**Effect of tillage on macropore flow and phosphorus transport to tile drains**

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**Key Points**

* Effect of tillage on event water contributions to tile discharge was assessed
* Event water accounted for between 26 and 69% of total tile discharge
* Tillage decreased event water and phosphorus delivery to tile drains

**Abstract**

Elevated phosphorus (P) concentrations in subsurface drainage water are thought to be the result of P bypassing the soil matrix via macropore flow. The objectives of this study were to quantify event water delivery to tile drains via macropore flow paths during storm events and to determine the effect of tillage practices on event water and P delivery to tiles. Tile discharge, total dissolved P (DP) and total P (TP) concentrations, and stable oxygen and deuterium isotopic signatures were measured from two adjacent tile-drained fields in Ohio, USA during seven spring storms. Fertilizer was surface-applied to both fields and disk tillage was used to incorporate the fertilizer on one field while the other remained in no-till. Median DP concentration in tile discharge prior to fertilizer application was 0.08 mg L-1 in both fields. Following fertilizer application, median DP concentration was significantly greater in the no-tilled field (1.19 mg L-1) compared to the tilled field (0.66 mg L-1), with concentrations remaining significantly greater in the no-till field for the remainder of the monitored storms. Both DP and TP concentrations in the no-till field were significantly related to event water contributions to tile discharge, while only TP concentration was significantly related to event water in the tilled field. Event water accounted for between 26-69% of total tile discharge from both fields, but tillage substantially reduced maximum contributions of event water. Collectively, these results suggest that incorporating surface-applied fertilizers has the potential to substantially reduce the risk of P transport from tile-drained fields.

**Keywords**

Event water, subsurface, preferential flow, isotope hydrograph separation, water quality

**1. Introduction**

Increases in the extent and severity of Harmful and Nuisance Algal Blooms (HNABs) in inland freshwater lakes around the world present a substantial risk to human and environmental health [e.g., Hudnell, 2010]. Proliferation of HNABs is, at least, partially due to excess phosphorus (P) loading from agricultural non-point sources [Smith et al., 2015]. Perceptions of P transport in agricultural landscapes have evolved over the past 30 years with both surface and subsurface flow pathways now recognized as important P delivery mechanisms [King et al., 2015a]. Throughout the Midwestern US and other poorly drained agricultural regions, P transport in tile drainage is of increasing environmental concern. In these regions, tile drains may export P at rates greater than those associated with overland flow [Jamieson et al., 2003; Reid et al., 2012], with concentrations commonly exceeding critical levels for accelerated eutrophication [King et al., 2015b].

Significant P loads are often measured in subsurface drainage water despite the normally high P adsorption capacity of subsoils [Djodjic et al., 1999]. Phosphorus buildup in surface soils following repeated applications of fertilizers and animal manures [Sharpley, 2003] combined with the rapid response of drainflow to tracer applications at the soil surface [e.g., Kung et al., 2000] and the visible connection between desiccation cracks, earthworm burrows, and tile drains [e.g., Shipitalo and Gibbs, 2000] has led many scientists to hypothesize that the high P loadings observed in tile drainage water during storm events are the result of P bypassing the soil matrix via macropore flow. Overwhelming support for this hypothesis has been documented [Simard et al., 2000; Geohring et al., 2001; Vidon and Cuadra, 2011; Klaus et al., 2013] and collectively these studies indicate that macropores are likely the primary flow pathway for P delivery to tile drains, especially in fine-textured soils [Beauchemin et al., 1998]. However, while results of these studies point to substantial P transport via macropore flow pathways, few studies have quantified event water contributions from tile-drained fields and assessed their relationship with P transport [Granger et al., 2010; Vidon and Cuadra, 2011; Klaus and McDonnell, 2013]

In addition to evaluating macropore flow in tile-drained landscapes, it is also of interest to understand how agricultural practices influence P transport in these flow paths. Agricultural practices, such as tillage, can substantially reduce the connectivity of macropores and the soil matrix infiltration capacity [Djodjic et al., 2002; Cullum, 2009]. Conceptually, tillage disrupts the continuity of the macropore network resulting in more torturous flow pathways for solute transport compared to no-tillage, which minimizes soil disturbance [Jarvis, 2007]. For instance, Andreini and Steenhius [1990] measured solute transport in soil columns that were either tilled or no-tilled. They found that in the no-tilled columns macropore flow resulted in the short-circuiting of the solute tracer, contrasting with predominantly matrix flow observed in the tilled columns. Despite the observed effects of tillage on the connectivity of macropores and on P transport, few studies have examined differences in macropore flow and P delivery to tile drains between tilled and no-tilled conditions at the field scale.

In this study, we extend recent work by Vidon and Cuadra [2010] and Klaus et al. [2013], who examined the impact of precipitation characteristics on soil hydrology and macropore-matrix interactions using isotope hydrograph separation (IHS), and use this approach to quantify macropore flow and P delivery in tile-drained fields with different management practices (i.e., tilled vs. no-tilled). IHS has provided hydrologists with new insights into streamflow generation over the past 40 years and has resulted in major advances in hydrologic research. IHS, however, has primarily been applied at the watershed scale in humid, forested systems, with only a few studies applying this approach in agricultural landscapes [Klaus and McDonnell, 2013]. Here we use a paired field experiment and employ multiple tracers within a series of seven spring storm events to investigate the source of discharging water at two tile-drained fields, the relationship between macropore flow and P transport, and the effect of fertilizer application and tillage practices on macropore flow and P delivery. Our specific research questions were:

1) What proportion of tile discharge is comprised of event and pre-event water?

2) What is the relationship between macropore flow and P delivery to tile drains?

3) Does tillage alter flow pathways through the soil and how does it influence P transport?

**2. Methods**

***2.1 Site description***

Two tile-drained fields in the Upper Big Walnut Creek (UBWC) watershed, located 40 km north of Columbus, Ohio (USA), were monitored as part of the current study (Fig. 1). The climate is humid continental (warm summer), with an average annual precipitation of 985 mm [King et al., 2014]. Both fields feature poorly to very poorly drained soils, which require subsurface drainage for economical agricultural production. Site characteristics for tile-drained field 1 (TD1) and tile-drained field 2 (TD2) are shown in Table 1. The drainage intensity of TD1 and TD2 is similar, with tile laterals spaced approximately every 15 m across both fields at a depth of 0.9 m. Historically, both fields were managed by the same producer and cultivated in 2- to 3-yr rotations of corn (*Zea mays L.*), soybean (*Glycine max L.*), and wheat (*Triticum aestivum L.*) using no-tillage (30+ yr). On May 6, 2014, the producer surface-applied monoammonium phosphate (MAP; 11-52-0) fertilizer and potash (K2O) to both fields. The MAP fertilizer application rate varied across the fields based on soil test values (Table 1). Figure 2 shows the field surface with the broadcasted fertilizer and visible soil cracking, which was representative of field conditions at both TD1 and TD2 following fertilizer application. Two days after fertilizer application (May 8, 2014), disk tillage was used to incorporate the fertilizer in TD1, while TD2 remained in no-till with the fertilizer broadcast on the soil surface.

***2.2 Precipitation and tile discharge measurements***

Precipitation and tile discharge were measured continuously from mid-April through mid-June 2014 (Fig. 3). Precipitation was measured using both a tipping bucket rain gauge (Teledyne Isco 674) and a standard rain gauge (NovaLynx 260-2510), which were located between TD1 and TD2 (Fig. 1). Tipping bucket measurements provided data on rainfall duration, intensity, and depth. The standard rain gauge provided an additional measurement of volumetric rainfall depth and also served to collect precipitation samples for analysis. Tile discharge was measured using compound weir inserts (Thel-Mar Co.) that were installed at the tile outlet. Each tile outlet was instrumented with an Isco 4230 Bubbler Flow Meter, which recorded flow depth every 10 min. An Isco 2150 Area Velocity Sensor was also installed in each tile outlet to determine discharge under submerged conditions. Tile discharge rates were calculated for both TD1 and TD2 using the 10-min measured stage in conjunction with the standard rating curve for the compound weir insert or the area velocity data.

***2.3 Water quality sampling and analysis***

Water samples from TD1 and TD2 were collected using an Isco 6712 Portable Sampler that was installed at each tile outlet. The sample collection line from each Isco sampler was located at least 1.0 m into the tile drain to prevent samples from being contaminated by stream water when the tiles were submerged. Based on previous monitoring of these fields, each sampler was triggered when the depth of water in the tile exceeded 0.1 m. When this depth threshold was met, water samples were collected every 15 min and four samples were composited into each 1 L bottle (i.e., 1 bottle = 1 h). A second Isco sampler at each tile outlet continuously collected water samples on a daily interval (1 sample/6 h; 4 samples/bottle). Daily samples were used to assess water quality conditions in tile discharge prior to each storm event.

All water samples (precipitation and tile drains) were analyzed for total dissolved P (DP), total P (TP), magnesium (Mg), potassium (K), and stable isotope ratios of oxygen (*δ18O*) and deuterium (*δD*). All water samples were retrieved quickly (<24 h) from the field following each storm, promptly separated into filtered (0.45 µm) and unfiltered subsamples, and were stored at 4oC prior to analysis. Water samples were analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES) on a Varian 730-ES Axial ICP Spectrometer, using methods adapted from U.S. EPA [1994]. Analysis of unfiltered samples followed aqua regia (25% 12 M HNO3 + 75% 12 M HCl) digestion. Oxygen-18 and deuterium isotopes in water were analyzed by wavelength-scanned cavity ring-down spectroscopy on a Picarro Model 2140i at the University of Utah Stable Isotope Ratio Facility for Environmental Research (SIRFER). Samples were analyzed against lab reference values calibrated to Vienna Standard Mean Ocean Water (VSMOW). Instrument precision for *δ18O* and *δD* values was ±0.1‰.

***2.4 Hydrograph separation and data analysis***

Hydrograph separation using *δ18O* and *δD* was employed to separate tile drain discharge into pre-event and event water components. Within the context of the current study, we defined pre-event water (or old water) as water that was stored in the field prior to the tile-flow generating precipitation event, while event water (or new water) was the water from the current precipitation event. Macropores can transport both event and pre-event water to tile drains [Klaus et al., 2013], but the transport of event water in macropores is commonly associated with the rapid delivery of solutes from the soil surface to tile drains [Vidon and Cuadra, 2010]. It was assumed that event water transported to tile drains within a storm event was only possible through macropore flow given the low saturated hydraulic conductivities of the soils at the study site (Table 1). Indeed, using the one-dimensional form of Darcy’s law with a saturated hydraulic conductivity of 30 mm h-1 and a soil porosity of 45%, it would take >24 h for event water to reach the tile drain in the absence of preferential transfer via soil macropores. The subsurface drainage network at TD1 and TD2 were installed years prior to data collection; therefore, it was assumed that flow pathways for water and P were similar between the backfill material above tile laterals and the soil between tile laterals. When event and pre-event end-members had a distinct difference in their isotopic signature, a mass balance approach was used to separate the stormflow hydrograph into flow components:

where *QT* is the tile discharge, *QP* the contribution of pre-event water, *QE* the contribution of event water, *CT*, *CP*, and *CE* are the *δ* values of tile discharge, pre-event water, and event water, and *FE* is the fraction of event water in tile discharge.

To estimate uncertainty associated with the pre-event and event water fractions of total tile discharge, the Gaussian standard error method of Genereux [1998] was applied:

where *W* is uncertainty, *C* is the tracer concentration, *f* is the mixing fraction, and the subscripts *P*, *E*, and *T* refer to the pre-event, event, and tile discharge components, respectively. Uncertainty in tile discharge values (*WCT*) for both *δ18O* and *δD* were set equal to the analytical error (0.1‰) [Carey and Quinton, 2005], while variation in daily water samples collected during the 3 d preceding each storm event were used to quantify uncertainty in pre-event signatures (*WCP*) (between 0.1-0.2‰ for both *δ18O* and *δD*). The spatial variability of event water isotopic signatures was assumed to be negligible over the small area (<10 ha) monitored in the current study; however, temporal variability can still be significant [McDonnell et al., 1990]. Since bulk precipitation samples were collected in the current study, a Monte Carlo approach was utilized to simulate the temporal variability of event water values. Hourly isotopic signatures for event water were randomly generated for each monitored storm from a normal distribution with a mean value equal to the bulk precipitation signature. A total of 1,000 simulations for both *δ18O* and *δD* were completed for each of the seven monitored storms. Using this approach, event water signatures varied up to ±10‰ within a simulated storm, which is consistent with measured data in Midwestern landscapes [Iqbal, 2008]. Following each simulation, event hourly water signatures were weighted by hourly rainfall depth to calculate an event weighted mean value [McDonnell et al., 1990]. The standard deviation of the event weighted mean values from all simulations was used as a measure of the uncertainty in event water isotopic signature (*WCE*) (between 0.2-0.5‰ for *δ18O* and between 0.5-1.0‰ for *δD*).

To test the effect of tillage practices on event water transport through macropores, tile discharge characteristics (maximum tile flow, average tile flow, hydrograph response time, and time to peak) as well as *FE* were compared before and after the tillage operation and between tilled and no-till fields. Mann-Whitney rank sum test was used to evaluate the effect of tillage practices on DP and TP concentrations in tile discharge. Linear regression was employed to determine the relationship between P concentrations and both tile discharge and *FE*. Cation concentration patterns were also used to qualitatively relate DP and TP concentration patterns to pre-event and event water contributions in tile discharge. DP and TP loads were calculated for each storm. To calculate nutrient load, the hourly analyte concentration was multiplied by the hourly volumetric tile discharge. All data were analyzed in SigmaStat 12.5 [Systat Software, 2013]. A probability level of 0.05 was used to evaluate statistical significance.

**3. Results**

***3.1 Storm characteristics and tile discharge***

A total of seven storm events were large enough to generate tile flow in excess of the minimum depth threshold required to initiate sampling (Fig. 3). With the exception of storms 2 and 6 (bulk precipitation < 17 mm), tile flow generating storms were between 26 and 35 mm bulk precipitation (mean bulk precipitation = 26.3 mm) (Table 2). Average and maximum precipitation intensities tended to increase over the study period as storms transitioned from late-spring rainfall to early-summer thunderstorms. Antecedent precipitation varied widely among storms, with 7-day antecedent precipitation ranging from 0.8 to 39.5 mm and 30-day antecedent precipitation between 87.4 and 146.7 mm (Table 2).

Tile discharge prior to start of each storm was generally less than 0.05 mm h-1 (Table 2). Average tile discharge during storms ranged from 0.11 to 1.19 mm h-1, with maximum discharge rates between 0.30 and 3.12 mm h-1. Average tile discharge was significantly related to both average precipitation intensity (R2 = 0.42; p = 0.012) and 7-day antecedent precipitation (R2 = 0.33; p = 0.030). The ratio of tile discharge to precipitation was also significantly related to 7-day antecedent precipitation (R2 = 0.48; p = 0.006) (Table 2). During storms 1 and 2, TD1 and TD2 responded similarly in terms of average and maximum tile discharge, hydrograph response time (i.e., the time between the beginning of precipitation and the beginning of a perceptible increase in discharge), and time to peak (i.e., time between the start of the rising limb and the peak in discharge). Tillage of TD1 was consistent with a substantial decrease in average and maximum tile discharge and an increase in the hydrograph response time and time to peak compared to TD2 during storm 3 (Table 2). Differences in average and maximum discharge and time to peak between TD1 and TD2 were also observed during storm 4, but minimal differences were observed during storms 5 through 7 (Table 2).

***3.2 Isotope hydrograph separation***

The *δ18O* and *δD* isotopic signature of precipitation and tile discharge were distinctly different for each storm; thus, the hydrographs could be separated into event and pre-event flow components. The *δ18O* signature of precipitation varied from -9.0 to -2.8‰ over the study period, while *δ18O*of pre-event tile water was similar between TD1 and TD2 and ranged from -8.0 to -7.3‰. The *δD* signature of precipitation was between -57.7 and -7.6‰, whereas the *δD* signature of pre-event tile water was between -49.6 and -45.4‰ for both TD1 and TD2. Patterns of *δ18O* and *δD* in tile discharge during storms were similar (Fig. 4; Fig. 5). Maximum values of *δ18O* and *δD* in tile discharge were observed in the first samples collected during a storm event and were also often associated with hydrograph peaks (Fig. 4; Fig. 5). Based on hydrograph separation conducted with *δ18O*, event water contributions to total tile discharge were between 26 and 69% for both TD1 and TD2, with an average of 44% (Table 3). Uncertainty estimates associated with the event water fraction of total tile discharge using *δ18O* values ranged from 2 to 16% (Table 3). Results from hydrograph separation using *δD* were not significantly different from hydrograph separation using *δ18O*, with event contributions to total tile discharge ranging from 14 to 62% (mean = 38%). Similar to *δ18O*, uncertainty estimates associated with the event water fraction of total tile discharge using *δD* values were between 4 and 12% (Table 3). Event water contributions to tile discharge for storms 1 through 4 are shown in Figures 4 and 5.

The event water fraction of total tile discharge was similar between TD1 and TD2, even after the tillage of TD1 (Table 3). However, reductions in tile discharge at TD1 following tillage resulted in larger volumes of event water at TD2 compared to TD1 (Table 3; Fig. 5). Prior to tillage (storms 1 and 2), total event water contributions to tile discharge were 12.6 and 10.8 mm at TD1 and TD2, respectively. After tillage (storms 3 through 7), total event water contributions to tile discharge were substantially greater at TD2 (23.0 mm) compared to TD1 (17.6 mm). Patterns of *δ18O* and *δD* during storms, which were similar between TD1 and TD2 prior to tillage (Fig. 4), also varied between fields following tillage, especially during storms 3 and 4 (Fig. 5). The *δ18O* and *δD* signature of tile water at TD2 exhibited a large peak on the rising limb of the hydrograph, followed by a rapid decline to pre-event values. In comparison, the peak in *δ18O* and *δD* of tile water on the rising limb of the hydrograph at TD1 was much smaller than that observed at TD2, but *δ18O* and *δD* levels at TD1 steadily declined and remained greater than those at TD2 throughout the falling limb of the hydrograph.

***3.3 Cation concentration patterns***

For all seven monitored storms, a clear dilution pattern was observed for Mg2+, with minimum Mg2+ concentrations between 3.0 and 5.0 mg L-1 observed during or immediately after the peak in tile discharge (Fig.4; Fig. 5). An opposite, but consistent, pattern was observed for K+ concentration (Fig. 4; Fig. 5). Maximum K+ concentrations were typically found during the rising limb of the hydrograph, with concentrations declining throughout the remainder of the storm. Similar to patterns of *δ18O* and *δD* in tile discharge, Mg2+ and K+ concentration patterns were affected by tillage (Fig. 4; Fig. 5). The dilution of Mg2+ concentration was more pronounced at TD2 than at TD1 after tillage compared to the storms prior to tillage. Peaks in K+ concentration at TD2 also tended to be larger than peaks in K+ concentration at TD1 after tillage and K+ concentrations returned to pre-event levels quicker at TD2 than at TD1.

***3.4 Phosphorus concentrations and loads***

Median DP concentration during storms 1 and 2 for both fields was 0.08 mg L-1, with concentrations ranging from 0.06 to 0.14 mg L-1 (Fig. 6). DP comprised between 17 and 21% of TP during these two storms (Table 4). Following fertilizer application, median DP and TP concentrations significantly increased in both TD1 and TD2. Median DP concentration during storm 3 was 0.66 mg L-1 at TD1 and 1.19 mg L-1 at TD2. Maximum measured DP concentrations during storm 3 were 1.11 and 4.69 mg L-1 for TD1 and TD2, respectively (Fig. 6). Compared to the storms prior to fertilizer application, DP accounted for a much larger proportion of TP during storm 3 through 6 (Table 4). Both median DP and TP concentrations decreased in each successive storm after fertilizer application and concentrations remained significantly greater at TD2 compared to TD1 (Fig. 6).

Patterns of DP and TP concentration during several of the monitored storms are shown in Figure 7. For both TD1 and TD2, DP concentrations showed little variability throughout storms 1 and 2. In comparison, TP concentrations tended to be greater on the rising limb of the hydrograph and during peak tile flow during these events. During storm 3, patterns of DP and TP were similar for both fields, with the greatest measured concentrations being observed during the rising limb and declining over the course of the storm. A similar pattern was observed for storms 4 through 7 for TD2 (Fig. 7). While TP concentrations during storms 4 through 7 at TD1 were greater on the rising limb of the hydrograph, greater DP concentrations were observed on the falling limb of the hydrograph (Fig. 7).

Neither DP nor TP concentration was related to tile discharge at TD2 (Table 4). However, TP concentration at TD2 was significantly related to event water contributions to tile flow during all of the monitored storms except for storm 2. Following fertilizer application (storms 3 to 7), DP concentration at TD2 was also significantly related to event water contributions (Table 4). Similar to TD2, TP concentration at TD1 was significantly related to event water contributions to tile flow during all of the monitored storms except for storm 2, but DP concentration was only significantly related to event water contributions to tile flow during storm 3. Phosphorus concentration at TD1 was also significantly related to tile discharge during storms 3 and 4 for DP and storms 3 through 5 for TP.

Phosphorus loads were calculated for each storm using measured concentrations and tile discharge from both TD1 and TD2 (Table 5). DP and TP loads were similar between both fields during the first two storms, with loads being slightly greater for TD2 compared to TD1. Cumulative DP loads for TD1 and TD2 during storms 1 and 2 were 29.1 and 32.1 g ha-1, respectively; while, cumulative TP loads were 152.4 and 186.3 g ha-1. Phosphorus loads were nearly 7× greater for TD2 compared to TD1 during storm 3, and 4× greater during storm 4 (Table 5). The cumulative DP load for all seven storms was 106.4 and 381.2 g ha-1 for TD1 and TD2, respectively, while the cumulative TP load was 362.3 and 738.0 g ha-1 for TD1 and TD2.

**4. Discussion**

***4.1 Macropore flow dynamics during storm events in drained agricultural landscapes***

Synthesizing results from the IHS and cation concentration patterns indicated that event water represented a significant portion of tile drain discharge. IHS showed that event water comprised between 25 and 69% of total tile discharge during spring storm events when using *δ18O* values and between 14 and 62% when using *δD* values. Increased K+ concentration and dilution of Mg2+ concentration in tile water as discharge and event water contributions increased were also consistent with the preferential transfer of water via soil macropores. Indeed, although K+ concentration in precipitation was not greater than that in tile discharge (0.1-0.3 mg L-1), potash (K2O) was surface-applied to both TD1 and TD2, and is typically associated with overland flow [e.g., Bertol et al., 2007]. Similarly, the dilution pattern observed for Mg2+ was consistent with the dilution of soil water (i.e., pre-event water) as tile discharge increased [e.g., Vidon and Cuadra, 2010]. Ratios of event water to total tile discharge reported in the literature vary widely (1 to >90%) between studies and among events likely due to differences in soil type, management, and precipitation characteristics. Results from the current study and others, however, suggest that generally between 10 and 50% of total tile discharge can be attributed to event water that is transported via macropores [Stone and Wilson, 2006; Granger et al., 2010; Vidon and Cuadra, 2010; Klaus et al., 2013]. A conceptual model of water flow pathways and processes in tile-drained fields as well as implications for P transport is presented in Figure 8.

Patterns of tile water isotopic signatures that were observed in the current study point toward contrasting mechanisms controlling macropore flow on the rising and receding limbs of the hydrograph. The largest relative contributions of event water to tile drain discharge occurred during the first samples collected on the rising limb of the hydrograph. This suggests that some macropore flow paths were active prior to saturation [Nimmo, 2012] and that this initial flow to tile drains was likely initiated at the soil surface [Weiler and Naef, 2003]. As the storm progressed and soils neared saturation, tile discharge transitioned from predominantly event water to a mixture of both event water and pre-event water, which was likely due to the interaction between macropore flow paths and the surrounding soil matrix [Arora et al., 2012; Greve et al., 2012; Klaus et al., 2013]. Specifically, Klaus et al. [2013] found that tile drain discharge during peak flow was sourced within the upper soil profile (0.2 to 0.4 m) and when this soil layer became saturated or nearly saturated macropore flow was initiated. They concluded that during peak flow water transport was governed by macropore flow, but the macropore flow itself was a mixture of event water and displaced pre-event water. Results from the current study therefore suggest the potential for both unsaturated and saturated macropore flow within a single storm event. We hypothesize that tile discharge on the rising limb of the hydrograph was dominated by unsaturated macropore flow, which was the result of precipitation entering cracks (and other preferential flow paths) at the soil surface and being rapidly transported to the tile drain with minimal interaction with the soil matrix (Fig. 8). As the soil became saturated, macropore flow continued to be the primary flow path to tile drains, but under nearly saturated or saturated conditions the interaction between macropores and matrix increased and as a result macropore flow was a mixture of event and pre-event water (Fig. 8).

Despite the tillage operation disrupting the soil surface, event water was still transported to TD1 during the storms immediately following disk tillage. The relative ratio of event water to total tile discharge during storms 3 and 4 was similar between tilled and no-tilled fields, but maximum relative contributions of event water on the rising limb of the hydrograph were substantially reduced in the tilled field compared to the no-tilled field. Even in tilled soils, macropore flow has been shown to occur under persistent or intense rain, either along ped faces or loose soil volumes between denser structural elements within the tilled layer or at the interface with the undisturbed subsoil [Jarvis, 2007] (Fig. 8). However, macropore density (i.e., macropores per unit area) and the direct connection between the soil surface and the tile drain was likely altered following tillage as evidenced by differences in the volume of tile discharge, the hydrograph response time, and time to peak between tilled and no-tilled fields. For example, Arora et al. [2011] found that macropore density significantly influenced water and solute transport in preferential flow pathways. As a result, the large initial contribution of event water on the rising limb of the hydrograph found in the no-till field during these storms was substantially dampened in the tilled field. It should also be noted that different tillage practices may have varying effects on the number, shape, continuity, and size distribution of the pore network [Strudley et al., 2008; Kahlon et al., 2013]; thus, under more intensive cultivation (e.g., moldboard plowing) the effect of tillage on disrupting macropore flow pathways would likely be greater than results observed in the current study.

The effects of disk tillage on tile drain discharge and event water contributions in the current study diminished rapidly (i.e., < 3 weeks; before storm 5) following the tillage operation. In fine-textured soils, raindrop impact and soil wetting and drying cycles after tillage can lead to consolidation, sealing, and crack formation of the soil surface, which creates a surface structure more susceptible to macropore flow; thereby negating any effects of the tillage practice [Mapa et al., 1986; Messing and Jarvis, 1993]. Several studies also have indicated that continuous macropores quickly re-establish after disruption by tillage. For instance, Andreini and Steenhuis [1990] reported that spring harrowing eliminated macropore flow, but when dye breakthrough experiments were replicated after harvest, they found no difference in macropore flow between tilled and no-tilled plots.

***4.2 Phosphorus dynamics during storm events in drained agricultural landscapes***

Elevated DP and TP concentrations in tile drainage coincided with peak event water contributions to discharge, especially in the no-till field, suggesting significant P loads were delivered to the drainage system via macropore flow pathways. Increased DP concentrations in tile drainage water during the storms immediately following surface application of fertilizer indicated that P transported to tile drains likely originated from P-rich surface soils (Fig. 8). Previous work using cesium-137 and phosphorus-33 isotopes, has also reported that elevated P concentrations in tile drain discharge originated from surface soil layers [Djodjic et al., 1999; Uusitalo et al., 2001] and that the addition of fertilizer to fields increases the risk of P delivery to tile drains [King et al., 2015a], with the largest risk of P loss occurring during the first event after application [Sharpley et al., 2001]. It is also possible that varying soil redox conditions due to episodic wetting-drying cycles [Scalenghe et al., 2012] and turbulent flow in macropores, which may erode sediment from the lining of these flow pathways [Beven and Germann, 2013], could both contribute to elevated P concentrations in tile discharge. Future work differentiating sources of P in tile discharge (i.e., P from the soil profile vs. P from applied fertilizers) is needed to better understand the relationship between macropore flow and P transport to tile drains and the interaction between macropores and the surrounding soil matrix.

Results of the current study indicate that tillage significantly decreased delivery of DP to tile drains during storm events. In the no-tilled field, DP concentration following fertilizer application was greatest on the rising limb of the hydrograph suggesting that precipitation entering cracks (and other preferential flow paths) at the soil surface transported the highly soluble MAP fertilizer to the tile drain (see Fig. 2 and Fig. 8). In comparison, tillage incorporated the fertilizer into the soil and reduced the likelihood that the fertilizer was in direct contact with macropore flow pathways [e.g., Simard et al., 2000]; thereby significantly decreasing DP concentration. Tillage also significantly impacted DP load by decreasing the maximum relative event water contributions to tile discharge and the total volume of water discharged in the tilled field compared to the no-tilled field during storms 3 and 4. The combined effects of tillage on DP concentration (e.g., incorporation) and soil hydrology (e.g., decreased maximum contributions of event water and tile discharge volume) during these two storms resulted in a cumulative DP load that was nearly 4× greater in the no-tilled field compared to the tilled field. While the effect of tillage on event water transport in macropore flow pathways and tile drain volume in the current study was only temporary, tillage after fertilizer application has the potential to substantially decrease seasonal and annual DP loadings to tile drains. These findings suggest that trade-offs need to be considered when using no-till as a best management practice for protecting water quality [e.g., Ulén et al., 2010]. Numerous studies have shown the benefits of no-till, such as increased infiltration (i.e., less surface runoff), increased soil organic matter, and reduced soil erosion, but results of this study indicate that no-till may lead to increased P delivery to receiving waters via subsurface flow pathways.

DP was the primary form of P measured in tile drainage water during storms immediately following fertilizer application, but ratios of DP concentration to TP concentration showed that for storms prior to fertilizer application particulate P (PP = TP – DP) was the main form of P. Previous work has also found that PP was the primary form of P in drainage water [Vidon and Cuadra, 2011], but following fertilizer or manure application, DP dominated P in tile drain discharge for a period of time before transitioning back to PP [Schelde et al., 2006]. The transition from DP back to PP following fertilizer application in the current study occurred quickly in the tilled field (after 1 storm event), but transitioned more slowly in the no-tilled field (after 4 events). This finding provides further evidence that the P delivered to tile drains in macropore flow pathways depends on the form of P present at the soil surface. Under the field conditions monitored in the current study, DP transport associated with event water was limited to the no-tilled field after surface application of fertilizer. In comparison, TP transport in association with event water occurred both before (PP dominated) and after (DP dominated) fertilizer application in the no-tilled field, as well as in the tilled field (PP dominated). It should be noted, however, that in fields with higher soil test P concentrations, results may vary compared to the results reported herein. We hypothesize that high soil test P levels in some fields could function as a labile source of P similar to a surface-applied fertilizer and result in delivery of DP to tile drains via macropore flow paths during storms throughout the year and not just immediately following fertilizer application.

**5. Conclusions**

Study results showed that disk tillage following fertilizer application decreased P concentrations and loads in tile drain discharge compared to a no-tilled field. In the no-tilled field, DP and TP concentrations were significantly related to event water contributions to tile drain discharge, with the largest P concentrations and contributions of event water occurring on the rising limb of the hydrograph. Event water transport through macropore flow pathways still occurred in the tilled field and was important for delivering TP to the tile drain, but by incorporating the fertilizer into the soil, reducing the maximum relative contributions of event water, and decreasing tile discharge volume, tillage decreased DP transport to tile drains. While the effect of tillage on the delivery of event water via macropore flow paths and tile drain discharge was temporary (< 3 weeks), P transport is often greatest during the storms immediately following fertilizer application. Thus, the effect of tillage on decreasing P loads during these critical events following application has the potential to substantially decrease annual P loads from tile-drained fields and highlights the need to consider trade-offs (e.g., increased infiltration, increased soil organic matter, and reduced soil erosion vs. increased P delivery vis subsurface flow pathways) when recommending no-till as a best management practice for protecting water quality.

It is important to note that the results from this study are only applicable to the spring season when vegetation cover is limited and evapotranspiration is moderate. As crop water demand and evapotranspiration losses increase throughout the summer, water and P transport to tile drains is likely to vary. Nevertheless, the spring season is the period of the year when most water and P losses from tile drains occur in the Midwest [King et al., 2015a, b]. Thus, study results significantly increase our understanding of macropore flow and the effect of tillage on P delivery in these pathways during a critical time of the year for water quality management. Future research should investigate macropore flow contributions to tile drains during different periods of the year to better understand their impact on annual water budgets. Differentiating between sources of P transported in tile drainage water (e.g., soil vs. fertilizer sources) and examining the effect of different tillage operations (e.g., moldboard plow, chisel plow) and application methods (e.g., banding or injection of fertilizer) will also be important for understanding how P is transported in macropore flow paths and the interaction between macropores and the surrounding matrix. In addition, incorporating the flow pathways and processes identified in this study into existing agricultural numerical models (e.g., APEX, DRAINMOD, SWAT, etc.) will be critical for improving estimates of P transport in tile-drained landscapes.

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**Tables**

**Table 1.** Characteristics of tile-drained field sites located in the UBWC watershed.

|  |  |  |
| --- | --- | --- |
| **Site characteristic** | **TD1** | **TD2** |
| Contributing area (ha) | 5.2 | 3.8 |
| Soil type (%) | | |
| Centerburg silt loam | 58.9 | 97.5 |
| Condit silt loam | 28.8 | - |
| Shoals silt loam | 12.2 | - |
| Sloan silt loam | - | 2.5 |
| Ksat (mm hr-1) † | | |
| 0 – 20 cm | 32.0-33.0 | 30.7-33.0 |
| 20 – 40 cm | 10.7-25.2 | 10.7-31.2 |
| 40 – 100 cm | 3.3-10.1 | 3.3-10.1 |
| Soil test phosphorus (mg kg-1)‡ | 35 (23-42) | 28 (23-38) |
| Fertilizer rate (kg P ha-1) | 47 (25-58) | 50 (25-58) |
| † Saturated hydraulic conductivity | | |
| ‡ Mehlich-3 soil test | | |

**Table 2.** Precipitation characteristics of seven spring storm events occurring between April and June 2014 and tile drain discharge characteristics from TD1 and TD2.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Precipitation characteristics** | | |  | |  | |  | |  | | | |
| Storm Event | Bulk precipitation | | Maximum intensity | | Average  intensity | | Event  duration | | 7 d antecedent precipitation | | 30 d antecedent precipitation | |
|  | (mm) | | (mm h-1) | | (mm h-1) | | (h) | | (mm) | | (mm) | |
| 1 (April 29) | 34.8 | | 8.7 | | 1.4 | | 24.5 | | 6.7 | | 138.7 | |
| 2 (April 30) | 16.3 | | 9.3 | | 0.9 | | 17.5 | | 39.5 | | 146.7 | |
| 3 (May 12) | 28.0 | | 9.9 | | 2.7 | | 10.5 | | 3.9 | | 87.4 | |
| 4 (May 15) | 30.9 | | 15.3 | | 1.8 | | 17.0 | | 38.1 | | 116.2 | |
| 5 (May 28) | 30.6 | | 24.6 | | 6.8 | | 4.5 | | 0.8 | | 118.8 | |
| 6 (June 4) | 16.7 | | 6.5 | | 3.4 | | 5.0 | | 30.6 | | 126.5 | |
| 7 (June 8) | 26.5 | | 16.9 | | 2.9 | | 9.0 | | 28.0 | | 143.0 | |
|  |  | |  | |  | |  | |  | |  | |
| **Tile drain discharge** | | | | |  | |  | |  | |  | |
| Storm Event | Baseflow | | Maximum tile flow | | Average tile flow | | Hydrograph response time | | Time to peak | | Discharge/ precipitation | |
|  | (mm h-1) | | (mm h-1) | | (mm h-1) | | (h) | | (h) | |  | |
|  | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 |
| 1 (April 29) | 0.00 | 0.05 | 2.06 | 2.47 | 0.49 | 0.43 | 2.0 | 2.0 | 22.5 | 20.5 | 0.47 | 0.43 |
| 2 (April 30)† | 0.28 | 0.12 | 2.69 | 2.82 | 0.87 | 0.98 | 0.5 | 0.5 | 14.0 | 13.5 | 1.15 | 1.22 |
| 3 (May 12) | 0.01 | 0.05 | 0.73 | 2.63 | 0.14 | 0.51 | 8.0 | 3.5 | 7.0 | 4.0 | 0.11 | 0.24 |
| 4 (May 15) | 0.03 | 0.08 | 2.18 | 3.12 | 0.63 | 1.19 | 1.5 | 1.0 | 15.0 | 8.5 | 0.83 | 0.89 |
| 5 (May 28) | 0.00 | 0.09 | 0.43 | 0.54 | 0.11 | 0.19 | 4.0 | 1.5 | 3.5 | 3.0 | 0.13 | 0.14 |
| 6 (June 4) | 0.00 | 0.02 | 0.30 | 0.62 | 0.15 | 0.27 | 3.5 | 3.5 | 4.0 | 4.0 | 0.14 | 0.19 |
| 7 (June 8) | 0.02 | 0.03 | 0.79 | 0.87 | 0.16 | 0.30 | 8.5 | 8.5 | 3.0 | 3.5 | 0.27 | 0.40 |
| † Discharge/precipitation for combined events 1 and 2: TD1 = 0.68; TD2 = 0.77 | | | | | | | | | | | | |

**Table 3.** Tile discharge, event water discharge determined by IHS, and the fraction of tile discharge comprised of event water for seven spring storm events. Uncertainty in event water contributions was estimated using the approach of Genereux [1998].

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Oxygen-18** | | | **Deuterium** | |
| **Tile** | **Event** | **QT** | | **QE** | **QE/QT** | **QE** | **QE/QT** |
|  |  | (mm) | | (mm) | (%) | (mm) | (%) |
| TD1 | 1 | 16.4 | | 5.7±1.0 | 35±6 | 4.4±0.6 | 27±4 |
|  | 2 | 18.7 | | 6.9±2.2 | 37±12 | 6.4±0.9 | 34±5 |
|  | 3 | 3.1 | | 1.6±0.1 | 53±4 | 1.5±0.2 | 48±7 |
|  | 4 | 25.6 | | 10.2±1.8 | 40±7 | 9.7±1.3 | 38±5 |
|  | 5 | 4.0 | | 2.0±0.6 | 50±16 | 1.9±0.4 | 47±10 |
|  | 6 | 2.3 | | 1.6±0.1 | 69±3 | 1.4±0.1 | 60±6 |
|  | 7 | 7.2 | | 2.2±0.8 | 31±11 | 1.2±0.6 | 16±8 |
|  |  |  | |  |  |  |  |
| TD2 | 1 | 15.0 | | 4.7±1.1 | 31±7 | 3.8±1.4 | 25±9 |
|  | 2 | 19.9 | | 5.2±3.0 | 26±15 | 5.2±1.2 | 26±6 |
|  | 3 | 6.7 | | 3.2±1.0 | 48±15 | 3.1±0.3 | 46±4 |
|  | 4 | 27.5 | | 11.6±1.7 | 42±6 | 11.0±1.9 | 40±7 |
|  | 5 | 4.3 | | 2.8±0.3 | 65±6 | 2.7±0.3 | 62±7 |
|  | 6 | 3.2 | | 2.0±0.1 | 63±3 | 1.7±0.2 | 53±5 |
|  | 7 | 10.6 | | 3.4±0.2 | 32±2 | 1.5±1.3 | 14±12 |
| QT = tile discharge; QE = event water; QE/QT = fraction of total tile discharge comprised of event water | | | | | | | |

**Table 4.** Mean percentage of DP in TP (%DP in TP) for each of the seven monitored storm events and the results from linear regression between both tile discharge and the fraction of event water in tile discharge and DP and TP concentrations.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Storm event** | **% DP in TP** | | **Discharge vs. DP** | | **Discharge vs. TP** | | **Event water**† **vs. DP** | | **Event water**† **vs. TP** | |
|  | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 | TD1 | TD2 |
| 1 (April 29) | 21 | 20 | 0.14 | 0.07 | 0.06 | 0.06 | 0.01 | 0.01 | 0.41\* | 0.45\* |
| 2 (April 30) | 20 | 17 | 0.03 | 0.00 | 0.14 | 0.03 | 0.07 | 0.00 | 0.14 | 0.02 |
| 3 (May 12) | 54 | 73 | 0.53\*‡ | 0.01 | 0.42\* | 0.01 | 0.75\* | 0.91\* | 0.49\* | 0.90\* |
| 4 (May 15) | 36 | 46 | 0.19\* | 0.10 | 0.47\* | 0.03 | 0.16 | 0.82\* | 0.24\* | 0.74\* |
| 5 (May 28) | 48 | 54 | 0.00 | 0.13 | 0.59\* | 0.00 | 0.16 | 0.98\* | 0.56\* | 0.62\* |
| 6 (June 4) | 46 | 70 | 0.07 | 0.03 | 0.09 | 0.12 | 0.02 | 0.74\* | 0.64\* | 0.60\* |
| 7 (June 8) | 28 | 31 | 0.04 | 0.00 | 0.11 | 0.06 | 0.13 | 0.71\* | 0.46\* | 0.65\* |
| † Percent of tile discharge attributed to event water. Event water contributions were determined using δ18O. | | | | | | | | | | |
| ‡ Asterisks indicate significant linear relationships (p < 0.05). | | | | | | | | | | |

**Table 5.** DP and TP loads from TD1 and TD2 during seven spring storm events. Total DP and TP loads for combined storms 1-2 (i.e., storms prior to tillage), storms 3-4 (i.e., first two events after tillage), storms 5-7, and total load for all seven storms are also shown.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Storm event** | **DP Load** | | **TP Load** | |
| **TD1** | **TD2** | **TD1** | **TD2** |
|  | (g ha-1) | | (g ha-1) | |
| 1 | 12.6 | 12.4 | 62.7 | 65.5 |
| 2 | 16.5 | 19.7 | 89.7 | 120.8 |
| 3 | 18.2 | 129.6 | 31.5 | 146.7 |
| 4 | 54.8 | 210.3 | 163.3 | 383.7 |
| 5 | 1.7 | 3.9 | 4.8 | 8.0 |
| 6 | 0.6 | 1.5 | 1.1 | 2.0 |
| 7 | 2.0 | 3.8 | 9.2 | 11.3 |
|  |  |  |  |  |
| 1-2 | 29.1 | 32.1 | 152.4 | 186.3 |
| 3-4 | 73.0 | 339.9 | 194.8 | 530.4 |
| 5-7 | 4.3 | 9.2 | 15.1 | 21.3 |
| Total | 106.4 | 381.2 | 362.3 | 738.0 |

**LIST OF FIGURES**

**Figure 1.** Map of two tile-drained fields (TD1 and TD2) located in central Ohio, USA that were monitored in this study.

**Figure 2.** Field surface with the broadcasted fertilizer and visible soil cracking, which was representative of conditions at both TD1 and TD2 following fertilizer application. Fertilizer prills are highlighted in green to aid in visualization.

**Figure 3.** Precipitation and tile discharge from TD1 and TD2 during seven storms between April and June 2014. Fertilizer was broadcast on May 6,2014. Disk tillage was used to incorporate the fertilizer at TD1 on May 8, 2014; TD2 remained in no-till.

**Figure 4.** Tile discharge, cation concentrations, and isotope signatures of tile water during storms 1 and 2. The ‘P’ symbols represent concentrations in pre-event water, while the ‘E’ symbols represent event water. The grey diamonds represent tile discharge attributed to event water contributions as determined by IHS.

**Figure 5.** Tile discharge, cation concentrations, and isotop*e* signatures of tile water during storms 3 and 4. The ‘P’ symbols represent concentrations in pre-event water, while the ‘E’ symbols represent event water. The grey diamonds represent tile discharge attributed to event water contributions as determined by IHS.

**Figure 6.** Boxplots of DP and TP concentration. Circles represent outliers, whiskers represent the 10th and 90th percentiles, the lower and upper edges of the boxes represent the 25th and 75th percentiles, and the horizontal line inside of the box represents the median. Letters denote statistical differences (p < 0.05) in median concentration between TD1 and TD2.

**Figure 7.** Tile discharge and DP and TP concentrations from TD1 and TD2 during storm events 1, 3, 5, and 7.

**Figure 8.** Conceptual model of macropore flow and phosphorus transport in tile-drained fields. (A) Macropore flow and non-macropore/matrix flow. Event water is rapidly transported to tile drains and bypasses the soil matrix when macropores are present compared to slower, tortuous flow pathways during non-macropore flow. (B) Unsaturated and saturated macropore flow. During unsaturated macropore flow, the majority of water delivered to tile drains is event water with elevated P concentrations from the soil surface. During saturated macropore flow, tile discharge is comprised of a mixture of event and pre-event water due to mixing along the flow pathway. P concentrations tend to be less than P concentrations during unsaturated macropore flow due to mixing with pre-event water and P adsorption. The length of the arrow indicates the relative contribution to tile drain discharge. (C) No-tillage and tillage. Relative contributions of event water are similar between no-tilled and tilled fields. P concentrations in no-tilled fields are often greater than P concentrations in tilled fields due to P stratification in no-tilled fields.

**Figure 1.** Map of two tile drained fields (TD1 and TD2) located in central Ohio, USA that were monitored in this study.



**TD2**

**TD1**

**0**

**100**

**200**

**meters**

Drainage area

Tile outlet

Rain gauge



Ohio, USA

UBWC

**Figure 2.** Field surface with the broadcasted fertilizer and visible soil cracking, which was representative of conditions at both TD1 and TD2 following fertilizer application. Fertilizer prills are highlighted in green to aid in visualization.



Fertilizer prill

**Figure 3.** Precipitation and tile discharge from TD1 and TD2 during seven storms between April and June 2014. Fertilizer was broadcast on May 6,2014. Disc tillage was used to incorporate the fertilizer at TD1 on May 8, 2014; TD2 remained in no-till.



**Figure 4.** Tile discharge, cation concentrations, and isotope signatures of tile water during storms 1 and 2. The solid line represents tile discharge. The ‘P’ symbols represent concentrations in pre-event water, while the ‘E’ symbols represent event water. The grey diamonds represent tile discharge attributed to event water contributions as determined by IHS. 

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Runoff

Precipitation

Tile drain

Non-macropore/

matrix flow

Macropore

flow

Precipitation

Runoff

Unsaturated

macropore flow

Saturated

macropore flow

Runoff

Precipitation

Tilled

No-tilled

**A)**

**B)**

**C)**

Event water

Pre-event water

Dissolved phosphorus

Particulate phosphorus

Macropore