Sediment and particulate phosphorus characteristics in grassed waterways from row crop corn and alfalfa fields collected by manual University of Exeter samplers and automatic sampling

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Abstract:

Phosphorus (P) export from agricultural lands above known threshold levels can result in adverse impacts to receiving water quality. Phosphorus loss occurs in dissolved and sediment-bound, or particulate phosphorous (PP), forms, with the latter often dominating losses from row-cropped systems. To target practices, land managers need good computer models and model developers need good monitoring data. Sediment monitoring data (e.g. radiometric finger printing and sediment P sorption capacity) can help identify sediment source areas and improve models, but require more sediment mass than is typically obtained by automatic sampling. This study compares a simple suspended sediment sampler developed at the University of Exeter (UE) with automatic sampling in intermittent channels draining corn and alfalfa fields. The corn field had a greater runoff coefficient (27%) than alfalfa (11%). No differences were found in enrichment ratios (sediment constituent/soil constituent) in PP (PPER) or percent loss on ignition (LOI ER) between paired UE samplers on corn. The median LOI ER for the UE samplers (1.9%) did not differ significantly (p > 0.13) from the automatic sampler (2.0%). The PPPER from the UE samplers was on average 20% lower than the automatic samplers. A correlation (r² = 0.75) was found between sediment PP and % LOI from automatic samplers and UE samplers for particles <50 µm, while for >50 µm PP concentration did not change with changes in % LOI. Sediment ammonium-oxalate extractable metals were similarly related to LOI, with the strongest correlation for iron (r² = 0.71) and magnesium (r² = 0.70). Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS runoff monitoring; particulate phosphorus; particle size; fine-grained sediment

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INTRODUCTION

Phosphorus (P) and nitrogen (N) export from upland areas to aquatic systems has been shown to degrade water quality and is therefore a concern for local, state and Federal regulatory agencies (Carpenter et al., 1998; Parry, 1998). Eutrophication reduces the beneficial use of receiving waters and can result in local, regional and national economic impacts. Phosphorus transport occurs in dissolved (DP) and sediment-bound, or particulate phosphorous (PP), forms, with the latter often dominating P losses from row-cropped agricultural systems (Gillingham and Thorrold, 2000; Usitalo et al., 2001). Watershed sediment and P export can be managed through the installation of best management practices (BMPs) that must be properly selected, sized and located on the landscape to be effective (Gitau et al., 2005). Recent research suggests that watershed P export is not uniformly distributed, but rather occurs in a spatially disproportionate manner (i.e. some landscape areas are more prone to P loss than others), in-turn suggesting a targeted approach to implementation should increase effectiveness and reduce cost (Nowak et al., 2006). In developing a targeted remediation strategy, watershed managers often rely on field monitoring data and physically based computer models when selecting, sizing and locating BMPs. In algorithm development, model developers rely extensively on good quality monitoring data to understand runoff pollutant characteristics, which is in turn essential for developing a technically sound watershed remediation strategy.

Field-scale runoff monitoring of ephemeral channels is often done using flumes to measure flow in conjunction with automatic sampling equipment to collect samples for analysis of pollutant concentrations. Monitoring systems of this type are costly and labour intensive to operate, but do provide high-quality flow and pollutant concentration data for runoff load calculations (Phillips et al., 2000). An automated system, however, may not be well
suited for sediment characterization studies (e.g. sediment finger printing and particle characterization) that require multiple sampling sites and substantial sediment mass collection at each site (Phillips et al., 2000). To address sampling needs for sediment studies of this type, the University of Exeter (UE), UK, has developed a simple, inexpensive, ambient-flow-based sampler. The UE sampler uses a 1 m long × 10.2 cm diameter tube placed directly in the flow stream (Phillips et al., 2000; Russell et al., 2000). The sampler has historically been used in perennial streams (Walling et al., 2008), and this study is the first application of UE samplers in an ephemeral (intermittent) flow channel (i.e. grassed waterway).

The physical and chemical characteristics of sediment play an important role in modelling the PP loss mechanism. The mixture of runoff and sediment generated within a field is physically transported across a field as sheet and rill flow. When sheet and rill flow reach the vegetative field edge, the increased roughness at this flow path transition point reduces flow velocity, resulting in sediment deposition. Larger particles settle, while fines remain in the flow, thus altering the particle size distribution of the transported sediment (Jin and Romkens, 2001). Accounting for, changes in sediment particle size is important for PP transport modelling as the majority of the PP mass is sorbed to fine (〈50 µm) particles (i.e. P enrichment) (Pierzynski et al., 1990; Panuska, et al., 2008a). The chemical characteristics of transported sediment can also impact P binding mechanisms. Organic matter (OM) and hydrous metal oxides have a high specific surface area per unit volume making them chemically active and an important component of the P binding mechanism. Previous research found a significant relationship between metal hydroxides and OM in streambed sediments (Jarve et al., 2008; Palmer-Felgate et al., 2009). We therefore chose to include metals and OM analyses in our investigation to better understand the role played by these materials in PP transport and delivery.

Existing research on sediment and PP characteristics in ephemeral channels is limited. Widely used decision support models such as the Agricultural Policy Environmental EXtender (APEX, 2010) and the Soil and Water Assessment Tool (SWAT, 2010) route sediment and pollutants through the watershed drainage network to the outlet. The ability to effectively route sediment and particulate-attached pollutants depends on knowing sediment characteristics (e.g. particle size distribution, OM content, particle P enrichment and mass distribution by particle size). Improved understanding of particle size, P content and P binding mechanisms for particulates transported in ephemeral channels can be used to improve decision support models and ultimately improve watershed remediation.

Several analytical methods are available to provide the much needed information on sediment source areas and transport potential. Some of these methods include radiometric finger printing (Walling et al., 2008), fractionation by gravity settling to get sediment mass and pollutant content by particle size (Alberts et al., 1983) and P sorption capacity (SERA 17, 2009). Radiometric fingerprinting can require 8–10 g, fractionation 2–4 g and P sorption capacity 1 g of sample. Having an inexpensive sampler able to collect a sufficient representative mass of sediment to conduct the aforementioned analyses is critical to particulate delivery research.

This research had three goals: (i) to compare the PP and OM content of samples collected using the UE sampler against those from stations using flumes with fully automated sampling, (ii) to describe the sediment characteristics (particle size distribution, LOI and particle—P enrichment and mass distribution) in ephemeral channels (i.e. grassed waterways) draining a row crop corn and alfalfa production system in southwestern Wisconsin, USA and (iii) gain greater insight into the role of metals and OM in sediment P binding.

MATERIALS AND METHODS

Study sites and management

We installed two UE samplers between May 25 and July 12 2008 in the ephemeral grassed waterways draining a tilled corn and an alfalfa field at University of Wisconsin (UW)—Platteville Pioneer Farm located near Platteville in southwestern Wisconsin (42° 43′N, 90° 23′W), (Figure 1). Both fields have silt loam surface soil (Fine-silty, mixed, superactive, mesic Typic Argudolls.), Tama and Ashdale series. In spring 2008, the corn field was tilled using a Krause soil finisher, model 6115 prior to planting on May 6. The alfalfa field was in its second year of established alfalfa. No manure or P fertilizer was spread on either field during the study, with only the corn receiving starter fertilizer. The most recent P application for the corn field was in fall 2005 with the incorporation of liquid dairy manure at a rate of 97 kg ha⁻¹ total phosphorous (TP). The most recent P application for the alfalfa field was during fall 2004 with the incorporation of dairy pack and liquid dairy manure at a total rate of 36 kg ha⁻¹ TP. The grass cover on both waterways was sufficient to maintain a uniform stable channel bottom, with no channel bottom scour observed. Additional watershed and channel characteristic data for the study sites are summarized in Table I.

We installed two (1 m long × 10.2 cm diameter tube) UE samplers in the centre of each ephemeral grassed waterway, 0-3 m apart and located a sufficient distance (~24 m) upstream of the automated flume stations to avoid backwater impacts (Figure 2). We installed a vent tube equal in diameter to the sampler intake and outlet tubing (4 mm) in the top, downstream end of each sampler and extended it to the top of the downstream support post. Adjustable hose clamps firmly secured each leveled sampler to a 1 m post driven into the ground. We sealed the threads on both the front and rear cap using Teflon tape to prevent leakage and depressed the upstream ends of all samplers slightly into the channel bottom, setting the intake heights approximately 5 cm above channel bottom as shown in Table I.
EVALUATING TWO RUNOFF SEDIMENT SAMPLING METHODS

Table I. Watershed and channel physical characteristics and University of Exeter sampler installation details for the tilled corn and alfalfa fields at the University of Wisconsin—Platteville Pioneer Farm during the summer of 2008

<table>
<thead>
<tr>
<th>Watershed/samplers</th>
<th>Corn</th>
<th>Alfalfa&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Grassed waterways</th>
<th>Corn</th>
<th>Alfalfa&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (ha)</td>
<td>7.48</td>
<td>5.77</td>
<td>Total channel length (m)</td>
<td>200</td>
<td>152</td>
</tr>
<tr>
<td>Tube inlet height above channel bottom (cm)</td>
<td>5.2</td>
<td>5.8</td>
<td>Channel width (m)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.79</td>
<td>4.88</td>
</tr>
<tr>
<td>Average field slope (%)</td>
<td>5</td>
<td>5</td>
<td>Distance from UE sampler to automatic monitoring station (m)</td>
<td>27.9</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average channel slope (%)</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

<sup>a</sup> Alfalfa harvested for hay during the monitoring period on 6/18, 7/15.

<sup>b</sup> Measured at the tube sampler locations.

Sample collection and analysis

During July 2008, we collected surface soil samples (5 cm depth) from the fields using a 3 cm diameter, hand-held core sampler at the sampling density recommended for routine soil sampling in Wisconsin, 10–15 cores composited per 2 ha (Peters et al., 2007). All runoff samples (UE and automatic sampler) were collected within 12 h of the end of runoff and analysed within a month of collection. We transported all runoff samples to the laboratory on ice and stored them at 4°C prior to analysis.

UE samplers. We emptied all UE samplers after each runoff event, collecting one half of the sample volume (≈3.8 L), agitating the sampler to mix the contents, removing the threaded cap on the downstream end and pouring the contents into a clean bucket. We rinsed the inside of the sampler with distilled water and reinstalled it level and empty. To evaluate differences between paired UE samplers, we stored and analysed the contents of each separately.

Automated stations. All automated sites were installed and maintained by the U.S. Geological Survey (USGS), with event runoff samples collected by Pioneer Farm staff. The corn (USGS Station 424 314 090 240 601, activated 2002) and alfalfa (USGS Station 424 259 090 231 301, activated 2003) sites are part of a long-term runoff monitoring programme at the Pioneer Farm. Sampling and sample analysis methods for the automatic stations are described in Stuntebeck et al. (2008). The flow rate was monitored by H-flumes (corn site = 0.76 m; alfalfa site = 0.61 m) with a nitrogen gas bubble metre for flow measurement. Discrete samples were collected throughout the runoff hydrograph by an ISCO 3700R refrigerated sampler. Event-based flow composited samples were collected, iced and delivered to the UW Stevens Point Environmental Laboratory for analysis. Chemical analysis relevant to this study included suspended sediment, loss on ignition, total dissolved P and TP (Stuntebeck et al., 2008). Particulate P (sediment-bound P) was calculated as the difference between TP and total dissolved P. Rainfall data were collected at each site via a continuous recording gauge.

We developed the approximate channel flow velocity and depth relationship (rating curve) for each channel using Manning’s equation ($n = 0.035$), the measured
Figure 2. University of Exeter samplers installed in the grassed waterway outlets from tilled corn field (left) and continuous automated station from the alfalfa field (right) at the University of Wisconsin—Platteville Pioneer Farm

cross section at the UE sampler locations, measured channel slope and flow data. These data were estimated for each event and summarized for the range of events. This was done to describe the flow conditions experienced by the UE samplers during the study and thus provide a context within which to interpret our observations.

Sediment and soil chemical analysis. We extracted completely mixed, wet sub-samples from a Phipps and Bird Jar Tester (Model PB-900; Richmond, VA). These sub-samples were dried between 103 and 105 °C for 24 h and the sediment was used to determine the total solid (TS) content and mass loss on ignition (LOI). We calculated LOI as the difference between the dried weight at 105 °C and the weight after heating to 550 °C (APHA et al., 1995). The ratio of LOI to TS (LOI/TS) was considered as a surrogate variable for the portion of sediment consisting of OM and is expressed as a percentage of total sediment mass (% LOI). We conducted the TP analysis on the dried sediment using a Lachat® Autoanalyzer (Hach Company, Loveland, CO) following the standard molybdate-based colorimetric method at a wavelength of 880 nm (Murphy and Riley, 1962) after digestion. Prior to colorimetric P analysis, we conducted a 5 : 1 nitric–sulphuric acid digestion (30 min at 250 °C followed by 40 min at 380 °C) on a Lachat® block-digester followed by dilution to 50 ml with MilliQ-grade deionized water. We analysed the digestate using P standards prepared in an acid matrix similar to that of the diluted digested sample (1 : 50 H2SO4). We also conducted an ammonium-oxalate extraction by shaking 1 g of dry sediment for 2 h in the dark with 20 ml of a 0.2 M (NH4)2C2O4 solution at pH 3.0 (McKeague and Day, 1966). Solutions were filtered through Whatman 42 filter paper and analysed for P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al and Na by inductively coupled plasma optical emission spectroscopy (ICP-OES) at the University of Wisconsin Soil and Plant Analysis Laboratory. Soil samples were analysed for TP, particle size and soil test P (Bray P1).

Sediment particle fractionation. For this discussion, sediment size distribution refers to that obtained for an undispersed mixture comprising both primary particles (i.e. sand, silt and clay) and agglomerates of primary-particles, clay and OM (aggregates). We separated (fractionated) the remaining wet sediment into four size classes: <2 µm (clay), 2–10 µm (fine silt), 10–50 µm (coarse silt) and >50 µm (Toy et al., 2002). Fractionation into different size classes was achieved using first order settling (Stokes’ law) in a stepwise manner starting with the largest size class. Stokes’ law was used to determine the settling time for particles of a given diameter over a specified vertical distance. After separation, we dried and weighed each fraction, which was then digested and analysed for TP. A more detailed discussion on sediment size analysis methods is available in Panuska et al. (2008a). We analysed both the pre-fractionated bulk sediment and each individual fraction for TP. The accuracy of the fractionation procedure was assessed by comparing the mass weighted PP concentration for each fraction to the pre-fractionated bulk sample. The pre-fractionation mass was also compared to the sum of the individual fractions as a mass balance control.

RESULTS AND DISCUSSION

Field soil

Soils for both fields were silt loams with 19% sand, 53% silt and 28% clay. The mean corn field Bray-1 soil test P, soil TP and LOI were 77 mg kg⁻¹, 630 mg kg⁻¹ and 3.9%, respectively. All three soil parameters for the corn field were significantly (p < 0.05) less than those of the alfalfa field, which had a Bray-1 soil test P of 135 mg kg⁻¹, TP of 820 mg kg⁻¹ and LOI of 4.7%. The
greater P and % LOI values found in the alfalfa field were likely from higher manure P applications over several decades because of the close proximity of this field to the barns.

Precipitation and flow data

During the course of the study, we monitored eight runoff events from the corn site and six from the alfalfa site. The monthly rainfall totals (May = 17-16, June = 20-30 and July = 14-33 cm) observed during the study period were greater than long-term averages for May, June and July of 9-14, 11-05 and 11-00 cm, respectively. June was the wettest month at 9-25 cm greater than the 30-year average. No significant difference was found between sites in rainfall volume (p = 0.12) and average intensity (p = 0.51). Alternatively, the mean runoff coefficient (runoff/rainfall) for corn of 0.27 was significantly greater (p = 0.017) than that of alfalfa (0.11). The median peak flow rate for corn (0.384 m³/s) was significantly greater (p = 0.004) than that of alfalfa (0.123 m³/s), even though the channel slope for alfalfa (7%) was nearly twice that of corn (4%).

These results suggest that differences in land surface cover between sites likely impacted the hydrology. The corn plant date (May 6) and the first runoff event date (May 25) resulted in limited corn canopy coverage during the early study period. The runoff coefficient increased linearly from 0.15 (5/25) to 0.48 (6/12), after which time it decreased to 0.33 (6/15), 0.18 (7/10) and 0.32 (7/12). This observed trend appears counter to what would be expected given the development of the corn canopy during this same time period. A well-established surface crust was observed throughout the corn field on July 15, suggesting one possible explanation for the greater runoff volumes and rates at the corn site. The tilled corn soil surface was exposed to several high-intensity rainfall events during May and June prior to crop canopy development (Table II) that could have facilitated crust development. A similar runoff response was previously reported with crust formation by Panuska et al. (2008a) from like-textured soils with similar rainfall intensities.

<table>
<thead>
<tr>
<th>Event date</th>
<th>Rainfall (cm)</th>
<th>Duration (h)</th>
<th>Runoff (cm)</th>
<th>Peak flow rate (m³ s⁻¹)</th>
<th>Rainfall (cm)</th>
<th>Duration (h)</th>
<th>Runoff (cm)</th>
<th>Peak flow rate (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/25</td>
<td>3.28</td>
<td>5.25</td>
<td>0.50</td>
<td>0.368</td>
<td>3.25</td>
<td>2.13</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>5/29</td>
<td>5.63</td>
<td>22.7</td>
<td>1.05</td>
<td>0.346</td>
<td>5.63</td>
<td>22.7</td>
<td>0.072</td>
<td>0.014</td>
</tr>
<tr>
<td>6/5</td>
<td>3.64</td>
<td>10.4</td>
<td>0.41</td>
<td>0.233</td>
<td>2.95</td>
<td>3.58</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>6/7</td>
<td>7.44</td>
<td>22.3</td>
<td>2.82</td>
<td>0.696</td>
<td>7.44</td>
<td>17.6</td>
<td>1.11</td>
<td>0.286</td>
</tr>
<tr>
<td>6/12</td>
<td>4.51</td>
<td>8.55</td>
<td>2.18</td>
<td>0.467</td>
<td>3.03</td>
<td>3.55</td>
<td>0.27</td>
<td>0.046</td>
</tr>
<tr>
<td>6/15</td>
<td>1.57</td>
<td>11.20</td>
<td>0.92</td>
<td>0.346</td>
<td>0.93</td>
<td>4.05</td>
<td>0.02</td>
<td>0.009</td>
</tr>
<tr>
<td>7/10</td>
<td>4.26</td>
<td>8.70</td>
<td>0.75</td>
<td>0.327</td>
<td>6.12</td>
<td>8.70</td>
<td>1.05</td>
<td>0.260</td>
</tr>
<tr>
<td>7/12</td>
<td>2.92</td>
<td>2.62</td>
<td>0.93</td>
<td>0.346</td>
<td>2.92</td>
<td>2.62</td>
<td>0.63</td>
<td>0.122</td>
</tr>
<tr>
<td>Median</td>
<td>3.95</td>
<td>9.53</td>
<td>0.84</td>
<td>0.346</td>
<td>3.14</td>
<td>6.38</td>
<td>0.45</td>
<td>0.084</td>
</tr>
</tbody>
</table>

*NR = no or insufficient runoff volume for water quality sample analysis.

Runoff and sediment chemical characteristics

Sediment size and LOI characteristics. The unit area bulk sediment delivery, P loss and flow weighted mean concentrations from the automated samplers are summarized in Table III. The sediment mass captured by the UE samplers for corn ranged from 16–27 with a median of 23 g and for alfalfa was 1.3–2.6 with a median of 1.6 g. The median UE sampler mass range for corn is 0.00055% and 0.0041% of the median calculated automatic sampler load, respectively. We found the sediment delivery, % LOI and PP watershed export for corn were significantly greater (p = 0.002) than alfalfa. These results appear reasonable given the greater overall sediment delivery from the tilled corn (494 kg ha⁻¹) versus the alfalfa (4-6 kg ha⁻¹). For corn, 91% of the TP from the automated samplers was PP, correlated with greater soil loss for corn, as opposed to alfalfa with only 26%. Greater PP export from row crop production systems compared with that from non-row crop systems is consistent with previous studies (Uusitalo et al., 2001; Panuska, et al., 2008b).

The tilled corn site yielded sufficient storm event sediment mass for a meaningful analysis but we were unable to adequately evaluate the UE sampler performance under lower soil loss conditions from alfalfa due to a lack of sufficient sediment mass. All subsequent discussions of UE sampler sediment pertain only to the tilled corn site. When using UE samplers to monitor drainage areas with low soil loss, one should consider installing a greater number of samplers or plan to combine several events into a single sample, representing a longer time period (i.e. monthly or seasonally). We used two samplers at each site in order to acquire greater sediment mass from each runoff event. If multiple UE samplers are used to increase the sample mass, it is important that chemical and physical sediment characteristics from the individual samplers not differ significantly from one another. To answer this question we analysed each sampler from the tilled corn site individually.

A comparison of paired UE samplers indicated no significant (p > 0.23) difference in the mean PP concentration and % LOI between replicate non-fractionated
sediment samples. In addition, no significant ($p > 0.29$) difference was found between the paired samplers for the fractionated median sediment mass, PP or % LOI in sediment size classes <2, 2–10, 10–50 and >50 µm shown in Table IV. These results suggest the ephemeral channel draining the corn site had sufficient flow turbulence to maintain well-mixed conditions during runoff and that when sufficient flow velocity ($0.70–1.0$ m s$^{-1}$) and flow depth (0.11–0.15 m) exist, paired UE samplers placed in close proximity to one another (~0.3 m) in an ephemeral channel are likely to collect bulk and fractionated sediments with similar PP and % LOI characteristics. This is consistent with field observations showing noticeable waterway turbulence in both channels during runoff events.

Given the similarity in sediment characteristics between replicate samplers, it appears reasonable to use the average constituent concentrations from the paired collectors to represent individual storm events. Combining the sediment from paired UE samplers produced sufficient sediment mass to conduct size fractionation for eight individual runoff events (Table V). For the purposes of this discussion, the PP enrichment ratio (PPER) is defined as the sediment PP divided by soil PP. The calculation normalizes a sediment chemical constituent relative to levels found in the contributing watershed soils. Sediments >50 µm had a mass, P mass fraction and PPER less than sediments <10 µm. The PPER for sediments >10 µm was between zero and one. For sediments <10 µm the PPER increased with decreasing sediment size. We found the greatest sediment mass in the (silt) size fractions, 10–50 µm (61%) followed by the 2–10 µm (25%). The 10–50 µm size fraction also contained the greatest percentage of PP mass (43%), (Table V). The greater PPER and % LOI values for sediments <10 µm size are consistent with finer sediments having greater specific surface area and greater chemical activity. The mean ionic strength of water in the UE samplers was 670 µS/cm.

Comparing University of Exeter and automatic samplers. Like the PPER, the % LOI can also be expressed as a percentage (% LOIER) . The median cor n % LOIER from the UE samplers (1.9%) did not differ significantly ($p > 0.13$) from the automatic sampler (2.0%). The LOIER values for the UE sampler and automated station ranged from 1.5 to 2.1 and 1.4 to 2.3, respectively (Figure 3). Phillips et al. (2000) report similar comparisons of the sediment organic fraction between UE samplers and grab sampling from streams in the southern UK. It is interesting to note the lack of difference in % LOI between the automatic and UE sampler. Given the lower specific gravity of OM relative to mineral particles and...
the corresponding difference in settling time, one would expect to see significant % LOI differences between sampling systems resulting from OM being carried by flow through the UE sampler without settling. That a significant difference in % LOI did not exist suggests that much of the OM may be transported in association with mineral particles as part of water stable aggregates.

No correlations were found between $P_{\text{PER}}$ and flow rate, flow velocity, sediment, or PP loss. As shown in Figure 3, event-based $P_{\text{PER}}$ values for all events from the UE samplers were less than for the automated system. The median UE sampler $P_{\text{PER}}$ of 1.2 was significantly ($p = 0.012$) less than the automated sampler $P_{\text{PER}}$ of (1.5). When interpreting the statistical analysis results it is important to consider the small sample size ($N = 8$). Clearly with our small sample size, additional studies must be done before any conclusions can be drawn.

The difference in $P_{\text{PER}}$ could result from either fine (<2 $\mu$m) P-enriched sediments passing through the UE sampler, or larger sediments, such as aggregates, settling upstream of the automated station flumes. The passage of fine-grained sediments through the UE sampler would result in disproportionately great trapping of larger, less P-enriched sediments resulting in smaller $P_{\text{PER}}$ values. It is likely that both processes were occurring to some degree. Another factor that could have suppressed the $P_{\text{PER}}$ in the UE samplers was that they were installed empty. Though an air relief vent was installed, it would still take time for the samplers to fill, during which fine sediments would not be able to settle due to turbulence inside the sampler. Unfortunately, we were unable to obtain sediment samples from the automatic samplers for size analysis, thus limiting our ability to conclusively explain differences between sampling systems. Clearly each sampling system has limitations; therefore, the decision as to which system is the ‘truth’ is subjective. Any sampling method that alters stream flow velocity, as both of these methods do, alters sediment transport, thereby introducing errors. There are also errors introduced with one common alternative, hand grab sampling for this type of application; given the shallow (~0.15 m) flow depth, it would be difficult to collect a representative sample without impacting the channel bottom.

### Sediment $PP_{\text{PER}}$–LOI relationship.

We noted a significant ($r^2 = 0.75$) linear relationship for corn across all events between $PP_{\text{PER}}$ and % LOI in the sediment from the UE and automatic samplers (Figure 4). This relationship suggests that an association between OM and sediment $P$ concentration plays a significant role in the sediment $P$ concentration. We therefore conducted additional investigation into this relationship. Our initial focus was on the interaction among clay-size particles and % LOI across all sediment sizes. As shown in Figure 4, the $PP_{\text{PER}}$ concentration follows an increasing linear trend as sediment size decreases; exhibiting a distinct cluster for each size fractionation and for the

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**Table IV. Median mass fraction, particulate phosphorus (PP) and loss on ignition (LOI) characteristics from replicated runoff samples from the tilled corn field summarized by sediment size and for bulk sediment collected by the University of Exeter samplers at the University of Wisconsin—Platteville Pioneer Farm between May and July, 2008**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tilled corn—sampler A</th>
<th>Tilled corn—sampler B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;50 um</td>
<td>10–50 um</td>
</tr>
<tr>
<td>Mass fraction (%)</td>
<td>7.0</td>
<td>60</td>
</tr>
<tr>
<td>PP concentration (mg/kg)</td>
<td>543</td>
<td>569</td>
</tr>
<tr>
<td>Percent LOI</td>
<td>10</td>
<td>5.8</td>
</tr>
<tr>
<td>Phosphorus enrichment ratio</td>
<td>0.87</td>
<td>0.91</td>
</tr>
<tr>
<td>Bulk sediment</td>
<td>PP = 767 ppm, LOI = 8.1%, Er = 1.23</td>
<td>PP = 766 ppm, LOI = 7.5%, Er = 1.22</td>
</tr>
</tbody>
</table>

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**Table V. Median waterway sediment mass fraction, particulate phosphorus (PP) concentration, sediment $P$ mass fraction, $P$ enrichment ratio and loss on ignition (LOI) by sediment size and bulk sediment for the tilled corn field from the University of Exeter sampler at the University of Wisconsin—Platteville Pioneer Farm between May and July, 2008**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tilled corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;50um</td>
</tr>
<tr>
<td>Sediment mass fraction (%)</td>
<td>8.0</td>
</tr>
<tr>
<td>PP concentration (ppm)</td>
<td>510</td>
</tr>
<tr>
<td>PP mass fraction (%)</td>
<td>6.0</td>
</tr>
<tr>
<td>TP enrichment ratio&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.81</td>
</tr>
<tr>
<td>Loss on ignition—LOI (%)</td>
<td>10</td>
</tr>
<tr>
<td>Bulk sediment</td>
<td>PP = 736 ppm, LOI = 7.5%, $P_{\text{PER}}$ = 1.2</td>
</tr>
</tbody>
</table>

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<sup>a</sup> $PP_{\text{PER}}$ = particulate phosphorus; LOI = loss on ignition.
<sup>b</sup> Phosphorus enrichment ratio ($Er$) equals the soil total P (mg/kg)/sediment total P (mg/kg).
<sup>c</sup> TP enrichment ratio equals the sediment total phosphorus (ppm)/soil total phosphorus (ppm).

---

1. Constituent enrichment ratio (sediment constituent / soil constituent).

2. No automatic sampler data were available for 6/7/2008.

Figure 3. Particulate phosphorus (PP) enrichment ratio by event for the University of Exeter and automatic samplers from the tilled corn field at the University of Wisconsin—Platteville Pioneer Farm between May and July, 2008.

Sediment ammonium oxalate extractions. Ammonium-oxalate extractions were conducted for the sediment collected by the UE samplers in an attempt to better describe the PP, % LOI and sediment size relationship. Only those metals having the greatest correlation with OM (% LOI), Al, Fe, Mg and Cu are shown in Figure 5.

As shown in Figure 5, aluminium had the strongest correlation ($r^2 = 0.82$) with % LOI followed by copper ($r^2 = 0.78$). Though the copper–% LOI correlation was strong, copper mass was among the least of the metals suite analysed, thus making copper unlikely to have a significant impact on PP binding. Iron ($r^2 = 0.71$) and magnesium ($r^2 = 0.70$) had the next greatest metal–% LOI correlation. On the basis of abundance and % LOI correlation, the data suggest that aluminium, iron and magnesium likely play a significant role in PP binding. Similar in behaviour to PP, the extractable metal concentration and % LOI increased as sediment size decreased (Figure 5). The elevated metal concentration in the smallest size fractions likely results from the predominance of clay minerals in this size fraction. Like the PP–% LOI relationship, extractable metal-LOI regressions for sediment sizes <50 µm alone were stronger than correlations when >50 µm sediments were
CONCLUSIONS

Paired passive suspended sediment samplers typically used in perennial streams were installed in two ephemeral grassed channels draining tilled corn and alfalfa fields. No significant differences were found between paired samplers in PP concentration and % LOI in the captured sediments. No differences were found in fractionated sediment mass, PP or % LOI in size classes <2, 2–10, 10–50 and >50 µm, thus suggesting paired UE samplers could be combined to represent an event. We found sediments >50 µm in size had a lower PP mass fraction and lower PPER than finer material (<10 µm). We also noted the PPER for sediments >10 µm was less than 1 and did not change with % LOI, while for sediments finer than 10 µm PPER increases with decreasing particle size and increasing % LOI. We found the greatest sediment mass first in the 10–50 µm (course silt, 61%) and then in the 2–10 (fine silt, 25%) size fractions. The greater % LOI and PPER measured in the automated samplers suggest the UE samplers may capture a greater proportion of larger, less P-enriched sediments than the automatic samplers. We also found the PP in the runoff associates with OM and certain metals across all sediment sizes in a manner consistent with the increased specific surface area found with finer sediment sizes.

Transport of eroded sediment and P from fields to water bodies is one area of research and modelling that has significant knowledge gaps, one reason being that the field monitoring required to generate data is expensive and time-consuming to conduct. Thus, inexpensive, simple and rapidly installed sediment monitoring techniques can help provide more field data to close knowledge gaps and improve model predictions. The current study shows inexpensive, passive sampling to be a viable field sediment sampling method, but there can be important differences in data generated between passive and automated sampling, especially in the sediment size captured. Understanding these differences can help improve the design of passive sampling. Data from the present study provides relationships between sediment OM, metal and P properties that can perhaps be used to develop empirical P transport equations. Translating these data into models can in turn improve their predictions and their utility in assessing land management practices to reduce P loss.

ADDITIONAL RESEARCH NEEDS

To our knowledge, this study is the first published evaluation of UE samplers in ephemeral channels and the first characterization of TP, % LOI and size for the sediment collected. This study was an initial attempt to compare UE and automatic sampling under actual field conditions, but clearly additional investigation is needed to more
completely compare these systems. Therefore, we recommend that this evaluation be extended to other types of cropping systems in varied landscapes and include different channel slopes, channel lengths and channel vegetated cover types. Further studies should also include upland fields with a range of soil textual classes and soil loss. Devising a means to capture greater sediment mass from watersheds with low sediment delivery is a key challenge. A focused investigation needs to include sediment size analysis from both sampling systems in combination with direct measurement of channel flow velocity. Sediment size analysis may be best accomplished using laser methods as the masses can be low from either system. It would also be beneficial to extend the sediment chemical analysis to include a greater number of constituents.

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