural Research Station (AARS) (89°20’ W, 43°17’ N) on a Plano silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiudoll) during the spring and fall of 2002 and 2003. Experiments were performed on cropland previously grown in corn under no-till conditions. The experimental layout consisted of a completely randomized design with two independent blocks (Fig. 1). Rainfall experiments were replicated twice (two independent microplots within a block; see Fig. 1) for every treatment (three residue $\times$ three manure application timing combinations) and data from quadruplicates were pooled for the statistical analysis. Steel frames inserted to a soil depth of 7.5 cm delineated 36 microplots measuring 2.0 m x 1.5 m. New microplots (four per treatment) were established for each of the four rainfall simulation periods. Further details on the experimental layout and simulated rainfall protocol can be found in Grande et al. (2005).

Three crop residue levels, achieved by different harvesting methods, corresponded to G, SH, and SL. Residue cover in each microplot (Table 1) was estimated by the pin drop method (Morrison et al., 1996). Each residue level was also subjected to one of three manure timing treatments: no manure, early application of manure (September 2001), and fall application of manure (November 2001).

<table>
<thead>
<tr>
<th>Table 1. Effect of corn harvesting method on soil surface coverage.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest method</td>
</tr>
<tr>
<td>Grain</td>
</tr>
<tr>
<td>High-cut silage</td>
</tr>
<tr>
<td>Low-cut silage</td>
</tr>
</tbody>
</table>
| ‡ Numbers in each column followed by the same letter are not significantly different at the 0.05 probability level; statistical differences are based on the means and standard deviations shown.
nure added, or dairy manure (90% water content with sawdust bedding) was surface-applied at a rate of 106 Mg ha⁻¹ using a Calumet spreader (Imperial Industries, Wausau, WI) in the spring (S) or preceding fall (F). Manure was applied in November 2001 and 2002 and April 2002 and 2003 to achieve a desired P loading rate of 50 kg P ha⁻¹. Actual loading rates ranged from 55 to 62 kg P ha⁻¹ (538-605 mg P kg⁻¹).

Rainfall simulations were performed just before planting (May–June 2002, May 2003) and after harvesting (September–October 2002, October 2003). A rainfall simulator based on the standard design for the National Phosphorus Research Project (2002) with a 1/2-inch HH50WSQ Fulljet nozzle (Spraying Systems, Wheaton, IL) positioned 3 m above the soil surface delivered rainfall at a rate of 76 mm h⁻¹ for 1 h. This intensity was equivalent to a 50-yr, 1-h event (Huff and Angel, 1992). Runoff was collected continuously from the down-slope end of each microplot for the duration of the 1-h simulation using a 0.02-MPa vacuum (Dixon and Peterson, 1968) and stored in a tared, 55-gallon (208-L) drum placed on a scale. Final runoff weight and volume were recorded after cessation of runoff. Two representative runoff subsamples were collected for each rainfall simulation: a 125-mL filtered (0.45 μm) sample (DRP) and a 3.8-L unfiltered sample (TP). Water for rainfall simulations came from a ground water well at the AARS and had average pH, electrical conductivity, total dissolved solids, and TP of 8.1, 669 μS cm⁻¹, 428 mg L⁻¹, and <0.01 mg P L⁻¹, respectively.

Before each rainfall simulation, residue cover was measured, and ten, 0- to 5-cm-deep soil cores were collected from immediately outside of each microplot and composited for later analysis. Soil test P, Bray-1 P (Bray and Kurtz, 1945), was analyzed at the UW Soil & Plant Analysis Laboratory while higher for the grain (0.27 kg [kg soil⁻¹]) compared with the silage treatments (0.24–0.25 kg [kg soil⁻¹]) and for plots receiving spring manure (0.26 kg [kg soil⁻¹]) compared with no-manure plots (0.24 kg [kg soil⁻¹]). Specific seasonal information on antecedent soil moisture condition was available before the rainfall experiments were not significant. When averaged over all seasons, the soil moisture was influenced by residue level (p < 0.01) and manure application timing (p = 0.03); it was for plots receiving spring manure (0.26 kg [kg soil⁻¹]) compared with no-manure plots (0.24 kg [kg soil⁻¹]), but was not significant. When averaged over all seasons, the soil moisture was influenced by residue level (p < 0.01) and manure application timing (p = 0.03); it was for plots receiving spring manure (0.26 kg [kg soil⁻¹]) compared with no-manure plots (0.24 kg [kg soil⁻¹]). Specific seasonal information on antecedent soil moisture for different treatment combinations can be found in Grande et al. (2005).

**RESULTS AND DISCUSSION**

Average Bray-1 P was higher for plots receiving fall or spring manure, 88 and 90 mg P kg⁻¹, respectively, compared with the no-manure plots (58 mg P kg⁻¹). Bray-1 P values were also higher in the second year of the study reflecting the cumulative impact of manure addition. Soil Bray-1 P and TP data are shown in Table 2. Few differences were observed in Bray-1 P among residue level and manure treatments within each of the four seasons.

**Dissolved Reactive Phosphorus: Concentration**

The DRP concentration in runoff was strongly influenced by manure application and its timing, but was less affected by residue level (Fig. 2 and Table 3). Spring-applied manure had the greatest impact on runoff, particularly during spring rainfall experiments, when DRP levels in runoff from spring manure (S) plots were four to five times higher than in runoff from no-manure (N) plots (Table 3). Fall manure added to silage plots similarly affected DRP levels in spring runoff, but to a lesser extent, increasing them two to three times compared with N plots at similar residue levels. The DRP concentrations in fall runoff were 47 to 94% lower than DRP levels in spring runoff (Table 3). This seasonal difference in DRP levels reflects the impact of P removal by crop uptake, runoff losses, and conversion of soluble P to more recalcitrant forms over time (Edwards and Daniel, 1993).

Our results (Table 3) clearly showed that DRP concentrations are sensitive to the time interval between manure application and runoff events. Similar observations have been reported elsewhere. Sharpley (1997) noted a 41% decrease in DRP concentration when rainfall occurred 35 d rather than 1 d after application of poultry
litter. Similarly, Kleinman and Sharpley (2003) reported a negative correlation between DRP concentration in runoff and number of days since application of dairy manure \((r^2 = 0.62, p < 0.01)\) or swine manure \((r^2 = 0.83, p < 0.001)\). Sharpley (1997) showed that DRP in runoff decreases with successive runoff events, while others have reported declines during the growing season. For example, Mueller et al. (1984) noted a DRP reduction in runoff from June to August (0.94 to 0.26 mg L \(^{-1}\)) from no-till plots receiving dairy manure in spring. Kleinman and Sharp ley (2003) attributed the temporal change in DRP in Year II compared with Year I, especially in spring runoff (Table 3), were likely attributable to lower than normal precipitation in 2003 (Grande, 2004), which could have limited translocation of P. For the period November–April, precipitation amounts in 2002–2003 compared with analogous no-manure plots, 0.08 to 0.11 mg P L \(^{-1}\). Higher DRP concentrations observed in Year II compared with Year I, especially in spring runoff (Table 3), were likely attributable to lower than normal precipitation in 2003 (Grande, 2004), which could have limited translocation of P. For the period November–April, precipitation amounts in 2002–2003

### Table 2. Total phosphorus (TP) and soil test P (Bray-1 P) levels of parent soil.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Manure</th>
<th>Spring 2002 TP</th>
<th>Spring 2003 TP</th>
<th>Fall 2002 TP</th>
<th>Fall 2003 TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>N</td>
<td>621 ± 23 abc</td>
<td>615 ± 49 abc</td>
<td>620 ± 36 ab</td>
<td>587 ± 53 a</td>
</tr>
<tr>
<td>SH</td>
<td>N</td>
<td>552 ± 112 ab</td>
<td>512 ± 19 bc</td>
<td>596 ± 56 ab</td>
<td>557 ± 63 a</td>
</tr>
<tr>
<td>SL</td>
<td>N</td>
<td>508 ± 26 b</td>
<td>506 ± 59 c</td>
<td>560 ± 61 ab</td>
<td>483 ± 82 a</td>
</tr>
<tr>
<td>G</td>
<td>F</td>
<td>565 ± 68 ab</td>
<td>627 ± 88 abc</td>
<td>514 ± 55 b</td>
<td>612 ± 68 a</td>
</tr>
<tr>
<td>SH</td>
<td>F</td>
<td>560 ± 48 ab</td>
<td>612 ± 41 abc</td>
<td>618 ± 60 ab</td>
<td>650 ± 50 a</td>
</tr>
<tr>
<td>SL</td>
<td>F</td>
<td>599 ± 34 ab</td>
<td>657 ± 80 a</td>
<td>570 ± 35 ab</td>
<td>606 ± 46 a</td>
</tr>
<tr>
<td>G</td>
<td>S</td>
<td>663 ± 56 a</td>
<td>646 ± 68 ab</td>
<td>650 ± 72 a</td>
<td>661 ± 110 a</td>
</tr>
<tr>
<td>SH</td>
<td>S</td>
<td>607 ± 26 ab</td>
<td>617 ± 25 abc</td>
<td>567 ± 30 ab</td>
<td>571 ± 131 a</td>
</tr>
<tr>
<td>SL</td>
<td>S</td>
<td>603 ± 56 ab</td>
<td>601 ± 46 ab</td>
<td>610 ± 59 ab</td>
<td>649 ± 23 a</td>
</tr>
</tbody>
</table>

† G, grain; SH, high-cut silage; SL, low-cut silage; N, no manure; F, fall manure; S, spring manure.
‡ Average of four replicates.
§ Numbers in each column followed by the same letter are not significantly different at the 0.05 probability level; statistical differences are based on the means and standard deviations shown.

Fig. 2. Effect of crop residue cover (%) on dissolved reactive phosphorus (DRP) concentration in runoff for three manure treatments. Data points are an average of four replicates from each of the four seasons. Residue cover ranges for the three harvesting schemes (G, grain; SH, high-cut silage; SL, low-cut silage) are highlighted. For clarity, confidence intervals are not plotted.
were 38% lower than in 2001–2002 and 54% below the 30-yr average.

Crop residue levels had a negligible impact on DRP concentrations in runoff. Significant differences were only observed in fall 2003 (Table 3). Others have reported that P leaching from crop residue remaining on the soil surface under conservation tillage and failure to incorporate fertilizer (Baker and Laflen, 1982; McDowell and McGregor, 1984) can result in higher DRP levels in runoff. Andraski et al. (1985) found no significant correlation between residue cover and dissolved P concentration in runoff. The current study also found no evidence that crop residue was a source of dissolved P. When no manure was applied, the relationship between DRP and percent residue cover (Fig. 2) was not significant \( (p = 0.16). \) Interestingly, after either spring or fall manure application, DRP concentration and percent residue cover were negatively correlated \( (p = 0.05). \) The statistical models for the spring and fall applied manure described in Fig. 2 were similar over the entire range of residue coverage.

### Dissolved Reactive Phosphorus: Load

Although DRP concentrations in runoff were higher following the application of manure, manure had a negligible effect on DRP loads, resulting in similar loads compared with plots receiving no manure (Table 4 and Fig. 3). This was achieved by manure lowering the runoff generated. Manure applied to SH and SL plots lowered spring runoff by 71 to 88% compared with plots receiving no manure, but had no significant effect on G plots due to the high residue level, which alone was sufficient to reduce runoff amounts. More information on the effect of manure on runoff volume can be found in Grande et al. (2005). Figure 4 shows the influence of time since manure application on increasing the runoff volume but not lowering the DRP load. For example, spring runoff shortly after spring manure application resulted in the least runoff while the no-manure (both spring and fall runoff) treatment had the highest runoff amounts. Increases in runoff with time were concomitant with reductions in DRP concentrations and, hence, DRP loads were similar among the manure treatments (Fig. 3). In both spring and fall 2002, DRP loads from the F and S plots were not significantly different from N plots at similar residue levels (Table 4). In 2003, the DRP load in spring runoff was lower from SH-F compared with SH-S while the converse held for fall runoff. Otherwise, manure application did not significantly affect the DRP loads for the other manure treatments at similar residue levels.

Residue cover influenced the DRP load to a greater extent than manure application. Dissolved reactive P losses were inversely related to percent residue cover (Fig. 3). Combined data from both spring and fall runoff

### Table 3. Average dissolved reactive phosphorus (DRP) concentration in runoff for nine (residue level × manure application timing) treatments.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Manure</th>
<th>DRP concentration‡</th>
<th>Spring 2002</th>
<th>Spring 2003</th>
<th>Fall 2002</th>
<th>Fall 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>G N</td>
<td>0.17 ± 0.04 cd§</td>
<td>0.29 ± 0.11 cde</td>
<td>0.13 ± 0.07 a</td>
<td>0.04 ± 0.04 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH N</td>
<td>0.14 ± 0.05 d</td>
<td>0.23 ± 0.03 de</td>
<td>0.13 ± 0.05 a</td>
<td>0.08 ± 0.05 bc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL N</td>
<td>0.14 ± 0.02 d</td>
<td>0.18 ± 0.02 e</td>
<td>0.11 ± 0.04 a</td>
<td>0.08 ± 0.04 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G F</td>
<td>0.26 ± 0.12 bed</td>
<td>0.64 ± 0.12 bed</td>
<td>0.14 ± 0.05 a</td>
<td>0.09 ± 0.07 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH F</td>
<td>0.38 ± 0.08 bc</td>
<td>0.74 ± 0.08 bc</td>
<td>0.19 ± 0.15 a</td>
<td>0.39 ± 0.10 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL F</td>
<td>0.39 ± 0.09 ab</td>
<td>0.97 ± 0.27 ab</td>
<td>0.17 ± 0.05 a</td>
<td>0.36 ± 0.11 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G S</td>
<td>0.84 ± 0.38 a</td>
<td>0.91 ± 0.29 ab</td>
<td>0.17 ± 0.12 a</td>
<td>0.05 ± 0.03 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH S</td>
<td>0.77 ± 0.25 a</td>
<td>1.08 ± 0.13 a</td>
<td>0.20 ± 0.10 a</td>
<td>0.14 ± 0.08 abc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL S</td>
<td>0.59 ± 0.14 a</td>
<td>0.91 ± 0.09 ab</td>
<td>0.26 ± 0.05 a</td>
<td>0.29 ± 0.07 ab</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† G, grain; SH, high-cut silage; SL, low-cut silage; N, no manure; F, fall manure; S, spring manure.
‡ Average of four replicates.
§ Numbers in each column followed by the same letter are not significantly different at the 0.05 probability level; letters correspond to nonparametric analysis based on data ranks rather than mean and standard deviation as shown.

### Table 4. Average dissolved reactive phosphorus (DRP) load in runoff for nine (residue level × manure application timing) treatments.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Manure</th>
<th>DRP load‡</th>
<th>Spring 2002</th>
<th>Spring 2003</th>
<th>Fall 2002</th>
<th>Fall 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>G N</td>
<td>1.7 ± 1.0 bc§</td>
<td>4.7 ± 3.0 c</td>
<td>0.3 ± 0.2 de</td>
<td>0.1 ± 0.2 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH N</td>
<td>11.9 ± 1.4 ab</td>
<td>15.4 ± 3.7 ab</td>
<td>4.1 ± 1.3 abce</td>
<td>0.3 ± 0.2 ab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL N</td>
<td>14.2 ± 5.7 ac</td>
<td>18.4 ± 5.8 ab</td>
<td>9.2 ± 5.1 ab</td>
<td>1.7 ± 0.7 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G F</td>
<td>2.3 ± 3.3 b</td>
<td>6.0 ± 4.0 bc</td>
<td>0.5 ± 0.5 d</td>
<td>0.2 ± 0.4 bc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH F</td>
<td>12.2 ± 6.4 ab</td>
<td>16.2 ± 6.8 ab</td>
<td>2.9 ± 1.8 bcd</td>
<td>3.3 ± 3.2 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL F</td>
<td>15.8 ± 7.2 ac</td>
<td>18.9 ± 8.5 ab</td>
<td>13.3 ± 4.0 a</td>
<td>6.1 ± 7.3 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G S</td>
<td>9.4 ± 8.1 ab</td>
<td>4.4 ± 4.8 c</td>
<td>1.2 ± 1.9 cd</td>
<td>0.02 ± 0.02 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH S</td>
<td>19.4 ± 5.2 a</td>
<td>26.0 ± 7.0 a</td>
<td>1.9 ± 1.8 bcd</td>
<td>0.2 ± 0.1 bc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL S</td>
<td>7.0 ± 6.0 ab</td>
<td>23.1 ± 16.8 ab</td>
<td>14.8 ± 4.8 a</td>
<td>1.7 ± 1.0 ab</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† G, grain; SH, high-cut silage; SL, low-cut silage; N, no manure; F, fall manure; S, spring manure.
‡ Average of four replicates.
§ Numbers in each column followed by the same letter are not significantly different at the 0.05 probability level; letters correspond to nonparametric analysis based on data ranks rather than mean and standard deviation as shown.
Fig. 3. Effect of crop residue cover (%) on dissolved reactive phosphorus (DRP) load for three manure treatments. Data points are an average of four replicates from each of the four seasons. Residue cover ranges for the three harvesting schemes (G, grain; SH, high-cut silage; SL, low-cut silage) are highlighted. For clarity, confidence intervals are not plotted.

were used to generate the plots and relationships in Fig. 3. While the statistical models for the three treatments are significant, the differences between them are not. The grain treatment significantly lowered DRP loads in fall runoff compared with SL under the three manure regimes; however, within a manure treatment, the higher residue level associated with G did not consistently lower DRP loads in spring runoff compared with SL (Table 4). Dissolved reactive P loads were also lower for G compared with SH in spring 2003 following spring manure application and in fall 2003 after manure application the previous fall (Table 4). Differences between SH and SL were significant only in fall 2002 and only when manure had been previously applied: DRP loads from SH plots were 85 to 87% lower than SL plots. As these examples show, the differences in residue cover levels alone (i.e., G vs. SH; SH vs. SL) were often insufficient to significantly reduce DRP loads, but the combined effects of higher residue cover and manure addition caused significant differences to be observed among the treatment combinations.

Total Phosphorus: Concentration

Few statistically significant differences were observed for the influence of manure and residue cover on TP concentrations in runoff (Table 5). Any differences seen were imparted by spring-applied manure; however, the impact was not consistent from season to season or year to year. In 2002, spring-applied manure on G plots (i.e., G-S) resulted in TP concentrations in fall runoff that were 70% lower than from SL-S plots, and TP levels in spring runoff from G-S that were 74% below those obtained for SH-F plots. In 2003, spring-applied manure

Fig. 4. Influence of time since manure application on runoff volume and its impact on dissolved reactive phosphorus (DRP) load. Note that a change in runoff does not affect the DRP load due to the dependence on DRP concentration (see text for details). Data points are an average of four replicates. Trend lines correspond to all residue levels (G, grain; SH, high-cut silage; SL, low-cut silage) for Years I (2002) and II (2003). For clarity, confidence intervals are not plotted.
on G plots reduced the TP level in spring runoff compared with G plots that received no manure. Otherwise, TP concentrations were similar among the nine treatments. High variability between replicates (Table 5) resulted in the inability to detect differences among treatment groups.

The effect of manure addition on TP concentrations in runoff mirrored its influence on sediment concentration: manure lowered the amount of sediment in runoff and, hence, the TP concentration. A strong relationship between sediment (SEDconc) and TP concentrations (TPconc = 0.50 × SEDconc + 0.42; r² = 0.88) existed because P losses from row crop agriculture are dominated by sediment-bound forms (Sharpley et al., 1999). Manure reduced TP (and sediment) levels immediately after being applied, and the influence diminished with time. A drier than normal year, as in 2003 (Grande, 2004), may prolong the beneficial effects of manure addition for TP (opposite effect observed for DRP levels), resulting in sediment/TP reductions to be observed for a longer time (i.e., in both spring and fall runoff).

Residue level had a limited impact on TP concentrations in runoff. The only statistically significant difference between the crop residue levels occurred in fall 2002, when TP was 70% lower from G-S compared with runoff from SL plots. Total P losses in runoff from G plots with a similar manure treatment were also lower than SH-N plots in fall 2002 and SH-F plots in fall 2003 (Table 6). Fewer differences between residue treatments were noticed in spring runoff. In 2002, the higher residue on G plots reduced the TP load in spring runoff more than 90% compared with either from row crop agriculture are dominated...A drier in spring 2003. This observation likely reflects relatively than normal year, as in 2003 (Grande, 2004), may pro-

## Table 6. Average total phosphorus (TP) load in runoff for nine (residue level × manure application timing) treatments.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>TP load‡</th>
<th>mg P L⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spring 2002</td>
<td>Spring 2003</td>
</tr>
<tr>
<td>G N</td>
<td>23.2 ± 17.7 cd</td>
<td>79.2 ± 42.6 abc</td>
</tr>
<tr>
<td>SH N</td>
<td>239.3 ± 58.0 a</td>
<td>133.3 ± 91.4 ab</td>
</tr>
<tr>
<td>SL N</td>
<td>312.5 ± 235.0 a</td>
<td>264.3 ± 96.6 abc</td>
</tr>
<tr>
<td>G F</td>
<td>9.8 ± 16.5 d</td>
<td>31.0 ± 35.5 bed</td>
</tr>
<tr>
<td>SH F</td>
<td>126.2 ± 109.9 abc</td>
<td>16.6 ± 11.5 ed</td>
</tr>
<tr>
<td>SL F</td>
<td>140.0 ± 107.6 ab</td>
<td>52.0 ± 23.5 bcedf</td>
</tr>
<tr>
<td>G S</td>
<td>9.0 ± 6.9 d</td>
<td>9.7 ± 11.4 d</td>
</tr>
<tr>
<td>SH S</td>
<td>32.2 ± 7.1 bcd</td>
<td>45.4 ± 16.0 bede</td>
</tr>
<tr>
<td>SL S</td>
<td>32.4 ± 42.1 bcd</td>
<td>59.8 ± 63.5 bede</td>
</tr>
</tbody>
</table>

† G, grain; SH, high-cut silage; SL, low-cut silage; N, no manure; F, fall manure; S, spring manure.
‡ Average of four replicates.
§ Numbers in each column followed by the same letter are not significantly different at the 0.05 probability level; letters correspond to nonparametric analysis based on data ranks rather than mean and standard deviation as shown.

## Total Phosphorus: Load

Residue cover strongly influenced TP losses, especially in the fall when residue levels were at their highest (Table 1). Under all three manure treatments, the TP load in fall runoff from G plots was lowered by >94% compared with runoff from SL plots. Total P losses in runoff from G plots with a similar manure treatment were also lower than SH-N plots in fall 2002 and SH-F plots in fall 2003 (Table 6). Fewer differences between residue treatments were noticed in spring runoff. In 2002, the higher residue on G plots reduced the TP load in spring runoff more than 90% compared with either silage treatment under the fall-applied or no-manure conditions. Interestingly, no significant differences in TP losses were observed among the G, SH, and SL plots in spring 2003. This observation likely reflects relatively low residue levels (Table 1), whose magnitudes may have been too small to produce treatment differences, or the high variability among replicates. Differences in the TP load between SH and SL plots were only observed in fall 2002, when the TP load from SH plots was 84 to 87% lower than similarly manured SL plots. Others have found that management practices that return higher levels of corn residue to the surface lower sediment and, consequently, TP loads in runoff (Andraski et al., 1985; Andraski et al., 2003).

Manure application and timing also strongly impacted TP loads; however, their effects were greater in the
spring when the time interval between application and rainfall experiments was the shortest. In 2002, spring-applied manure lowered TP loads from SH and SL plots by 87 to 90% compared with plots not receiving manure but at a similar residue level. In 2003, TP loads in spring runoff were 77 to 88% lower from G and SL plots following spring manure application and 88% lower from SH plots that received fall manure compared with plots not receiving manure. The beneficial effect of manure addition on TP loads was not evident in fall runoff (Table 6) and was probably masked by residue levels, which were the highest for all treatments in the fall right after harvest. Our results agree with the findings of Bundy et al. (2001) who reported that unincorporated manure added to no-till plots lowered TP losses by increasing infiltration and lowering sediment losses.

Figure 5 shows the inverse relationship between the TP load in runoff and percent residue cover, but more importantly it highlights the impact of manure on this relationship. Statistical models for the spring and fall applied manure treatments were similar over the entire residue cover range. Below 20 to 24% residue cover, differences between the no-manure and fall–spring manure models were significant. Above this range, the 95% confidence intervals overlapped as all treatments converged to 0 TP load. Interestingly, below a residue cover of 24%, the presence of manure had a pronounced effect on reducing (up to 76%) the TP load in runoff. For example, at 5% residue cover, the addition of manure lowered the TP load by an amount equivalent to the no-manure plot with 20 to 27% residue cover.

Although TP loads in runoff from SH-N and SL-N were not significantly different in any of the four seasons, manure applied to SH-N plots reduced the TP load compared with SL-N. Spring-applied manure impacted the TP load in all seasons except spring 2003, lowering it by 84 to 96%, while fall manure reduced the TP load by 94% in spring 2003 and 83% in fall 2002. Residue level differences alone were insufficient to cause reductions in the TP load; however, increased residue in combination with manure application surpassed a residue level threshold above which the differences between SH and SL were detectable.

**Dissolved vs. Particulate Phosphorus Losses**

Phosphorus losses in runoff occur in both dissolved and particulate (PP) (sediment-bound) forms; however, a majority of P losses from tilled land is associated with sediments. This latter point is supported by the strong relationship between sediment (SED) and TP loads ($TP_{load} = 0.54 \times SED_{load} + 1.96; r^2 = 0.98$). Compiling data from small-plot studies, Andraski and Bundy (2003) reported that an average of 86% of TP losses from row crop production systems was in the sediment-bound form. The current study found that 92% of P lost in runoff from plots not receiving manure was PP (PP was determined as the difference between TP and DRP; for plots receiving no manure, DRP and total dissolved P levels were nearly identical), and recent manure additions increased the DRP fraction of TP (Fig. 6). The DRP fraction in spring runoff from G-S,
SH-S, and SL-S plots was 4 to 11 times higher than in runoff from plots with similar residue levels but receiving no manure. The higher DRP fraction (39–73% compared with 5–15% of TP) underscores that surface-applied manure is a significant source of soluble P, which in turn increases the relative contribution of DRP to TP losses. Fall-applied manure also increased the dissolved P fraction in spring runoff; however, the effect was limited to G-F (6×) and SL-F (5.5×) plots in 2003 and G-F (4×) plots in 2002 (Fig. 6). The DRP fraction of TP losses in fall runoff was generally unaffected by manure application. In 2003, spring-applied manure increased the DRP fraction in runoff from SL-S by nearly sixfold compared with SL-N. Otherwise, treatment differences in fall runoff were not significant. Recent manure additions had the most significant effect on P partitioning while residue cover apparently had no effect.

**Phosphorus Concentration by Sediment Size Class**

Total P concentrations in sediments from the four size classes (Table 7) were influenced by manure application and timing but were not affected by differences in crop residue cover. Spring-applied manure exerted a significant effect on sediment P levels. Compared with sediments from plots receiving no manure, TP concentrations in the 0- to 2-µm fraction were 79 to 125% higher while sediments in the 2- to 10- and 10- to 50-µm classes increased by 32 to 57% following spring manure application. Manure did not significantly affect the P concentration in the 50- to 500-µm fraction. Although sediments from no-manure plots had significantly lower TP levels than those from plots with spring manure, plots receiving fall manure or no manure yielded sediments with similar P levels (Table 7).

Manure represents a valuable source of P for agricultural crops. After manure is applied, the various P forms interact with soil over time and some P is sorbed to soil particles, particularly to clays that have a greater specific surface area and higher sorption capacity (Young and Onstad, 1976). The substantial increase in the TP levels of 0- to 2-µm particles could have resulted from sorption processes. Similarly, increases in the TP content of the silt-sized fractions (10–50 and 2–10 µm) may reflect the aggregation of clay-sized particles facilitated by manure addition.

Sediment TP concentrations were highest in the smallest measured particle size. The highest average P concentrations were in the 2- to 10- and 0- to 2-µm size classes, 1225 and 1215 mg P kg⁻¹, respectively. These levels compare with 667 mg P kg⁻¹ for 50- to 500-µm particles and 774 mg P kg⁻¹ for 10- to 50-µm particles. Sediment TP concentrations were also consistently higher in spring 2003 compared with fall 2002 (data not shown). Otherwise, seasonal differences were not statistically significant.

Few studies have examined the P concentration of eroded sediments (Alberts et al., 1981; Alberts and Moldenhauer, 1981) and they had larger plot areas where sediment transport could have been dominated by rill erosion. Most sediment was transported by interrill flow in the current study. This distinction between interrill and rill erosion is important because higher runoff velocity associated with rill flow has greater transport capacity than slower-moving interrill flow, and this can shift the particle size distribution of eroded sediment. Alberts and Moldenhauer (1981) reported that 8 to 40% of eroded sediments were >500 µm, while the current study generally found <1% in that range (Grande et al., 2005). Alberts and Moldenhauer (1981) also found that the highest P concentrations were in the 50- to 210-µm fraction and greater residue cover lowered the P concentration of sediments in each size class by 15 to 20%. In the current study, crop residue level did not significantly affect the P concentration within a size class and P levels increased from coarse (50–500 and 10–50 µm) to fine (2–10 and 0–2 µm) sized particles independent of residue level. Our results also show that manure, particularly when applied in spring, could have a dominant effect in increasing sediment TP concentrations.

**Phosphorus Partitioning Among Sediment Size Classes**

Figure 7 illustrates the P partitioning on a mass basis among the four sediment size classes for which TP was determined. It shows that the majority of P (45–71%) was associated with the silt-sized fractions (2–10 and 10–50 µm) and that manure applied in the spring shifted a considerable portion of P from the 10- to 50-µm to...
Fig. 7. Phosphorus partitioning, on a mass basis, among the four particle size classes (from the top: 0–2, 2–10, 10–50, and 50–500 μm) for nine treatments (G, grain; SH, high-cut silage; SL, low-cut silage; N, no manure; F, fall manure; S, spring manure). Each bar represents a composite distribution of 9 to 15 replicates, based on the number of available samples, averaged over the four seasons.

Phosphorus Enrichment Ratios

Phosphorus enrichment ratios (PER), shown in Fig. 8, which compare the P concentration in sediment to that of the parent soil from which runoff was collected, were calculated for all residue–manure treatment combinations. The PER values were always greater than 1, attributable to selectivity in the sediment detachment–transport process leading to movement of more finer-sized particles in interrill flow. The PER for sediments transported in spring runoff averaged 1.62 ± 0.39 (N = 65) and ranged from 1.00 to 2.48 while fall sediments had a lower ratio, 1.42 ± 0.16 (N = 34), and narrower range, 1.21 to 1.78 (Fig. 8). Importantly, P enrichment of spring sediments was enhanced by manure application and timing but was not influenced by residue level. Spring sediments from plots with recently applied spring manure had a significantly higher average PER (2.09) compared with plots receiving fall-applied (1.61) or no manure (1.31). The P enrichment phenomenon tends to diminish as the fields go through a cropping season or as more time elapses between manure application and runoff generation. Consequently, the PER for fall sediments was generally not affected by either residue level or manure application (Fig. 8).

CONCLUSIONS

Crop residue level had a negligible impact on the DRP and TP concentrations in runoff. When differences were observed between the G, SH, and SL treatments, they were the result of a residue level–manure interaction. However, residue level had a strong influence on both the DRP and TP loads, particularly in fall when the percent residue cover was at its highest. Phosphorus losses were inversely related to percent residue cover. Higher residue cover resulted in less runoff and consequently lower DRP and TP loads. Both DRP and TP loads were significantly lower from G compared with SL. Differences in residue cover between SH and SL alone were often insufficient to reduce P losses; however, increased residue in combination with manure addition helped surpass a residue level threshold above which differences between SH and SL could be detected. Finally, TP concentrations of sediments in the four particle size classes and the P enrichment ratio of sediments were not affected by residue cover level.

Manure application strongly influenced the DRP concentration in runoff but had no effect on the DRP loads. Reductions in runoff volume resulting from manure addition compensated for a higher DRP concentration thereby resulting in no difference in DRP loads compared with no manure application. Dissolved reactive...
P concentrations in runoff were highly dependent on the time interval between manure application and runoff initiation. They were highest shortly after application and became lower with increasing time. A similar time dependency with opposite trends held for TP loads. Recent manure applications substantially lowered the TP load, by >77%, but these reductions became smaller over time. Total P reductions were achieved primarily by manure lowering runoff (and sediment) losses. Few differences were observed for the influence of manure on TP concentrations and they were caused by spring-applied manure; however, the impact was not consistent from season to season or year to year. Spring-applied manure was also found to (i) increase the DRP fraction of total P losses, (ii) increase the TP concentration of sediments in the size range of 0 to 50 μm, (iii) shift P from the 10- to 50-μm fraction to the 0- to 2-μm fraction, and (iv) increase the P enrichment ratio of sediments in spring runoff. This study demonstrated that manure application in combination with a higher level of residue cover, achieved by high cutting silage, can lower total P losses without substantially increasing DRP losses. These findings may have practical implications for the management of nutrient losses from agricultural lands.

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